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Joint inversion of PP- and PSV-wave amplitude data for estimating P- and S-wave moduli and attenuation factor

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Abstract

We first propose frequency-dependent P- and S-wave moduli in terms of P- and S-wave moduli at a reference frequency and P-wave maximum attenuation factor, and we derive frequency-component PP- and PSV-wave reflection coefficients as a function of P-wave maximum attenuation factor. We establish a two-step inversion approach, which involves the estimation of attenuative PP- and PSV-wave anelastic impedances from frequency-components of partially-stacked seismic data, and the prediction of unknown parameter vector (P- and S-wave moduli, density and P-wave maximum attenuation factor) using the estimated PP- and PSV-wave anelastic impedances. Tests on synthetic and real data sets confirm that the unknown parameters are estimated stably and reliably and reliable results of P-wave maximum attenuation factor are obtained.

Introduction

Attenuation factor $1/Q$ is sensitive to rock properties (shale volume, porosity and permeability) and fluid content, which is useful for reservoir characterization. In the case of fractured rocks, seismic wave propagation is strongly affected by fractures and fluids within fractures. For the partially liquid-saturated fractured rock (e.g. fractures are filled with the mixture of gas and oil), seismic wave amplitude is influenced by frequency-dependent attenuation. Based on attenuation rock physics theory and effective models, geophysicists can analyze how the attenuation factor changes with rock properties and fluids given different values of frequency and implement the estimation of attenuation using seismic amplitude data.

The effect of attenuation factor on reflection coefficient has been studied. Morozov (2011) studies anelastic acoustic impedance in detail and explains how attenuation contrasts produce phase-shifted reflections. Based on extended Zoeppritz equations, Innanen (2011) presents expressions of attenuative reflection coefficients of P and S waves in terms of perturbations in P- and S-wave quality factors Q_{P} and Q_{S}. Using the reflection coefficients amplitude-variation-with-frequency (AVF) data are employed to estimate attenuation factors $1/Q_{\mathrm{P}}$ and $1/Q_{\mathrm{S}}$. Moradi and Innanen (2015) propose expressions of scattering of homogeneous and inhomogeneous seismic waves in low-loss viscoelastic media and express how reflection coefficients vary with offset and how features of amplitude variation with offset/angle (AVO/AVA) are influenced by attenuation angle. Starting with attenuative rock physics model, Chen et al. (2018) propose frequency-dependent reflection coefficient and anelastic impedance as a function of P- and S-wave attenuation factors.

In the present study, we begin with re-expressing P- and S-wave velocities and moduli in terms of P-wave attenuation factor, and we derive approximate and linearized frequency-dependent PP- and PSV-wave reflection coefficients by solving the Zoeppritz equations, and we also present expression of anelastic impedances of PP and PSV waves using the derived reflection coefficients. We present a two-step inversion approach of employing partially-incidence-stacked PP- and PSV-wave seismic data to estimate the unknown parameter vector involving P- and S-wave moduli, density and P-wave attenuation factor. Synthetic tests confirm the proposed inversion approach is stable and robust. Real data case verifies that reliable results of P- and S-wave moduli and P-wave attenuation factor can be estimated, which may provide an additional proof for reservoir characterization and fluid identification.

Methods

We derive the approximate and linearized reflection coefficients of PP and PSV waves by solving Zoeppritz equations

$$\begin{aligned} R_{\mathrm{PP}}\left(\theta_{\mathrm{P}},\omega\right) \approx & a_M\left(\theta_{\mathrm{P}}\right)\frac{\Delta M}{M} + a_{\mu}\left(\theta_{\mathrm{P}}\right)\frac{\Delta\mu}{\mu} + a_{\rho}\left(\theta_{\mathrm{P}}\right)\frac{\Delta\rho}{\rho} \\ & + a_Q\left(\theta_{\mathrm{P}},\omega\right)\Delta\left(\frac{1}{Q_{\mathrm{Pm}}}\right), \\ R_{\mathrm{PS}}\left(\theta_{\mathrm{P}},\omega\right) \approx & b_{\mu}\left(\theta_{\mathrm{P}}\right)\frac{\Delta\mu}{\mu} + b_{\rho}\left(\theta_{\mathrm{P}}\right)\frac{\Delta\rho}{\rho} \\ & + b_Q\left(\theta_{\mathrm{P}},\omega\right)\Delta\left(\frac{1}{Q_{\mathrm{Pm}}}\right), \end{aligned} \tag{1}$$

We first employ a model-constrained and damping least-squares algorithm to estimate PP- and PSV-wave anelastic impedances $\mathrm{EI}_{\mathrm{PP}}$ and $\mathrm{EI}_{\mathrm{PS}}$

$$\begin{aligned} \mathbf{e}_{\mathrm{PP}}\left(\theta_{\mathrm{P}I},\omega_k\right) = & \mathbf{e}_{\mathrm{PP}}^{\mathrm{mod}}\left(\theta_{\mathrm{P}I},\omega_k\right) \\ & + \left(\mathbf{L}_{\mathrm{PP}}^{\dagger}\,\mathbf{L}_{\mathrm{PP}} + \sigma_{\mathrm{P}}\mathbf{I}\right)^{-1}\mathbf{L}_{\mathrm{PP}}^{\dagger}\left[\mathbf{s}_{\mathrm{PP}}\left(\theta_{\mathrm{P}I},\omega_k\right) - \mathbf{L}_{\mathrm{PP}}\,\mathbf{e}_{\mathrm{PP}}^{\mathrm{mod}}\left(\theta_{\mathrm{P}I},\omega_k\right)\right], \\ \mathbf{e}_{\mathrm{PS}}\left(\theta_{\mathrm{P}I},\omega_k\right) = & \mathbf{e}_{\mathrm{PS}}^{\mathrm{mod}}\left(\theta_{\mathrm{P}I},\omega_k\right) \\ & + \left(\mathbf{L}_{\mathrm{PS}}^{\dagger}\,\mathbf{L}_{\mathrm{PS}} + \sigma_{\mathrm{S}}\mathbf{I}\right)^{-1}\mathbf{L}_{\mathrm{PS}}^{\dagger}\left[\mathbf{s}_{\mathrm{PS}}\left(\theta_{\mathrm{P}I},\omega_k\right) - \mathbf{L}_{\mathrm{PS}}\,\mathbf{e}_{\mathrm{PS}}^{\mathrm{mod}}\left(\theta_{\mathrm{P}I},\omega_k\right)\right]. \end{aligned} \tag{2}$$

We proceed to the prediction of unknown parameter vector that involves P- and S-wave moduli, density and P-wave maximum attenuation factor. Relationship between the vector of EI datasets **d** and the unknown parameter vector **m** is given by

$$\mathbf{d} = \mathbf{G}\left(\mathbf{m}\right), \tag{3}$$

where

$$\mathbf{d} = \begin{bmatrix} \mathbf{e}_{\mathrm{PP}} \\ \mathbf{e}_{\mathrm{PS}} \end{bmatrix}, \quad \mathbf{m} = \begin{bmatrix} M \\ \mu \\ \rho \\ 1/Q_{\mathrm{Pm}} \end{bmatrix}, \tag{4}$$

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

$$\mathbf{m} = \mathbf{m}_0 + \zeta\Delta\mathbf{m}, \tag{5}$$

where $\mathbf{m}_0$ is initial guess of unknown parameter vector, and ζ is the vector of step length.

Results

Synthetic example

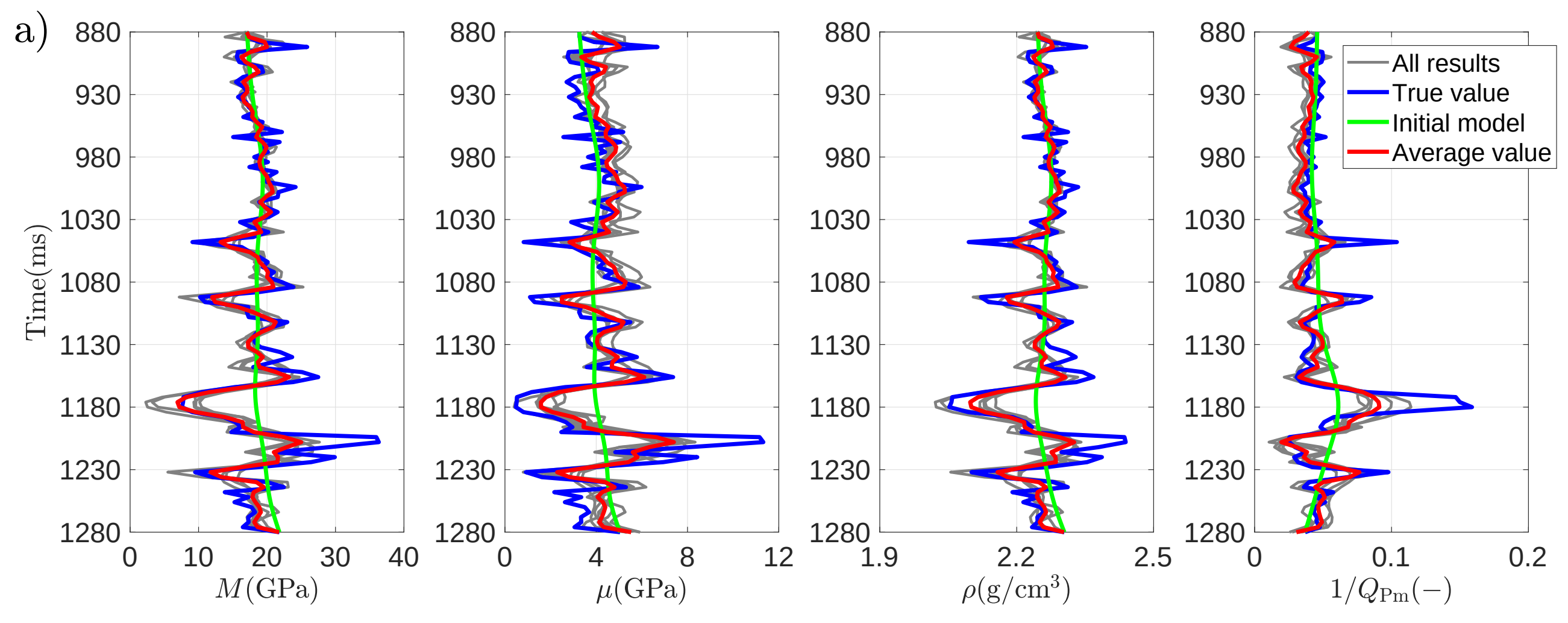

Figure: Comparisons between inversion results and true values of P- and S-wave moduli, density and P-wave maximum attenuation factor. a) SNR=5

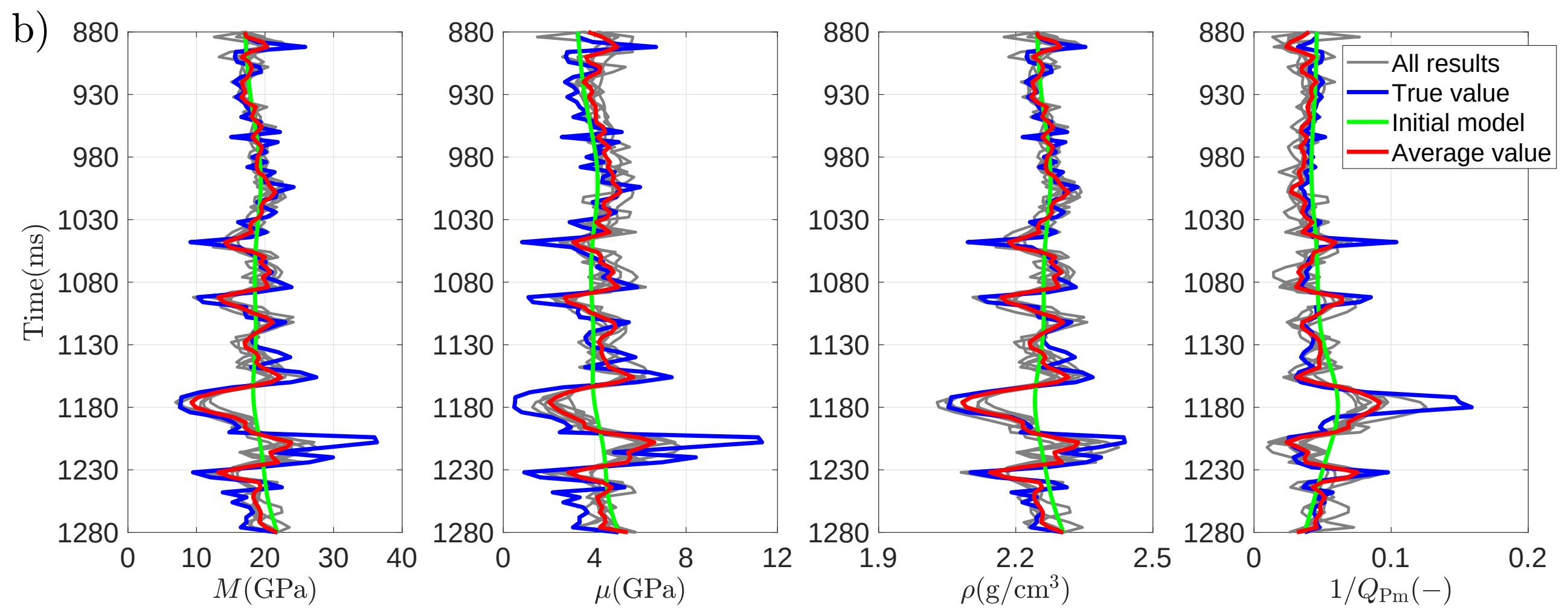

Figure: Comparisons between inversion results and true values of P- and S-wave moduli, density and P-wave maximum attenuation factor. b) SNR=2

Real data

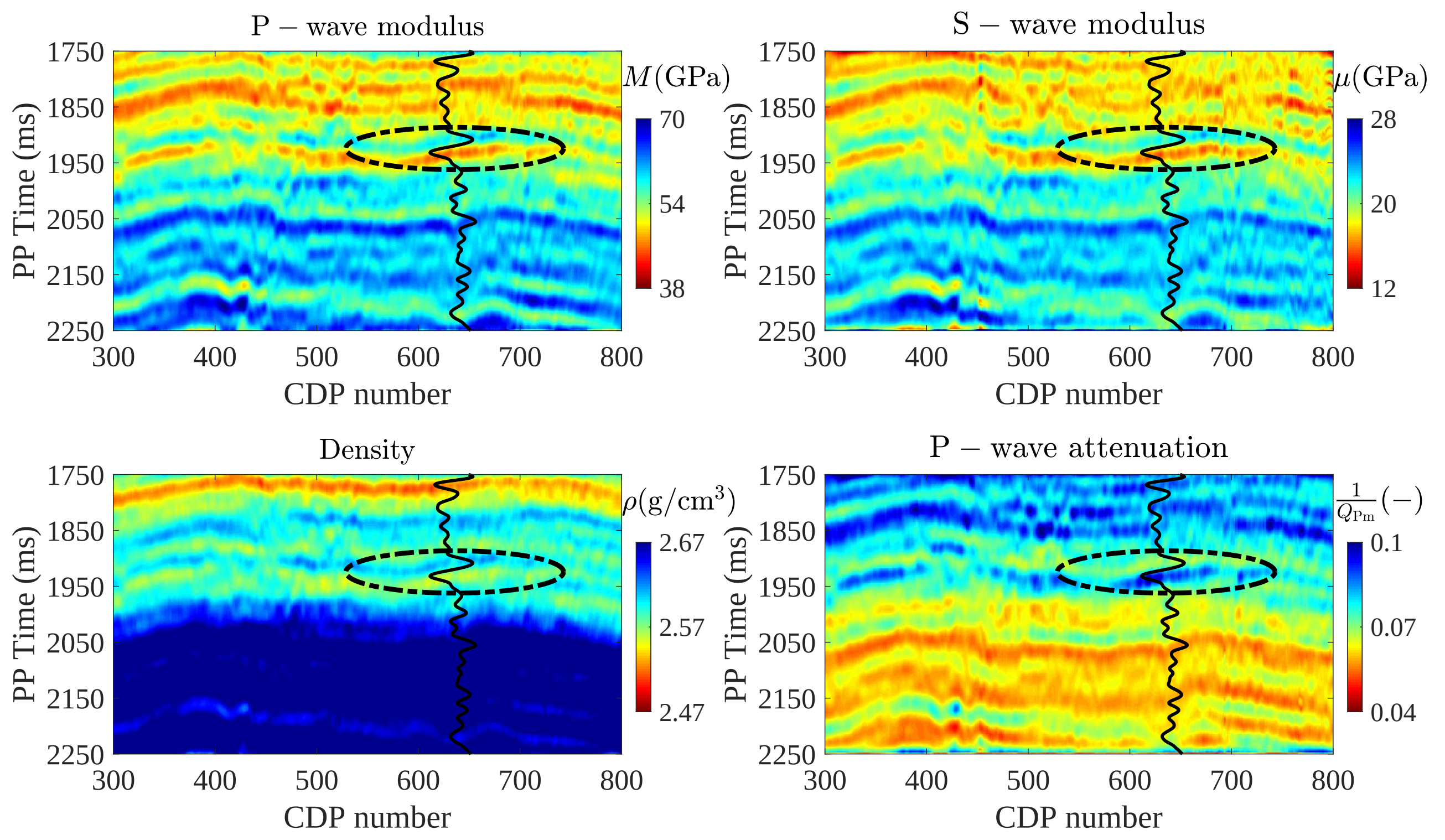

Figure: Inversion results of P- and S-wave moduli, density and P-wave attenuation factor. Dashed ellipse indicates the location of oil-bearing reservoir. Black curve represents P-wave velocity provided by well log.

Conclusions

1) We derive PP- and PSV-wave approximate and linearized reflection coefficients and anelastic impedances as a function of P-wave maximum attenuation factor by solving Zoeppritz equations;
2) We propose an inversion approach and workflow of utilizing PP- and PSV-wave anelastic impedances that are estimated from partially-incidence-angle stacked seismic data using a least-squares inversion algorithm to predict unknown parameters involving P- and S-wave moduli, density and P-wave attenuation factor;
3) Tests on synthetic data of signal-to-noise ratio (SNR) of 5 and 2 verify the stability and robustness of the inversion approach, and applying the approach to real data, we obtain reliable results of attenuation factors, which may provide additional and valuable result for fluid identification.

References

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