3D elastic orthorhombic anisotropic full waveform inversion: Application to field OBC data

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Summary

For the purpose of extracting higher resolution information from a 3D field data set, we apply a 3D elastic orthorhombic (ORT) anisotropic full waveform inversion (FWI) to hopefully better represent the physics of the Earth. We utilize what we consider as the optimal parameterization for surface acquired seismic data over a potentially orthorhombic media. This parameterization admits the possibility of incorporating a hierarchical implementation moving from higher anisotropy symmetry to lower ones. From the analysis of the radiation pattern of this new parameterization, we focus the inversion of the 3D data on the parameters that may have imprint on the data with minimal tradeoff, and as a result we invert for the horizontal P-wave velocity model, an ε_1 model, its orthorhombic deviation, and the shear wave velocity. The inverted higher resolution models provide reasonable insights of the medium.

Introduction

In multi-parameter FWI, the choice of an optimal parameterization and a proper strategy are crucial to a successful inversion of the medium parameters because of the potential for tradeoff between the parameters. Many of the studies have focused on the VTI (Vertical Transverse Isotropic) medium, mainly based on the acoustic assumption; in which several studies have been dedicated to choosing the best medium parameterization (Operto et al., 2013; Gholami et al., 2013; Alkhalifah and Plessix, 2014). By focusing on reflection data from surface seismic acquisition, Alkhalifah and Plessix (2014) compared several acoustic VTI parameterizations and concluded that choosing horizontal P-wave velocity (v_{ph}) and two dimensionless parameters (ε and η) can be the best choice to recover P-wave velocity in the presence of diving waves. Based on this acoustic VTI parameterization, Alkhalifah (2016) showed that the influence of η is negligible so that we can perform the FWI for v_{ph} and ε only for the acoustic VTI FWI.

However, when we deal with orthorhombic (ORT) anisotropy, the inverse problem becomes more complicated because the large number of parameters involved in representing the medium, resulting in potentially large trade-off between the parameters. Based on the acoustic VTI parameterization of Alkhalifah (2016), Masmoudi and Alkhalifah (2016) suggested an acoustic ORT parameterization, in which two deviation parameters are introduced to take into account additional HTI influences. When we deal with elastic orthorhombic anisotropy, the inverse problem includes multi component data and the role

of shear wave velocities. In this case, the orthorhombic elastic medium is described by additional 3 parameters related to the role of shear waves. To find an optimal parameterization, Oh and Alkhalifah (2016) suggested a new elastic ORT parameterization that has reasonable hierarchical features, extending the acoustic ORT parameterization of Masmoudi and Alkhalifah (2016) to the elastic case.

In this study, based on elastic ORT parameterization suggested by Oh and Alkhalifah (2016), we describe a practical strategy to recover the ORT anisotropy. We apply this strategy of elastic ORT inversion to real field data from the North Sea.

Methodology

The objective function of the time-domain waveform inversion using the l_2 norm of residuals between modelled (u_s) and field (d_s) data can be expressed as

$$E(\mathbf{p}) = \sum_s \sum_r \int [d_s(r, t) - u_s(r, t, \mathbf{p})]^2 dt, \quad (1)$$

with

$$u_s(r, t, \mathbf{p}) = G_s(r, t, \mathbf{p}) * f_s(t), \quad (2)$$

where r , s and t denote the receiver, source and time, respectively; $\mathbf{p}$ represents the model parameter; $G_s(r, t, \mathbf{p})$ and $f_s(t)$ represent the Green's function and the seismic source function, respectively. To find the model parameter vector, $\mathbf{p}$, which minimizes the above objective function, we calculate the gradient direction necessary update $\mathbf{p}$ by taking the partial derivative of the objective function with respect to the model parameters as follows:

$$\frac{\partial E}{\partial p_k} = \sum_s \sum_r \int J_{s,k}(r, t, \mathbf{p}) [d_s(r, t) - u_s(r, t, \mathbf{p})] dt \quad (3)$$

where $J_{s,k}(r, t, \mathbf{p})$ is the partial derivative wavefields with respect to k^{th} model parameter. As shown in eq. (3), the gradient direction is obtained from the zero-lag cross correlation of the partial derivative wavefields with residual data. This means that the radiation patterns of the partial derivative wavefields for each parameter determines which part of the data will be used to invert that parameter.

For the forward modeling, we solve the elastic wave equation for ORT media using a 4th-order finite difference approximation (Graves, 1996) with CPML (Convolutional Perfectly Matched Layer; Rodenm and Gedney, 2000) to mitigate artificial reflections from the edge boundaries. To solve large-scale 3D elastic problem efficiently, we apply the domain decomposition method of Bohlen (2002). Thus, we utilize parallel computing to solve the elastic wave equation for each source and each sub domain. We conduct this large computational task on our local supercomputer made up of a Cray XC40 system (named 'Shaheen II').

To calculate the gradient direction, we use a hybrid domain approach, in which the forward and backward wavefields are calculated in the time domain, but the gradients are calculated in the frequency domain using a discrete Fourier transform (DFT) executed on the fly (Sirgue et al., 2007; Brossier et al., 2013). We scale the gradient direction using a pseudo Hessian matrix (Shin et al., 2001), and the source wavelet is estimated after every ten iterations (Kim et al., 2011).

Choice of the parameterization

Analyzing the radiation patterns of the partial derivative wavefields is a powerful tool to determine which parameterization is optimal and which strategy is proper for that parameterization. Based on the radiation patterns of 3D elastic ORT parameters, Oh and Alkhalifah (2016) suggested using the following elastic ORT parameters, using three deviation parameters, as follows:

$$(v_{p1} \ v_{s1} \ \varepsilon_1 \ \eta_1 \ \gamma_1 \ \delta_3 \ \varepsilon_D \ \eta_D \ \gamma_D) \quad (4)$$

The three deviation parameters are defined as

$$\varepsilon_D = \frac{\varepsilon_2 - \varepsilon_1}{1 + 2\varepsilon_1} \quad (5), \quad \eta_D = \frac{\eta_2 - \eta_1}{1 + 2\eta_1} \quad (6) \quad \text{and} \quad \gamma_D = \frac{\gamma_1 - \gamma_2}{1 + 2\gamma_2} \quad (7).$$

The seismic velocities, v_{p1} and v_{s1} , denote the horizontal P-wave velocity in x direction and the vertical S-wave velocity that are polarized in the $[x, z]$ plane. The parameter δ_3 indicates an anisotropic parameter δ in $[x, y]$ plane measured from the x axis. The parameters, $(\varepsilon_1, \eta_1, \gamma_1)$ and $(\varepsilon_2, \eta_2, \gamma_2)$, indicate the VTI parameters in the symmetry planes $[x, z]$ and $[y, z]$, respectively (Tsvankin, 1997; Alkhalifah, 2003). Figure 1 shows the P-P reflection radiation patterns, which are derived from an isotropic background medium with a horizontal layer and plotted as an opening angle that is summation of incidence and reflected angles (Oh and Alkhalifah, 2016). As Oh and Alkhalifah (2016) suggested, this parameterization has reasonable hierarchical features as we explain below.

Choice of the parameter-update strategy

Based on the radiation patterns of elastic ORT parameters, we introduce a hierarchical parameter-update strategy for real field data. From the radiation patterns (Figure 1), we observe three features. First, as Oh and Alkhalifah (2016) suggested, the 9 elastic ORT parameters can be divided into three groups; $(v_{p1}$ and $v_{s1})$, $(\varepsilon_1, \eta_1$ and $\gamma_1)$ and $(\delta_3, \varepsilon_D, \eta_D$ and $\gamma_D)$. Each group includes isotropic, VTI and ORT parameters, respectively, so that we can build up 9 ORT parameters in a hierarchical manner. In addition, the parameter γ_1 has no scattering potential along the reflection path, and the parameter δ_3 requires large offsets in the 45° acquisition azimuth angle (with respect to the symmetry axis) for resolution; weak imprint on our data. Secondly,

four parameters, S-wave velocity, η_1 , η_D and γ_D , suffer from severe trade-offs at 90° opening angle. This means that, if the S-wave velocity does not converge, the FWI for the other three dimensionless parameters should suffer from strong trade-offs with the S-wave velocity since the S-wave velocity is more influential. However, for real data, there is no guarantee that S-wave velocity converges to the true Earth value. For this reason, it would be a better choice if we invert only S-wave velocity without η_1 , η_D and γ_D .

Thirdly, there is minor trade-offs between ε_1 and ε_D . We expect highly resolved ε_1 as Alkhalifah (2016) mentioned. In contrast, we expect low resolution in ε_D at relatively shallow depths. For the deeper part, larger offset data along wide azimuth angle are required.

From the above three observations, we suggest a multi-stage FWI approach for the elastic ORT FWI. In the 1st stage, we invert for v_{p1} and v_{s1} to recover isotropic model. Then, we invert for ε_1 to recover the VTI characteristics with high resolution. This ε_1 represents mainly reflectivity information. Finally, we invert for ε_D to recover additional HTI characteristics using wide azimuth data.

Figure 1: P-P reflection radiation patterns of elastic orthorhombic parameters (Oh and Alkhalifah, 2016).

Application to field data

To test the elastic ORT FWI strategy on field data, we perform the multi-parameter FWI to 3D OBC dataset, which is acquired over the Volve field in the North Sea (Szydluk et al., 2007). The dimension of the FWI model is 12.3 km × 6.8 km × 4.5 km. The wavefields at the sea bottom are recorded using 12 cables with 400 m separation. Each cable contained 240 geophones with 25 m interval. The maximum offset is 5 km for all azimuth direction. For FWI, we choose 1200 shots, and we only use vertical

displacements as observed data. For cost purposes, the frequencies utilized in FWI are from 2.75 Hz to 5 Hz.

As a 1st stage of 3D elastic ORT FWI, we perform FWI to update only v_{p1} and v_{s1} to recover an isotropic elastic model. Figure 2 shows vertical slices of the initial and inverted P- and S-wave velocities after 50 iterations. We can observe horizontally layered structures at shallow depths. At 3.1 km depth, we observe a clear low velocity layer that could be a possible reservoir (Szydlik et al., 2007). From the depth slices in Figures 5d and 5e, some interesting structures are also observed at the reservoir level, such as the low velocity area.

In the 2nd stage, we invert ϵ_1 (20 iterations), which scatters its maximum energy at narrow opening angle, thus we can expect high-resolution information in the deeper structure. It will also help us fit the amplitude better. In the vertical sections (Figure 3), we observe that ϵ_1 in the low velocity layer at 3.1 km in depth also decreases. This observation indicates that the low velocity layer might be isotropic, but bounded by anisotropic layers (Figure 5f). After the 2nd stage, we invert for ϵ_D (10 iterations). We observed some HTI features that could be an influence of fractures (Figure 6f) show up. However, as we concluded from the radiation patterns, only shallow information (not reservoir-depth) of ϵ_D is recoverable (Figure 4). In Figure 7, we observe some improvements (green arrows) in the RTM image.

Conclusions

To make the complex 3D elastic orthorhombic anisotropic FWI more practical on real data, we implemented a hierarchical elastic ORT FWI strategy utilizing a new parameterization of the anisotropy. This parameterization includes two isotropic parameters (v_{p1} and v_{s1}), three VTI parameters (ϵ_1 , η_1 and γ_1) and 4 ORT parameters (δ_3 , ϵ_D , η_D and γ_D). Based on the parameterization using three deviation parameters, we developed a hierarchical parameter-update strategy, in which most of the parameters that influence the data are recovered moving from isotropic to VTI to ORT description of the model. Thus, for the OBC data we inverted for (v_{p1} , v_{s1} , ϵ_1 and ϵ_D), and the resulting models provided interesting insights into the medium and its anisotropic features.

Acknowledgments

The authors would like to thank Statoil ASA and the Volve license partners ExxonMobil E&P Norway and Bayergas Norge AS, for the release of the Volve data. The authors would like to thank Marianne Houbiers from Statoil for providing some helpful suggestions and corrections. We also thank the Shaheen II administrator team at KAUST for the computational support. We also thank the members of SWAG in KAUST, particularly Nabil Masmoudi and Ramzi Djebbi, for helpful discussions.

Figure 2: Initial (a and c) and inverted (b and d) models after 1st stage of FWI for horizontal P-wave (a and b) and S-wave velocities (c and d). The inline and crossline slices are chosen at 2.75 km and 9 km, respectively.

Figure 3: (a) Initial and (b) inverted models after 2nd stage of FWI for ϵ_1 at the same slices as Figure 2.

Figure 4: (a) Initial and (b) inverted models after 3rd stage of FWI for ε_D at the same slices as Figure 2.

Figure 5: Depth slices at 3.1 km of initial (a, b and c) and inverted (d, e and f) models: P- (a and d), S-wave velocities (b and e) and ε_I (c and f).

Figure 6: Depth slices at 1.5 km of initial (a, b and c) and inverted (d, e and f) models: P-wave velocity (a and d), ε_I (b and e) and ε_D (c and f).

Figure 7: Acoustic orthorhombic RTM results for (a) initial and (b) inverted models. Green arrows indicate interesting structures and green dashed lines indicate the locations of each slice.

EDITED REFERENCES

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