Nonlinear inversion of seismic amplitude data for attenuation and layer-weaknesses

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Abstract

Based on a model of periodically layered media, we first express frequency-dependent stiffness parameters in terms of P-wave attenuation factor and lay-weaknesses. Using perturbations in frequency-dependent stiffness parameters for an interface separating two periodically layered media, we derive a linearized P-to-P reflection coefficient as a function of layer-weaknesses and P-wave attenuation factor, from which an expression of anisotropic and anelastic impedance is proposed. In order to estimate layer-weaknesses and P-wave attenuation factor, we first utilize a model-based damped least-squares inversion approach to estimate the anisotropic and anelastic impedances from frequency-components of partially-stacked seismic data. Using the estimated anisotropic and anelastic impedances, we implement nonlinear inversion for unknown parameter vector (P- and S-wave moduli, density, layer-weaknesses and P-wave attenuation factor), in which Bayesian Markov chain Monte Carlo algorithm is employed. Synthetic tests confirm that the unknown parameter vector involving P- and S-wave moduli, density, layer-weaknesses and P-wave attenuation factor is estimated stably and reliably in the case of signal-to-noise ratio of 2. Applying the inversion approach to a field data set, we observe that reliable results of layer-weaknesses and P-wave attenuation factor are obtained. We conclude that the proposed inversion approach may provide additional proofs for reservoir characterization and fluid identification.

Introduction

Seismic waves exhibit anisotropy and attenuation characteristics when propagating in underground porous and cracked layers. Many studies focus on anisotropy features of seismic wave propagation that are induced by thin layers of sediments, and anisotropic features that are caused by vertical or sub-vertical fractures. Attenuation of seismic wave, which is caused by fluid movement between pores and fractures when wave passing the rock (known as wave-induced fluid flow, WIFF), have been well studied in the aspect of seismic rock physics.

Estimation of anisotropy and attenuation has become an important part of reservoir characterization. seismic inversion for VTI media focuses on employing seismic data of relatively large offset to estimate weak anisotropy parameters; for HTI media, amplitude variation with offset and azimuth (AVOAz) data are utilized for estimating variables sensitive to fractures, e.g., azimuthal seismic inversion for fracture weaknesses and compliances (Downton et al., 2015). Amplitude-variation with frequency data are employed to predict attenuation factor $1/Q$ based on the derived frequency-dependent reflection coefficient (Innanen, 2011). Chen et al. (2018) propose an inversion approach of employing frequency components of seismic data to estimate P- and S-wave attenuation factors based on anelastic impedance.

In the present study, we first express simplified stiffness parameters in terms of lay-weaknesses and attenuation factor based the periodically layered model, and then we derive an approximate frequency-dependent reflection coefficient and anisotropic anelastic impedance as a function of attenuation factor and layer-weaknesses. We establish an inversion approach and workflow of employing frequency-components extracted from seismic data to estimate unknown parameters involving P- and S-wave moduli, density, attenuation factor and layer-weaknesses. Noisy synthetic seismic data are utilized to testify the stability and robustness of the proposed inversion approach; and applying the inversion approach and workflow to real data sets, we generate reliable results of attenuation factors and layer-weaknesses.

Methods

In this section we will propose simplified stiffness parameters as functions of attenuation factors and weaknesses for periodically layered media that are constructed by a compliance layer and a stiff porous layer.

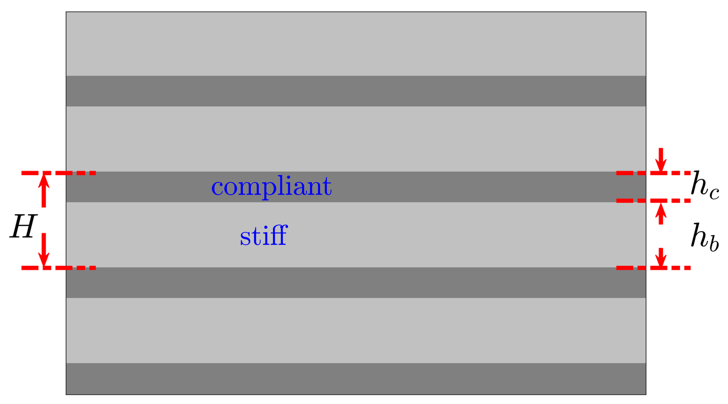

Figure: Periodically layered media. The quantities h_c and h_b represent thicknesses of compliant and stiff layers, and $H = h_c + h_b$.

Based on the model of periodically layered media and its stiffness matrix, we derive the approximate and linearized P-to-P reflection coefficient as

$$R_{PP}(\theta, f) = \frac{1}{4}\sec^2\theta\frac{\Delta M}{M} - 2\kappa\sin^2\theta\frac{\Delta\mu}{\mu} + \frac{\cos 2\theta}{4\cos^2\theta}\frac{\Delta\rho}{\rho} + \left[\frac{1}{2}\sec^2\theta - 2\kappa\sin^2\theta\left(\xi+1\right)\right]\Gamma_f\Delta\frac{1}{Q_P} - \frac{1}{4}\sec^2\theta\left(1-2\kappa\sin^2\theta\right)\Delta\delta_N + \kappa\sin^2\theta\Delta\delta_T. \quad (1)$$

We propose the normalized anelastic impedance as

$$\mathcal{A}_{EI}(\theta, f) = \left(\sqrt{M_0\rho_0}\right)\left(\frac{M}{M_0}\right)^{\mathcal{P}_M(\theta)}\left(\frac{\mu}{\mu_0}\right)^{\mathcal{P}_\mu(\theta)}\left(\frac{\rho}{\rho_0}\right)^{\mathcal{P}_\rho(\theta)} \exp\left[\mathcal{P}_Q(\theta, f)\frac{1}{Q_P} + \mathcal{P}_{\delta_N}(\theta)\delta_N + \mathcal{P}_{\delta_T}(\theta)\delta_T\right], \quad (2)$$

where M_0, μ_0, and ρ_0 are constants of P- and S-wave moduli and density, which can provided by well log data.
We proceed to the establishment of an approach that utilizes estimated results of $\mathcal{A}_{EI}$ to predict unknown parameters stably. The succinct relationship between anelastic impedance vector **d** and the unknown parameter vector **m** is expressed as

$$\mathbf{d} = \mathbf{G}(\mathbf{m}), \quad (3)$$

where

$$\mathbf{d} = \mathbf{A}_{EI}(\theta_i, f_j),$$
$$\mathbf{m} = \left[\mathbf{M}\ \boldsymbol{\mu}\ \boldsymbol{\rho}\ \mathbf{Q}_n\ \boldsymbol{\delta}_N\ \boldsymbol{\delta}_T\right]^T, \quad (4)$$

and **G** is an operator related to incidence angle and frequency. The solution of **m** is given by

$$\mathbf{m} = \mathbf{m}_0 + \zeta\Delta\mathbf{m}, \quad (5)$$

where $\mathbf{m}_0$ is initial guess of unknown parameter vector, and ζ is the vector of step length.
The initial model of attenuation factor is constructed using the function of *fakeq* in CREWES toolbox.

Results

Synthetic example

We generate seismic data using the generalized Zoeppritz equations, and then we add Gaussian random noise into the synthetic data (SNR=2), which are preserved as the input for estimating anelastic impedances, and then we utilize the estimated anelastic impedances to predict unknown parameters.

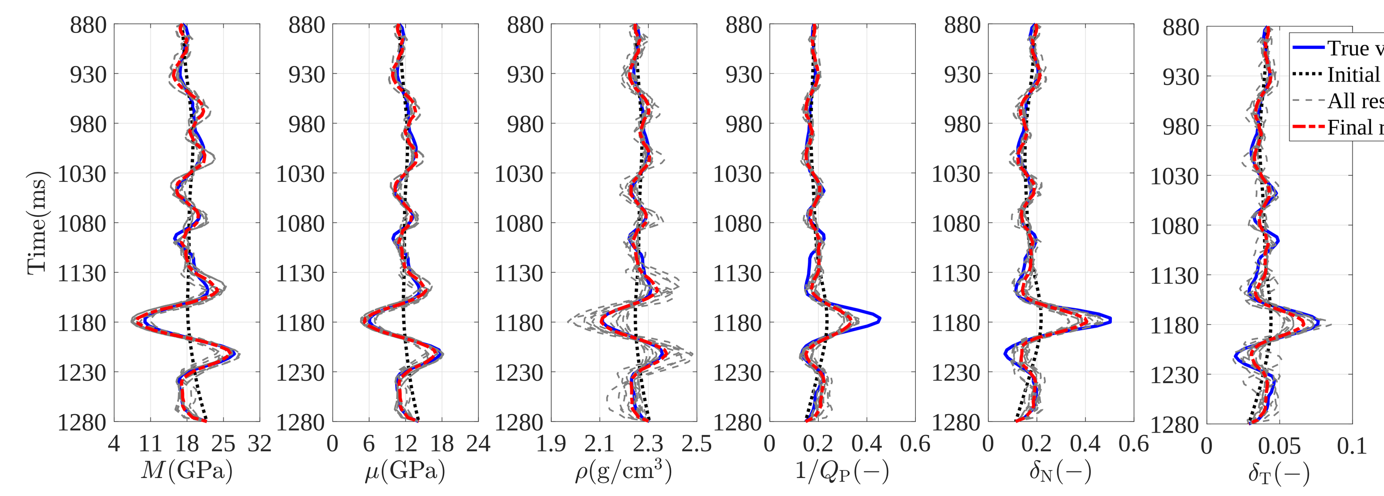

Figure: Comparisons between all the inversion results and true values of unknown parameters.

Real data

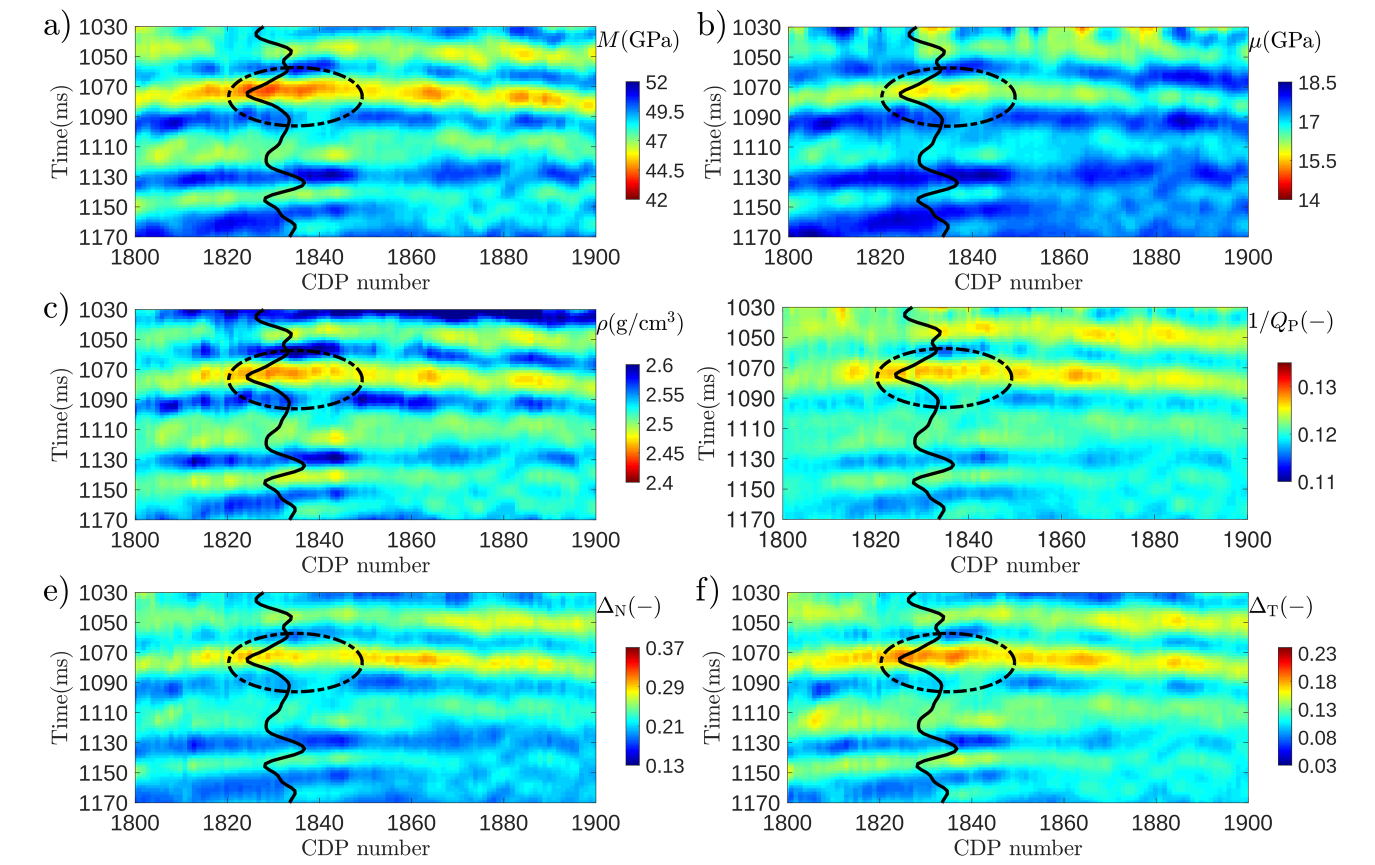

Figure: Inversion results of P- and S-wave moduli, density, P-wave attenuation factor and layer-weaknesses. The black curve indicates the P-wave velocity, and the ellipse indicates the location of gas-reservoir.

Conclusions

1) We derive the frequency-dependent and linearized P-to-P reflection coefficient as a function of reflectivities of P- and S-wave moduli and density and changes in attenuation factor and lay-weaknesses;
2) We establish an inversion approach and workflow of employing different frequency components of partially-incidence-stacked seismic data to estimate the unknown parameter vector using a Bayesian MCMC algorithm;
3) Test on synthetic data confirms that the inversion approach may produce stable results of unknown parameters in the case of SNR of 2. We finally apply the inversion approach and workflow to real data sets, from which reliable results of attenuation factor and lay-weaknesses that well match the reservoir, are obtained.

References

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