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Migration Velocity Analysis with Multiple Modeling: an Inversion Toolbox

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Summary

The standard processing approach to transform raw shot records into final products suited to geological interpretation involves cascading numerous steps that can be classified in: pre-processing, which aims at correcting acquisition imperfections or undesired effects (designature, deghosting, geometry), velocity model building which identifies mapping from the data domain to the depth domain and imaging, which applies this mapping. In this paper we show how a Migration Velocity Analysis (MVA) scheme can evolve into a flexible inversion framework that can perform all three steps by inversions.We demonstrate on a 2D real dataset how it handles pre-processing issues and demultiple,as well as providing the velocity model and image domain final products.

Introduction

MVA uses a migration to estimate reflectivity from the data, and finds the best velocity model by optimizing a particular criterion of the reflectivity. It has long been hampered by 'gradient artifacts' that prevent convergence. Another problem is that, like any velocity estimation tool, it is perturbed by the presence of multiples (Zhang et al., 2014). More generally, the question of how to pre-process data before MVA has to be addressed before applying the method to real data.

Migration Velocity Analysis with Gauss-Newton update

Noting d_0 the recorded data, v the velocity model, r the reflectivity, and $G(v)$ the modeling operator that produces the modeled data d with the linear modeling equation $d = G(v)r$, r and v can be estimated by minimizing the energy of the data misfit $e = d - d_0$. The extended space parametrization for the reflectivity r (Symes (2008)) gives extra degrees of freedom to match the data with a wrong velocity model. These extra degrees of freedom are controlled by a term $||Ar||^2$ added to the energy of the data misfit that penalizes unfocused energy with a weight σ. The cost function is:

$$C(r,v) = \frac{1}{2}\left[G(v)r - d_0\right]^* \left[G(v)r - d_0\right] + \frac{\sigma}{2}||Ar||^2 \tag{1}$$

We have shown (Soubaras and Gratacos (2017)) that, as the extended reflectivity space allows the data misfit to be small from the first iteration, a second order Gauss-Newton scheme can be used and that the deconvolution of the gradient included in this scheme suppresses the 'gradient-artifacts'. The gradient and the approximate Hessian of C in r and v are:

$$g(r,v) = \begin{bmatrix} \frac{\partial C}{\partial r^*} \\ \frac{\partial C}{\partial v^T} \end{bmatrix} = \begin{bmatrix} G^* \\ \frac{\partial (Gr)^*}{\partial v^T} \end{bmatrix} e + \sigma \begin{bmatrix} A^*Ar \\ 0 \end{bmatrix}, H(r,v) = \begin{bmatrix} G^* \\ \frac{\partial (Gr)^*}{\partial v^T} \end{bmatrix} \begin{bmatrix} G & \frac{\partial (Gr)}{\partial v} \end{bmatrix} + \sigma \begin{bmatrix} A^*A & 0 \\ 0 & 0 \end{bmatrix} \tag{2}$$

So $H(r,v)$ depends on the first derivatives of $G(v)$ only, and has no dependence on the data d_0. The Gauss-Newton scheme consists of simultaneously updating the velocity and the reflectivity by:

$$\begin{bmatrix} r_{n+1} \\ v_{n+1} \end{bmatrix} = \begin{bmatrix} r_n \\ v_n \end{bmatrix} - \lambda_n H_n^{-1}(r_n, v_n) g_n(r_n, v_n) \tag{3}$$

where g_n is the total gradient, computed with the adjoint-state method, and $h_n = H_n^{-1} g_n$ the total deconvolved gradient. h_n is obtained solving $H_n h_n = g_n$ with a linear conjugate gradient algorithm. The application of the Hessian H to a vector h is performed cascading a "direct-state" method and an adjoint state method. Once h_n is computed, the step-length λ_n is determined with line-search minimization .
Because r_n minimizes the energy of the data misfit, it is the least-squares migration of the data d_0 for the velocity v_n. Therefore the Gauss-Newton scheme yields an Inversion Velocity Analysis (IVA) scheme (Liu et al. (2014), Chauris et al. (2015)) where each iteration provides the least squares migration associated with the velocity model.
We can illustrate the deconvolution of the gradient on the Marmousi velocity model. Figure 1 shows the velocity model during the convergence of the approach. It is quite good above 2.5 km. The velocity gradient computed at that point is shown in Figure 2, and the deconvolved gradient in Figure 3.

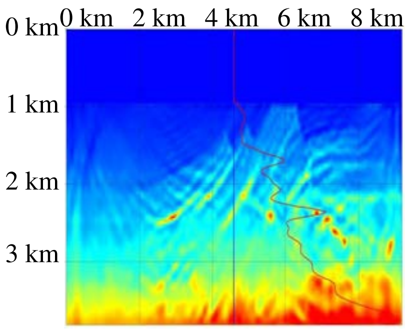

***Figure 1** Velocity*

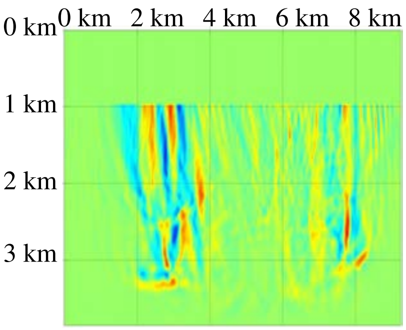

***Figure 2** Gradient*

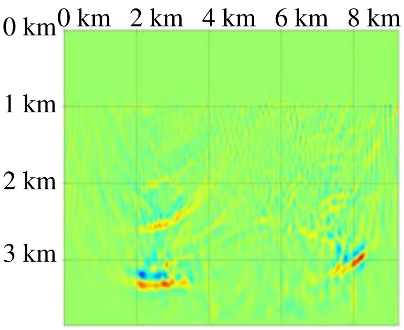

***Figure 3** Deconvolved gradient*

MVA as an inversion toolbox

The usual processing flow for marine seismic data is: pre-processing (wavelet estimation, designature, source+receiver deghosting, regularization, multiple attenuation), velocity model estimation and imaging (migration producing a reflectivity). A possible way to perform MVA on real data is to do a classical pre-processing and to use the MVA to provide the velocity model and the reflectivity. However, the pre-processing sequence is usually quite heavy for broadband processing, as extra care is required to preserve the lowest frequencies (Sablon et al. (2016)).

An alternative is to include in the forward modeling the source wavelet (without ghost), the source and receiver ghosts and the multiple generator in order to feed a global inversion algorithm with raw shots. When using one-way wave-equation propagation, this is decomposed in: modeling the source with the wavelet, building the initial downgoing wavelet with the source ghost, propagating the downgoing wavelet in the velocity model, obtaining the upgoing wavefield with the reflectivity model, reflecting at the water surface and repeating the process N times, N being the user-defined multiple order (Berkhout and Verschuur (1994)). The modeled shot records are built by sampling the upgoing (primaries) and downgoing (ghosts) wavefields at the receivers location. Each modeled trace $m_i(t)$ is therefore the sum of $2N+1$ components ($dw_0(t)$ being the direct arrival):

$$m_i(t) = dw_0(t) + \sum_{n=1}^{N} [up_n(t) + dw_n(t)] \tag{4}$$

Because the modeling takes into account the source wavelet, the reflectivity, the ghosts and the multiples, building an inversion based on this model can perform all three pre-processing, velocity estimation and imaging steps. The three components of the inversion: source wavelet, velocity model and extended reflectivity can be estimated globally, but the convergence of a three terms joint inversion from crude initial estimates can be problematic.

We propose a sequential approach, where three inversions are performed, replacing the pre-processing, velocity estimation and imaging steps:

- The first inversion, which corresponds to pre-processing, uses a frozen crude initial velocity model (constant water velocity or linear gradient from the water-bottom) and jointly estimates the source wavelet and an unconstrained extended reflectivity ($\sigma \approx 0$ in equation (1)). The data is correctly modeled because the unconstrained extended reflectivity compensates the errors in the velocity model and takes into account the AVA effects. This step corresponds to pre-processing because once the modeled traces of equation (4) are obtained, the $2N+1$ components of this model, which are models of the ghosts and of the multiples, can be used in optional deghosting and multiple attenuation steps.
- The second inversion, which corresponds to velocity estimation, freezes the estimated wavelet, and jointly estimates the velocity model and a constrained extended reflectivity. This is the classical MVA scheme where the velocity model is adjusted in order to focus the reflectivity.
- The third inversion, which corresponds to imaging, freezes the estimated wavelet and velocity model and estimates an unconstrained extended reflectivity. Accurate angle gathers can be produced from this final reflectivity. This last inversion is fed with raw shot records and uses ghosts and multiples modeling: therefore ghosts and multiples are used for the imaging, instead of being treated as noise.

Real data example

Our sequential inversion approach is illustrated on a 2D line acquired offshore NW Australia using a variable depth streamer acquisition. The receivers used were restricted to the first 3km of the steamer, and the maximum frequency used was 80 Hz. Using the crude initial velocity model of Figure 4 (linear gradient from the water-bottom), the inversion with a multiple model and a frozen velocity provided the wavelet of Figure 5, the spectrum of which is represented on Figure 6. The inverted wavelet had an accurate time-zero, scale and polarity. Freezing this wavelet, the velocity model shown in Figure 7 was obtained with a 40 Hz inversion. In the third step, the velocity was frozen and an 80 Hz inversion provided the reflectivity shown in Figure 7, with an angle gather shown on the left. In order to check we have correctly inverted the raw shot records, Figure 8-a shows an input raw shot, with just a bandpass [2.5-80 Hz] filter applied. Figure 8-b is the reconstructed shot using the inverted wavelet of Figure 5, the velocity and reflectivity of Figure 7, with a modeling including source wavelet, source and receiver ghosts and water-surface multiples. The two shots are very similar, with a correlation over 0.96, which validates the proposed approach. Figure 9-a is the shot processed with a complex state-of-the-art broad-band flow, with source deconvolution, source and receiver deghosting, noise attenuation, surface-related multiple attenuation (Sablon et al., 2016). Figure 9-b is the reconstructed shot with a Dirac-wavelet, without ghosts modeling nor multiple modeling. We observe again that they are very similar.

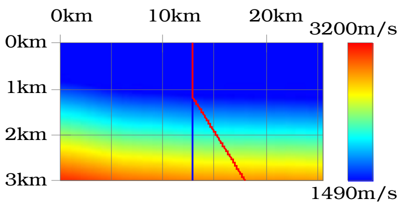

Figure 4 *Initial velocity*

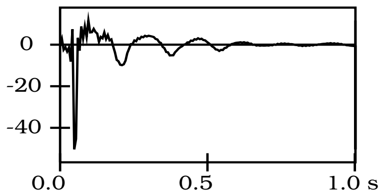

Figure 5 *Inverted wavelet*

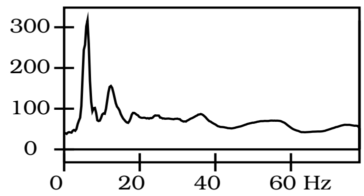

Figure 6 *Wavelet spectrum*

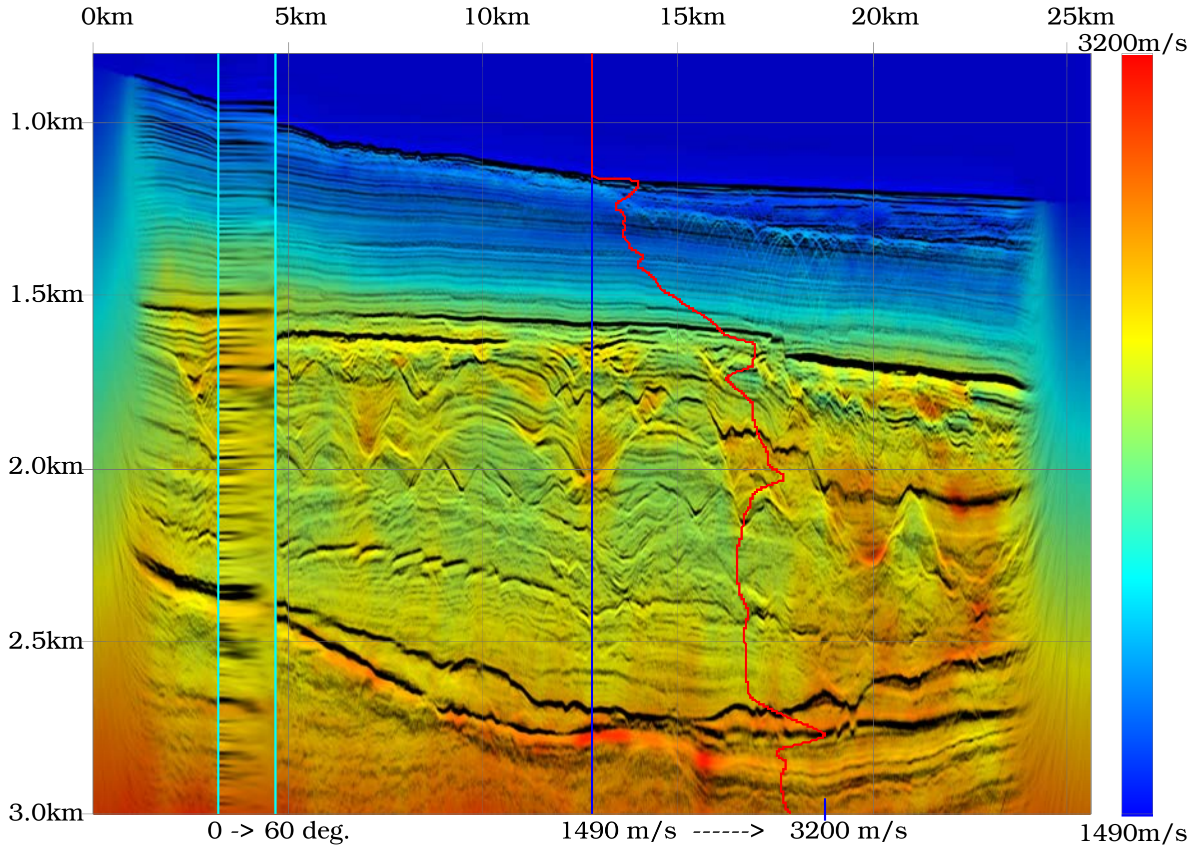

Figure 7 *Velocity and reflectivity. On the left: 0-60 deg. angle gather. red curve: velocity at the location of the blue line*

Conclusions

The MVA scheme exposed in this paper demonstrates the possibility of replacing all three pre-processing, velocity estimation and imaging steps by inversions. By including in the modeling the source wavelet, the source and receiver ghosts, and the water-surface multiple reflections, we were able to estimate the source signature, perform source deghosting, receiver deghosting, remove the surface-related multiples, and estimate a detailed velocity model that produced a high quality final image with angle gathers.

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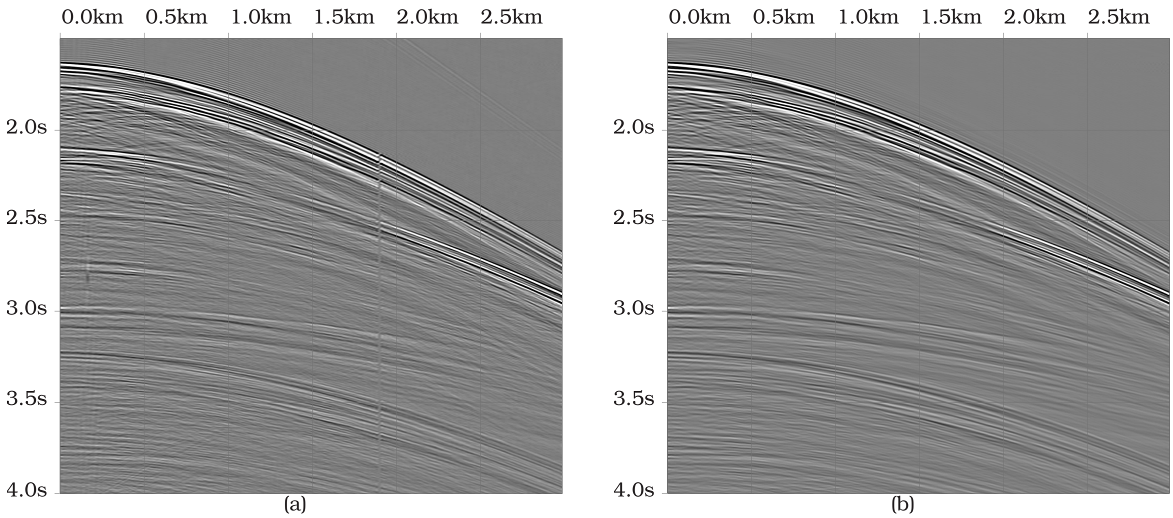

Figure 8 *(a) raw shot bandpass 2.5-80 Hz, (b) modeled shot*

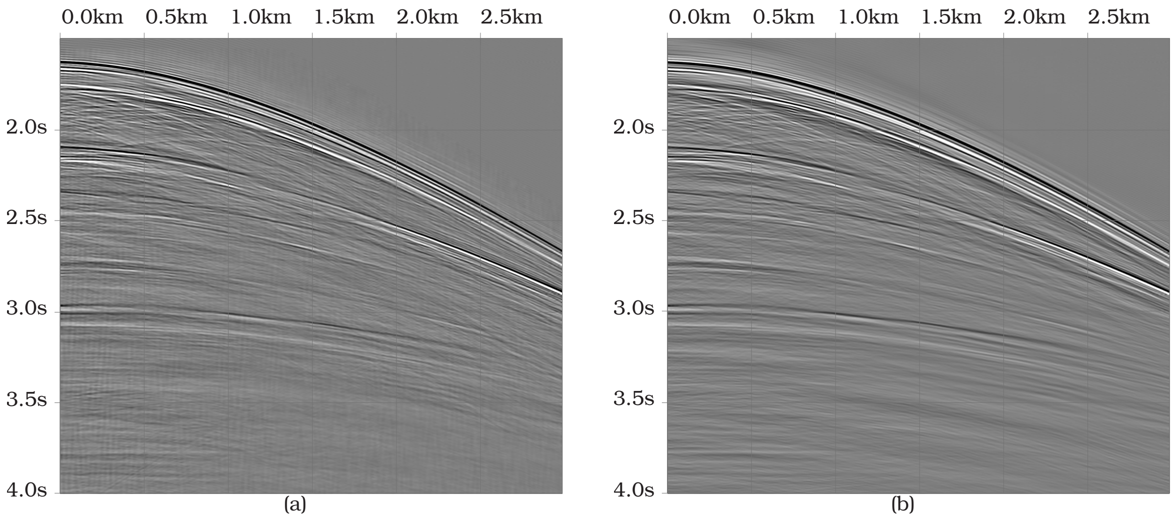

Figure 9 *(a) state-of-the-art broadband preprocessing of Figure 8-a, (b) modeled shot without wavelet, ghosts and multiples*