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Viscoelastic Full Waveform Inversion of Wide-Angle Data: Application to Ultra-Long Offset Data from Mentawai Basin, Indonesia

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Summary

Full Waveform Inversion (FWI) is a powerful tool to quantify the Earth's subsurface structure. However, most of the FWI applications have been limited to acoustic media. In geological settings, such as gas clouds, gas sand, melt lens, where the attenuation becomes important, one must use a viscoelastic FWI. Here we present the theory and application of a viscoelastic FWI in the time domain. First, we carried out sensitivity analyses for back-scattered, reflected and transmitted waves. We find that the presence of attenuation has a significant effect on post-critical reflections, but it has little or no effect on near-offset reflection data, suggesting that the inversion of port-critical reflections can help to reduce the cross talks between attenuation and velocity contrast or propagation effects. We have first tested the method on synthetic data and then applied to 15 km long offset data acquired by CGG Offshore central Sumatra, Indonesia. Apart from the recovery of attenuation parameters, the viscoelastic inversion provides sharper P-wave velocity image as compared to the elastic FWI.

Introduction

Full waveform inversion (FWI) is a powerful method to obtain quantitative structures of the subsurface. Due to the limitations of the physics embedded in FWI schemes, it is still challenging to image geologically interesting features such as gas clouds, hydrate bearing sediments, unconsolidated sediments or magma chambers, where anelastic effects are important. Attenuation can be included in FWI in the frequency domain by using complex velocities for acoustic media (e.g., Malinowski et al., 2011). Nevertheless, the implementation of attenuation in the elastic media in the time domain is not straightforward and has remained challenging. The time-domain FWI is interesting due to its implicit capability of extracting information on full, frequency-wise, waveform data.

The success of FWI will depend on the availability of large offset seismic data, since they enable to invert both refracted and reflected waves (Shipp and Singh, 2002). In order to demonstrate the effect of attenuation, we calculated reflection coefficients as function of offset and attenuation. Figure 1 shows the amplitude of reflection coefficients for an incident P and reflected P-waves (Rpp) for six different values of Qp above the reflector. The behaviour of the viscoelastic reflection coefficients is not impacted at pre-critical angles, but at larger angles, the Qp plays an important role, especially for low Qp values. Similarly, the effect of attenuation on the P-to-S reflection coefficient (Rps) also starts at the critical angle. These results suggest that it is possible to extract information on attenuation structure by inverting longer offset data. In this paper, we assess the importance of attenuation for FWI of long offset data, and apply it to an ultra-long offset streamer data offshore central Sumatra.

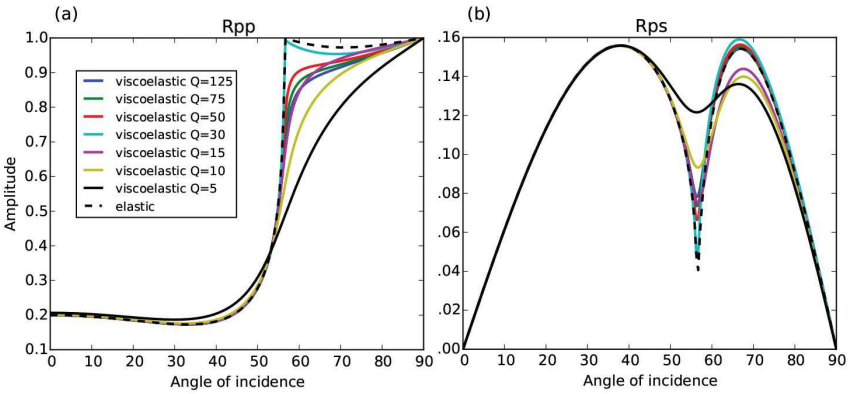


Figure 1 *The reflection coefficient for P-wave (Rpp) and S-wave (Rps) for different values of P-wave attenuation (Qp) as a function of angle of incidence. Other parameters are kept constant (Vp_1 =2500 m/s, Vs_1=1200 m/s, Vp_2=3000 m/s, Vs_2=1400 m/s).*

Viscoelastic Full Waveform Inversion in the Time Domain

Our inversion method is based on the solution of the viscoelastic wave equation in the time domain where the time dependent stiffness tensor is used

$$\sigma^{ij}(\mathbf{x},t) = \int_{-\infty}^{+\infty} d\tau \Psi^{ijkl}(\mathbf{x},t-\tau)\dot{\varepsilon}^{kl}(\mathbf{x},t)$$

where σ_{ij} is stress, ε_{ij} is strain, Ψ^{ijkl} is the time-dependent stiffness tensor and the dot denotes time derivation.

We use Standard Linear Solids (SLS), constituted of a dashpot and springs to parameterise Ψ^{ijkl}. Superposing SLSs allows us to replace the convolution equations by a set of ordinary partial differential equations, including memory variables that accounts for the dissipation of energy over time (Robertsson et al., 1994). In this study we use only one SLS to parameterise each cell of the model. This simplifies the mapping of the P- and S-wave velocities and the quality factors Qp and Qs to the Lamé parameters needed for the modelling.

The inversion consists in the minimisation of the misfit between the observed and synthetic data. We use a conjugate gradient technique to minimise the misfit. The method iteratively updates the Vp, Vs, Qp and Qs parameters.

Synthetic Example

We have tested our inversion algorithm for different synthetic models, starting from 1D to complex 2D Marmousi model (Figure 2). We use 62 shots spaced at 125 m and 351 receivers at 25 m, leading to maximum offset of 8.75 km. The model was discretized at 6.25 m grid spacing and the time was 0.5 ms. A Ricker wavelet with a dominant frequency of 7.5 Hz was used as a source wavelet. We invert frequencies between 0 and 5.5 Hz. We invert pressure component of data down to 5 s. We tested different inversion strategies, including hierarchical and simultaneous. We inverted all four parameters, Vp, Vs, Qp and Qs. The density was not inverted but was modified at each iterations using an empirical relationship with P-wave velocity. The starting model was a smoothed version of the true model. Figure 3a presents the initial residual showing that a significant part of the data requires fitting. Forty iterations of the inversion were performed. Figure 3b shows the residual after the inversion, indicating that a significant part (81%) of the data has been fitted, specially at long offsets.

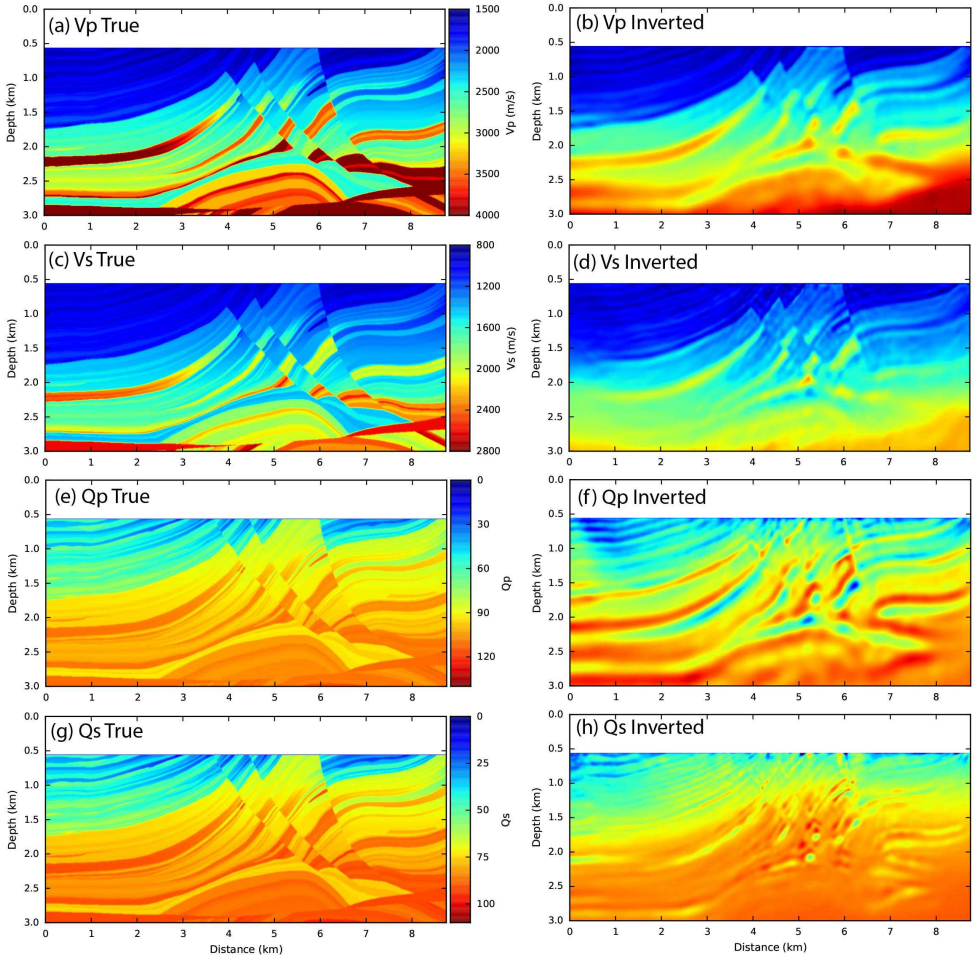


Figure 2 *Results of viscoelastic full waveform inversion for the Marmousi Model. Left (a,c,e,g): true models and right (b,d,f,h:; inverted models for Vp, Vs, Qp and Qs, respectively.*

The final inverted Vp and Vs models (Figure 2b) show that the inversion has been successful in retrieving the true models down to 2 km depth. The sharp layer boundaries are well recovered.

Below 2 km depth, the structures have been recovered but the resolution is poor. This is due to poor ray coverage at wide-angles from these depths. The recovery of the Qp is very good down to 1.5 km depth whereas Qs is recovered down to 1 km depth. These results suggest that our viscoelastic FWI is capable of inverting four parameters from the data that contain wide-angle arrivals, consistent with the sensitivity analyses shown in Figure 1.

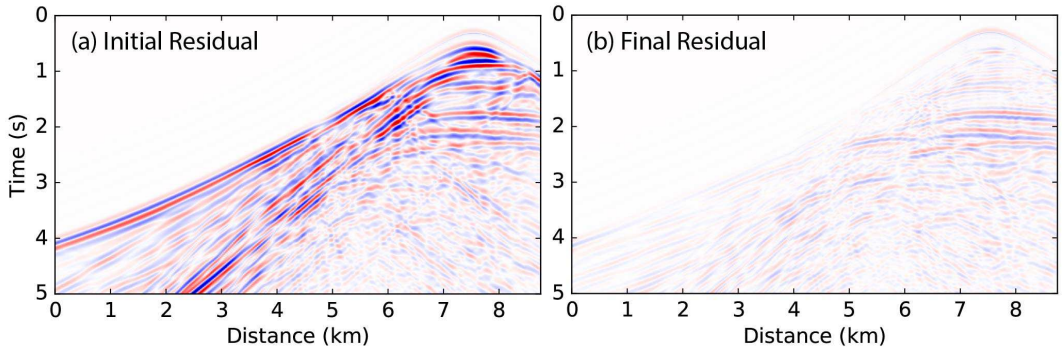


Figure 3 *The initial residual (difference between true synthetic and starting synthetic) (a) and the final residual after the inversion for a shot gather placed at 7.5 km distance over the Marmousi model (Figure 2).*

Application to Real Data

We have applied our viscoelastic FWI to a real data set acquired by CGG using a 15 km long streamer. The source was an array of 48 air guns deployed at 15 m. The streamer was towed at 22.5 m depth to enhance the low frequencies. The shot interval was 50 m and record length was 20 s, sampled at 2 ms.

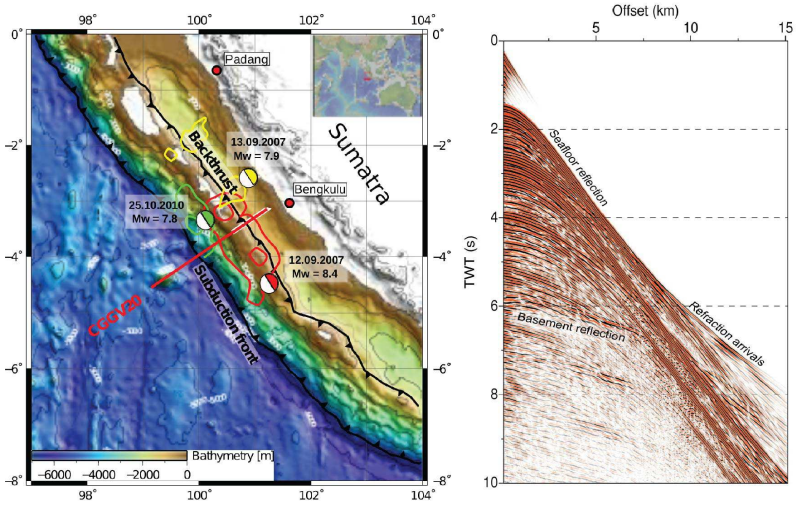


Figure 4 *Left: The location of the seismic profile CGG20 (red) and the part of the profile using in this study (white). The rupture area of 2007 Sumatra earthquakes (red and yellow). Right: A shot gather showing different arrivals.*

The study area lies offshore central Sumatra in the region of the 2007 Mw=8.4 earthquake (Figure 4). The seismic profile was shot orthogonal to the subduction system and covers the subducting oceanic plate, forearc and Mentawai forearc basin. A shot gather from the forearc basin is shown in Figure 4. These data clearly show reflections down to 6 s zero-offset travel time and refraction arrivals from the sediments starting from 7.5 km up to 15 km offsets. Critical and post-critical reflections are also present. We only present the analyses of data from the forearc basin.

We picked the first arrivals to determine the large-scale P-wave velocity using a travel time tomographic method (Huot and Singh, 2018). This starting model was used to determine Vs and density using empirical relationships. The model is 80 km large and 10 km deep. The water depth varies from 50 m to 1100 m. The seismic reflection image (Huot and Singh, 2018) shows 5 km thick sub-horizontal sediments starting from 45 km distance along the profile. Huot and Singh (2018) have performed elastic full waveform inversion and we follow the same strategy here. We first invert the long offset data between 7.5 km and 15 km offsets that cover both refractions and wide-angle reflection. We then perform inversion of near offset reflection data for shallow target and then invert for deep targets. In each runs, forty iterations of inversion were performed. We only inverted for Vp and Qp and the results are shown in Figure 5. These results show the presence of low sediment velocity down to 2 km depth along the whole profile. A 400 m thick high velocity layer is observed between 2 and 3 km depth starting from 32 km distance range. Beneath this high velocity layer, we observe a low velocity layer that extends down to 6 km depth between 35 and 45 km distance range. The Qp inversion results show the presence low attenuation in the top 2.5 km depths. Below this depth, it follows Vp inversion results. Huot and Singh (2018) suggest that the observed low velocity is due to the presence gas. The inverted Vp image shown here is sharper than that obtained by Huot and Singh (2018), suggesting that the inversion of attenuation is important for better quantitative imaging.

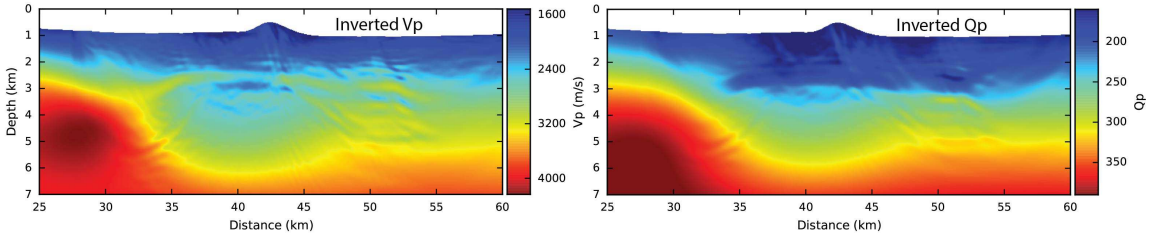


Figure 5 *Left***:** *Inverted P-wave velocity model; Right: Inverted P-wave attenuation for Sumatra data.*

Conclusions

Using the sensitivity analyses, we found that the attenuation is most sensitive to critical and post-critical reflection data. We have developed a viscoelastic full waveform inversion and have successfully applied to Marmousi model, which demonstrate that Vp, Vs and Qp can be inverted with a high confidence. The application of the inversion to real data shows that the Vp image is sharper when attenuation is also inverted.

Acknowledgements

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