2D acoustic full waveform tomography of marine streamer data – data preparation and choice of inversion strategies

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Abstract

In recent years, many synthetic studies have shown the great resolution potential of full waveform tomography. Nevertheless, application to field data is not a common standard yet. This study discusses some of the problems related to the inversion of conventional single sensor marine streamer data in the 2D acoustic approximation. To reconstruct realistic velocity models from the field data additional effort is required to overcome the problem of the local minima and to improve the convergence of the waveform inversion. This mainly concerns the field data preprocessing and the choice of adequate inversion strategies.

For a marine field data set we experienced that the application of a 3D-2D correction, a data de-noising algorithm, and amplitude corrections are essential preprocessing steps. Furthermore, we investigate synthetic case studies which mimic real acquisition geometries and source signals to evaluate the benefits of different preconditioning approaches and model assumptions.

Introduction

In recent years, many numerical case studies with synthetic seismic data have shown that full waveform tomography (FWT) has the potential to become an important method for determining high-resolution multi-parameter models of complex subsurface structures. The application of FWT to field data is not yet common practice. However, a few successful applications have been published (e. g., Hicks and Pratt, 2001; Shipp and Singh, 2002; Boonyasiriwat et al., 2010).

To reconstruct the distribution of the material parameters the inversion algorithm has to minimize the residuals between modeled data and observed data in an iterative process. Because of the high non-linearity of the inverse problem, the success of waveform inversion depends mainly on the accuracy of the starting model and on the presence of low frequencies and sufficient offset range in the recorded data. In practice, when inverting real marine data, we have to deal with some additional challenges including elastic and attenuation effects, unknown source wavelet and source radiation pattern, random and coherent noise. These factors can lead to poor convergence and may deteriorate the recovery of velocity models. Therefore, some extra processing steps and a careful choice of different inversion strategies are required for the successful inversion of real data.

In this study we discuss the problems with data preprocessing which have been encountered during the application of the 2D acoustic time-domain FWT to streamer field data acquired in the North Sea. We then illustrate how essential it is to include a priori information on the model parameters, in particular to include the density information. Moreover, we analyze how the preconditioning of the gradient and of the data affects the convergence of the waveform inversion and the recovery of velocity models.

Data preparation

Prior to the waveform inversion, a specific preprocessing has to be applied to raw field data. This data preparation is a fundamental prerequisite for FWT. The main objectives are to improve the signal-to-noise ratio, to transform the field data such that they reflect the approximations made in the 2D acoustic modeling, and to reduce the non-linearity of the inverse problem.

The acquisitiong geometry of the 2D marine data presented in this study consists of a 160-channel, 4000 m streamer towed at the depth of 6 m. The source is an airgun array, a total amount of 1064 shots with a spacing of 25 m were recorded. From the available data, we selected a sub-region that extends over 3.1 km and consists of 50 shots, with the shot spacing of 50 m. The average depth of the seafloor is about 300 m.

To enable the direct comparison between the real and modeled data, it is necessary to transform the field seismograms so that they reflect wave propagation in a 2D medium. To correct the 3D geometrical spreading of the field data we apply the standard 3D to 2D correction: (a) data multiplication with $\sqrt{t}$, and (b) convolution with $1/\sqrt{t}$. However, the alternative approach based on the Fourier-Bessel 3D to 2D transformation proposed by Amundsen and Retain (1994) should be considered instead, since it is also valid for stratified media.

To include both, amplitude and phase information to FWT a careful trace quality control is essential. Trace interpolation is not a prerequisite, since the method can also handle any irregular geometry configuration. Moreover, an efficient removal of different noise types is a substantial issue. Marine noise comprises mainly noise generated due to hydrostatic pressure fluctuations, swell noise, and noise from the vessel. This high-amplitude noise normally contains frequencies from 0-10(15) Hz, and without an appropriate de-noising of seismic data it would produce artifacts in the inverted models. Low frequencies dominated by the hydrostatic pressure variations and swell noise can be removed by applying a low-cut filter. However, since the presence of low frequencies in the recorded data is crucial for the convergence of FWT, the standard low-cut filters that remove unwanted noise together with the large parts of the useful seismic signal are not advisable. As an alternative we have chosen a time-frequency de-noising algorithm proposed by Elboth et al. (2008). It is a localized method that identifies the parts of the frequency spectrum that are affected by noise, and afterwards estimates the actual amplitude of the affected frequency.

To compensate for the unknown source strength a specific amplitude calibration is necessary. This is performed by scaling the amplitudes of the observed and synthetic direct arrivals at the nearest offset channel for each shot gather. This approach requires a good estimate of the source signature and an accurate modeling of the airgun array directivity effects. In contrast to balancing the amplitudes of the seabed reflection, this method allows the update in the seafloor region during inversion.

Comparing the amplitude-versus-offset (AVO) trends of synthetic and field data (Figure 1), we observe a reasonably good fit for the seabed reflection (offset up to 1600 m), but there is a large amplitude discrepancy between the observed and modeled refracted waves (offset greater than 1600 m). This amplitude misfit between the observed and modeled first arrivals might by caused by an insufficient description of the seafloor parameters, by some lateral heterogeneities, or by the 3D to 2D transformation which is valid for body waves, only. If we want to include the far offset data in the inversion it would be necessary to apply an offset-dependent amplitude correction to mimic the modeled AVO decay. However, before applying this correction, we have performed an additional partial inversion run using the subset of the data that contains only the near offset seabed reflection. In this way, the FWT can reconstruct the parameters of the seafloor region so that the observed seabed reflection will be better matched by its synthetic counterpart.

Another challenge related to the inversion of streamer data are seafloor multiples. To properly handle these multiples in the inversion scheme, the forward modeling should provide the correct description of these events. The modeling errors due to ignoring the variability of the sea surface topography, as well as elastic and attenuation effects will have implications on providing the accurate amplitudes and arrival times of synthetic multiples. Since these events have high amplitudes, they dominate the misfit function. Thus, any mismatch in modeling of these wave types would produce artifacts in the reconstructed models. For that reason, it seems plausible to attenuate multiples in the field data. At the same time the free surface conditions in the modeling scheme must be replaced with an absorbing boundary at the top of the model. This procedure requires to remove the source and receiver ghosts from the observed data, i. e. to decompose the total pressure waveform into the upgoing and downgoing components. Multiple attenuation should reduce the ambiguity of the inversion and improve the recovery of true velocity structures.

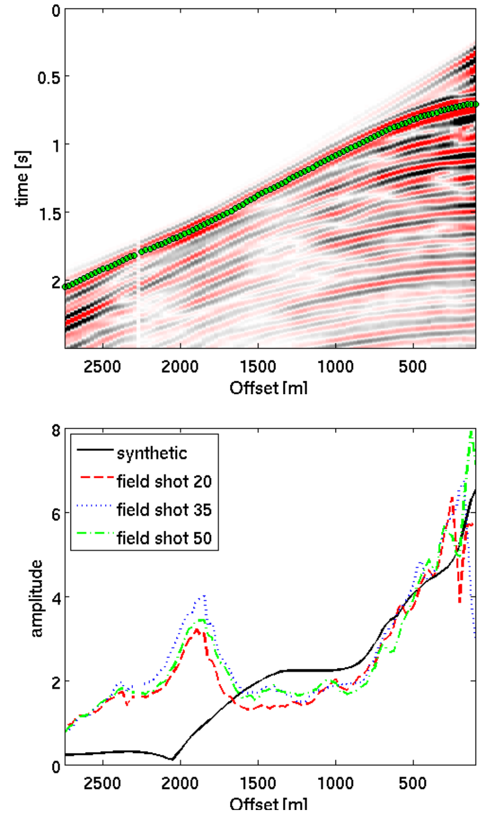


Figure 1: a) Typical field shot gather (shot 20) after quality control, mute before first arrivals, de-noising, 3D to 2D spreading correction, band-pass frequency filtering (2-20 Hz), and time resampling. b) The AVO trend of the seafloor reflection (offset $<$ 1600 m) and the first-arrival refraction (offset $>$ 1600 m) for the synthetic seismograms of the starting model and field seismograms. The nearest offset traces with the sharp amplitude variations are precluded from inversion.

The effect of the density information

In acoustic waveform tomography the forward problem can be based on the constant-density acoustic wave equation. However, the amplitude of the field pressure waveform is sensitive not only to the P-wave velocity but also to the mass density. For that reason we investigated the effect of the density information on the recovery of P-wave velocity models. In this synthetic study the pressure data set was generated for the V_P and density checkerboard models (Figure 2), together with a realistic acquisition setup and a source wavelet estimated from the field data. An initial V_P model for the waveform inversion is a smooth representation of the true model. Such a good starting model will significantly mitigate the non-linearity of the inversion problem. Moreover, it will allow us to explicitly illustrate how the presence or absence of the realistic density information affects the reconstruction of the P-wave velocity.

In the first test we use a constant density model. The absence of the realistic density distribution causes a degradation of the inverted velocity image mainly in the seafloor region (Figure 3). Poor recovery of the velocity model is also reflected in high amplitudes of the residual waveform (Figure 3c). This effect is particularly related to the reflection coefficient at the seafloor, which value is primarily governed by a high density contrast in this region. Excluding the density from inversion causes modeling errors in amplitudes of the seafloor reflections and multiples, and as a result, produces strong artifacts in the inverted velocity model. In the second test a more realistic density model is included (Figure 4c)in the inversion scheme. It is linked with the starting P-wave velocity model using Gardner's relationship. The density model remains fixed during the inversion. The velocity-density relationship used to generate true data is different to that assumed in the inversion scheme, therefore the estimated density model does not represent the true large-scale density distribution. In spite of this, the final inversion result (Figure 4) shows a significant improvement in the recovery of upper parts of the P-wave model.

In addition, we tested other strategies of including the density information, i. e., updating the density model from the V_P model at each iteration step, and applying the separate velocity and density inversion. However, for this particular case, these two additional strategies had no substantial improvement on the reconstruction of the velocity model in comparison to the result obtained in the second test presented in this study. Tarantola (1986) found that the misfit function of marine data is most sensitive to updates of the seismic velocities, and the effects from the density model updates are much smaller. This implies that the inversion scheme is least sensitive to errors in density and even a poor starting density model (see Figure 4) should have no significant influence on the quality of the velocity models. We found, however, that selecting an arbitrary density value produces strong artifacts in the reconstructed velocity model. Therefore, it is essential to include a realistic density information to the inversion scheme. The starting density models can be build using empirical velocity-density relationships.

Inversion strategies

The aim of the full waveform tomography is to find a model of the subsurface which explains the observed data, i. e. that minimizes the data misfit function between observed and modeled data. The data residuals δu are measured by the L-2 norm, and an optimum model can be found in the minimum of the residual energy. Therefore the objective function to be minimized reads

$$E = |L_2| = \frac{1}{2}\delta u^T \delta u \rightarrow \text{min}. \quad (1)$$

Our inversion scheme is based on the adjoint method proposed by Tarantola (1984): to find an optimum model the material parameters velocity and density are updated iteratively along the conjugate gradient direction δc with the step length μ_n:

$$m_{n+1} = m_n - P\mu_n \delta c_n \quad (2)$$

where m_{n+1} is the model update at iteration i+1, and P denotes the preconditioning operator.

The calculation of the velocity gradient resulting from the waveform cross-correlation is a crucial part in the waveform tomography. This quantity describes how to optimize the starting model or the model from the previous iteration step. The raw gradient can be modified by the preconditioning operator that imposes constraints on the model parameters update.

In some cases the high complexity of the seismic data and/or high noise level may cause a very complex and nonlinear data misfit function and, as a result, an unrealistic model parameter update can be generated. Moreover, if the low frequencies ($<$ 5 Hz) are not present in the data, the succes of the waveform tomography strongly depends on the choice of the starting model. In such a case a good starting model containing the large-scale features of the subsurface is required. Otherwise, the inverse problem tends to converge to a local minimum and produces unrealistic results. To control the model update and to improve the convergence and/or the linearity of the inverse problem different preconditioning methods can be used. A regularization scheme in the time domain can be realized by applying time windowing and frequency filtering to the data, or by applying a preconditioning operator P that modifies the gradient.

We performed several synthetic tests to demonstrate the effect of different inversion strategies. Synthetic data are calculated from the checkerboard model (Figure 2a) using a realistic source wavelet which covers a frequency bandwidth from 3 to 20 Hz. We build the starting model by smoothing the true model and increasing the velocities by 6 % (Figure 5b - dashed line). This relatively poor initial velocity model is supposed to point out the local minima problem.

For the first inversion test no preconditioning methods were applied. Figure 5 shows the inverted V_P model after 500 iterations. The velocity structures of the true model are well recovered only in the upper part of the model, but resolution and accuracy decrease rapidly with depth. Moreover, a lot of strong artifacts are present in the inverted model, especially in the vicinity of the air/water interface, around sources and receivers, and in the water column. This inversion example clearly shows that the lack of low frequencies in the data combined with a poor initial model significantly reduces the resolving power of the waveform tomography.

To suppress large gradient values within the water layer and around sources and receivers we have designed a spatial preconditioning operator that modifies the raw gradient. It sets the gradient in the water layer to zero, i. e. it turns off the velocity update in this part of the model. To improve the stability of the inversion, especially in the real data case, the gradient smoothing operator can be applied. Such a 2D spatial filter removes high frequency artifacts from the gradient. Furthermore, the linear gradient scaling with depth is implemented. It is supposed to correct for the amplitude loss with depth due to the geometrical spreading and, thus, to enhance deeper parts of the model. Otherwise, the early arrivals would dominate the data fitting in the inversion scheme, and velocity updates in the upper parts of the model would be more significant than in the deeper parts. After application of the preconditioning operator all strong artifacts within the water layer are removed, and there is an improved recovery of deeper structures (Figure 6).

Another inversion run was performed to illustrate the effect of the combined application of frequency filtering and time windowing. By using the time windowing during the inversion process, the amount of information is gradually increased with the increasing propagation time of seismic waves. The reduction of data done by muting allows the algorithm to update the upper part of the model in the first instance and then to proceed to the deeper parts. If a poor starting model is used, time windowing can improve the convergence efficiency of the waveform inversion. Moreover, the non-linearity of the objective function is frequency dependent, i. e., the shape of the objective function depends on the frequency content of the seismic data. At lower frequencies the objective function is smooth, whereas a lot of local minima are present at higher frequencies. Therefore, the inversion should start at the lowest possible frequency and incorporate the higher frequency content gradually (Bunks et al., 1995). In the next test the multi-stage inversion approach is performed. In stage 1, only data containing frequencies of 3-7 Hz are inverted, in stage 2 of 3-15 Hz, and in stage 3 of 3-20 Hz. The result from each lower frequency inversion is used as a starting model for the next higher frequency inversion. At each stage 300 iterations are carried out. For each iteration the time windowing is applied to the data and the preconditioning operator described in the previous paragraph is applied to the gradient. Figure 7 shows the final reconstructed image after all three stages. The very good fit between the final and the true model is also reflected in the final residuals.

The combination of the multi-stage inversion with the preconditioning of the gradient direction is a necessary strategy to overcome the problem of the local minima and to improve the convergence accuracy of the inversion algorithm.

Conclusions

We have demonstrated that the effectiveness of the FWT depends not only on the choice of the starting model, but also on methods which reduce the complexity of of the inverse problem. The field data preparation must take into account several effects like coherent seismic noise or characteristics of the airgun source. Generally, there is no common preprocessing work flow, rather it has to be designed for the particular data type and the forward problem solver. Furthermore, the application of different preconditioning strategies such as time windowing, frequency filtering, gradient preconditioning, and including the density information leads to significant improvements in the subsurface reconstruction.

References

Amundsen, L. and Retain, A. (1994). Transformation from 2-D to 3-D wave propagation for horizontally layered media. *Geophysics*, 59(12):1920–1926.

Boonyasiriwat, C., Schuster, G., Valasek, P., and Cao, W. (2010). Applications of multiscale waveform inversion to marine data using a flooding technique and dynamic early-arrival windows. *Geophysics*, 75(6):R129–R136.

Bunks, C., Saleck, F., Zaleski, S., and Chavent, G. (1995). Multiscale seismic waveform inversion. *Geophysics*, 60(5):1457–1473.

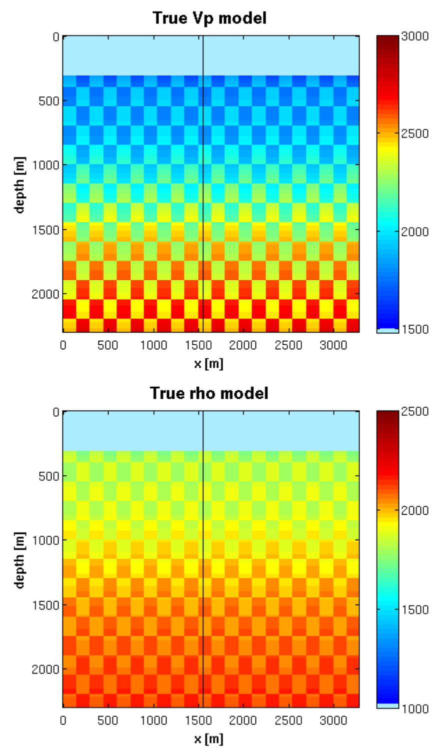
Elboth, T., Qaisrani, H., and Hertweck, T. (2008). De-noising seismic data in the time-frequency domain. *SEG Technical Program Expanded Abstracts*, 27.

Hicks, G. and Pratt, G. (2001). Reflection waveform inversion using local descent methods: Estimating attenuation and velocity over a gas-sand deposit. *Geophysics*, 66(2):598–612.

Shipp, R. and Singh, S. (2002). Two-dimensional full wavefield inversion of wide-aperture marine seismic streamer data. *Geophys. J. Int.*, 151:325–344.

Tarantola, A. (1984). Inversion of seismic reflection data in the acoustic approximation. *Geophysics*, 49:1259–1266.

Tarantola, A. (1986). A strategy for nonlinear elastic inversion of seismic reflection data. *Geophysics*, 51:1893–1903.



[a] [b]

Figure 2: (a) True velocity [m/s] and (b) density models [kg/m^3].

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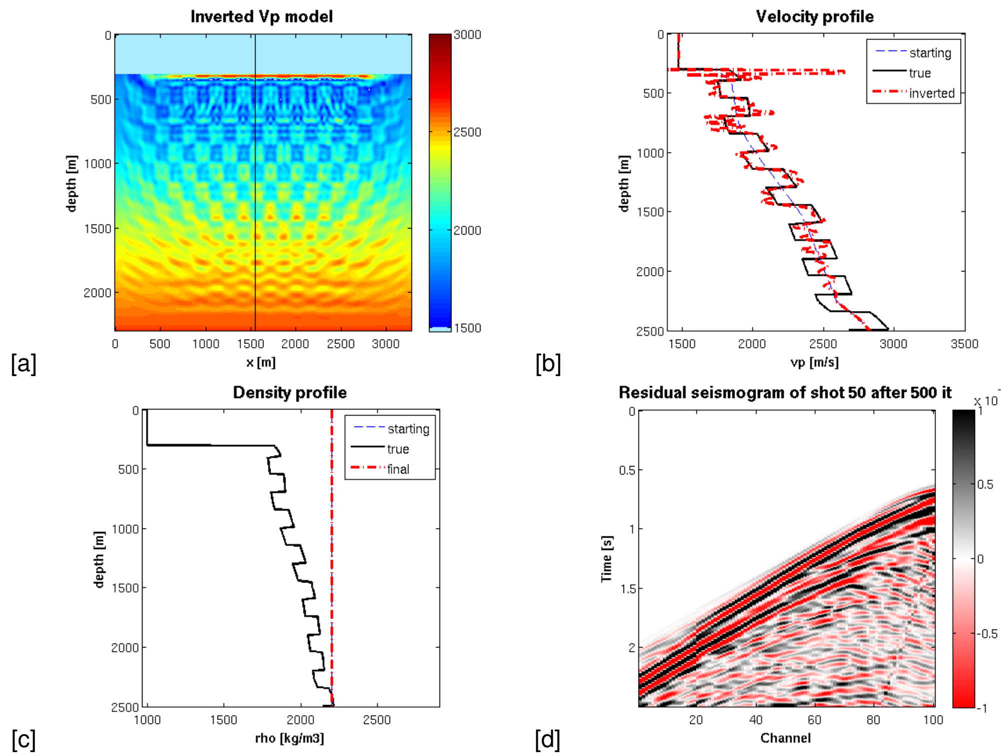

Figure 3: FWT results after 500 iterations for the homogeneous density model. a) Inverted V_P model [m/s]. Note the artifacts in the seafloor region. b) P-wave velocity and c) density profiles of the true, starting, and the final models, d) final residuals.

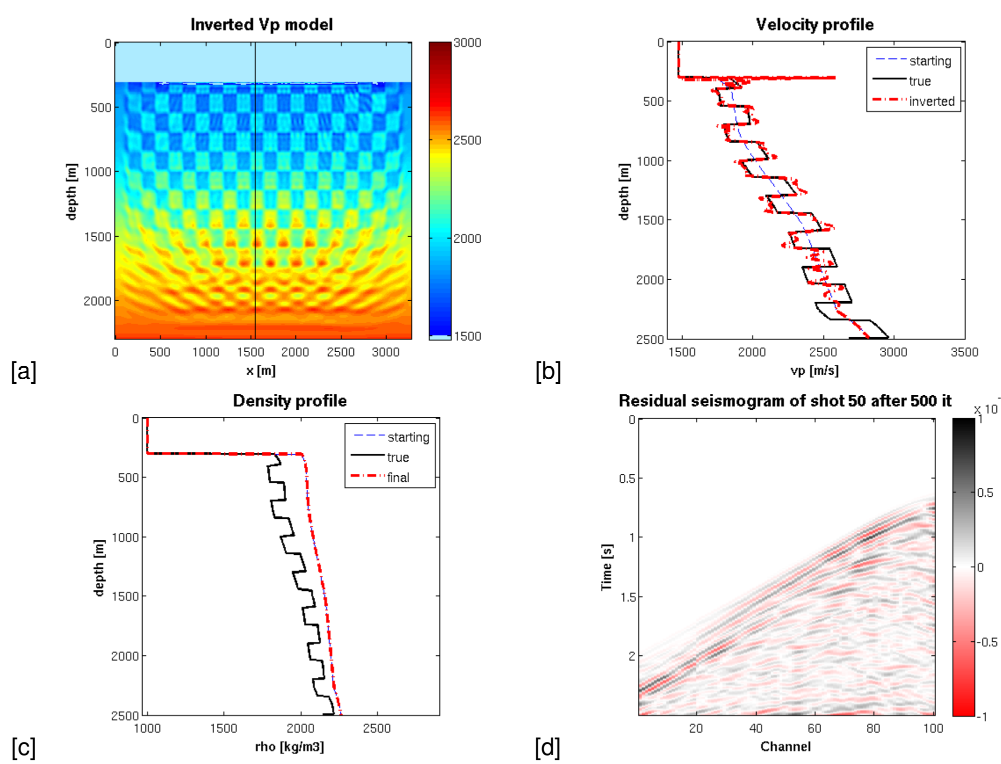

Figure 4: FWT results after 500 iterations for the fixed density model, computed from the starting V_p model using Gardner's relationship. a) Inverted V_P model [m/s]. The artifacts in the seafloor region are reduced. b) P-wave velocity and c) density profiles of the true, starting, and the final models, d) final residuals.

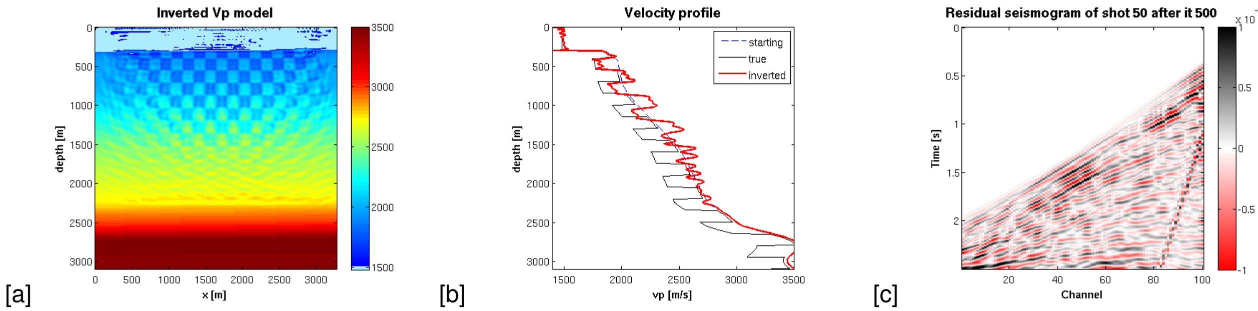

Figure 5: FWT results after 500 iterations, no preconditioning applied. (a) Inverted V_p model [m/s], (b) velocity profiles, (c) final residuals.

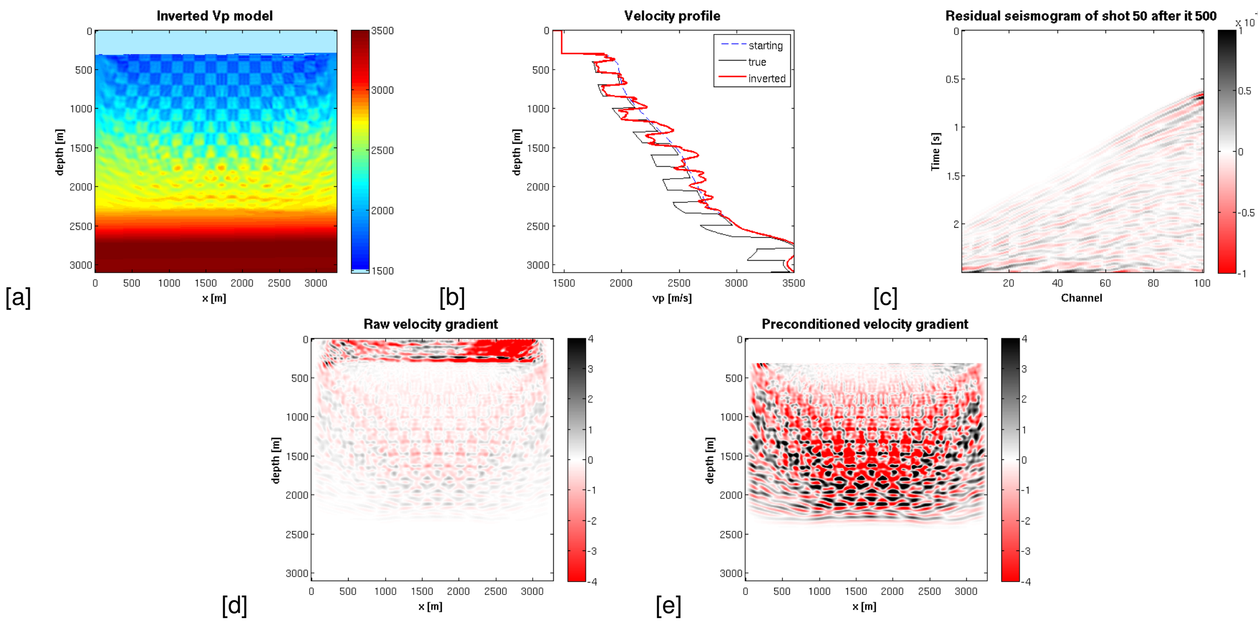

Figure 6: FWT results after 500 iterations; velocity gradient scaling with depth and gradient taper within the water layer are applied. (a) Inverted V_p model [m/s], (b) velocity profiles, (c) final residuals, (d) raw V_p gradient, (e) preconditioned V_p gradient.

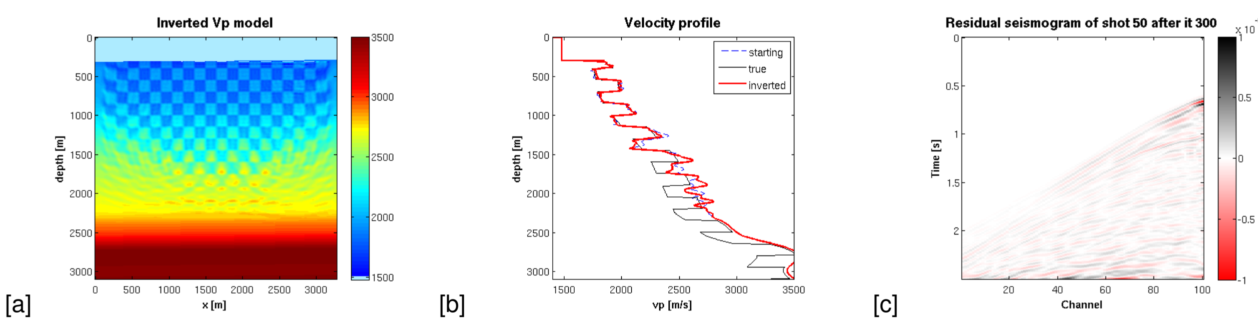

Figure 7: FWT results for the multi-stage inversion. (a) Final inverted V_p model [m/s], (b) velocity profiles, (c) final residuals.