MADRID 2015
1-4 June 2015 | IFEMA Madrid

Tu N104 08

Combining Full Waveform Inversion and Tomography: Full Waveform Inversion-guided Tomography

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SUMMARY

With the new broadband acquisitions, allowing to record frequencies down to 2.5 Hz, and the new tomographic tools, allowing to resolve for vertical velocity components up to 6 Hz, we have moved velocity model building from the situation of a “mid-frequency gap” to the situation of an overlapping area in terms of the resolution we can expect from tomography and migration-inversion approaches. Full waveform inversion-guided migration velocity analysis has been proposed to take advantage of this new situation. We show here a first real data application of this innovative approach.

Introduction

The estimation of seismic velocities is of primary importance in exploration geophysics because accurate velocities are necessary for correctly imaging the subsurface structures and, moreover, a detailed velocity model allows a quantitative characterisation of the geology.
In seismic imaging two families of methods can address the challenge of velocity model estimation: tomographic methods, which are based on kinematic information (typically dip and residual move out), and waveform inversion methods, which are based on amplitude and waveform (migration + AVO-AVA analysis or full waveform inversion, FWI). The resolution that can be expected from both approaches has been analysed in a famous sketch by Jon Claerbout (1985) (Figure 1). This sketch emphasizes the existence of a "mid-frequency gap" between the resolution that can be obtained from both types of approaches. For a long time this statement has been well acknowledged but recent technological developments now lead to its re-evaluation.
Firstly, in recent years tomographic methods have gone through tremendous improvements (Lambaré *et al*., 2014). While they were believed to reveal quantitatively accurate seismic velocities up to 2 Hz only, it is now recognized that they can achieve resolution up to 6 Hz, thanks to dense picking methods and high resolution tomography schemes. Secondly, coming from the other side of the frequency spectrum, the lowest usable frequency in the recorded data has decreased from ~10 Hz down to ~2.5 Hz now routinely being obtained in broadband acquisitions. Hence, the so-called "mid-frequency gap" is then no longer a gap, but actually an overlap (Figure 1) (Nichols, 2012; Lambaré *et al*., 2014).

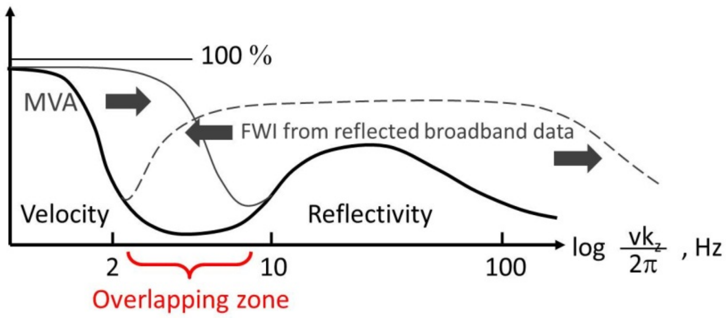

Figure 1 *The accuracy of our knowledge of the subsurface with respect to the vertical frequency (the curve with the solid black line is derived from Claerbout, 1985).*

As pointed out by Nichols (2012) the challenge is then to combine both types of approaches for the benefit of more accurate and stable velocity model building. Initial attempts have been made based on a composite cost function where a tomographic type cost function, for example, from wave equation or tomographic migration velocity analysis, is added to the classical *L2* misfit cost function of FWI (Symes and Carazzone, 1991; Fleury and Perrone, 2012). Balancing the two components of the cost function appears challenging in practice, as they do not exhibit the same sensitivity in term of linearity and non-linearity and do not solve for the same wavelength components of the velocity model. Other approaches have been investigated, for example, a relaxation approach where FWI and tomographic updates are done alternatively (Mothi and Kumar, 2014).
In this context, Allemand and Lambaré (2014) proposed a new technique combining FWI and migration velocity analysis (MVA). In their method MVA is used as the velocity model building criterion, but the velocity update is guided by the velocity updates coming from a migration-inversion process. We show here a real data application of this approach where MVA is performed with a non-linear slope tomographic approach (Guillaume *et al.*, 2008) and FWI is done through preserved amplitude ray + Born inversion (Thierry *et al*., 1999).

FWI-guided tomography

The resolution and structural conformity of FWI is a key component of its success. Unfortunately in many cases it does not come with a systematic improvement in terms of gather flatness even if updating for anisotropy and/or a pseudo-density parameter helps in areas investigated by recorded diving waves (Plessix *et al*., 2014). To take advantage of the resolution and structural conformity of

FWI, while insuring the flatness of common image gathers (CIGs), Allemand and Lambaré (2014) propose to guide MVA by FWI (in a similar way as proposed by Zhou *et al*. (2013) for tomography of attenuation) (Figure 2).
In this approach the velocity model is updated iteratively by a local optimization scheme providing a set of velocity models $[v_n(\mathbf{x})]$, $n = 0, N$. The originality in this work is that, at each iteration, the velocity update, Δv, is constrained from the velocity perturbation obtained by migration-inversion, $g(x)$ (the guide). The constraint preserves structural conformity but modifies the amplitude of the guide by applying a smooth scaling factor, $\alpha(x)$: $\Delta v(x) = \alpha(x) g(x)$.
The optimization scheme updates the smooth scaling factor, $\alpha(x)$, and then applies it to the guide, $g(x)$, to build the velocity update. Considering that the problem is non-linear, the guide should be updated at each linear iteration (Figure 2) (or at least some stretching should be applied to take into account the change of the background velocity model).

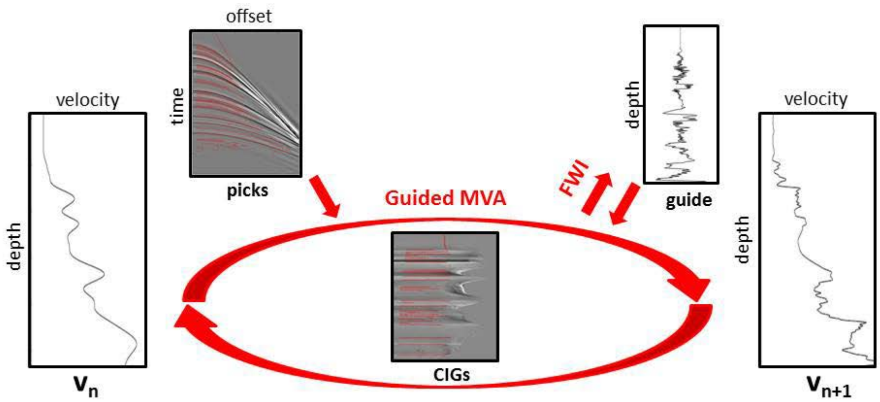

Figure 2 *FWI-guided MVA: the MVA criterion is used for assessing the quality of the velocity model (v_n is velocity model at iteration n) but, at each iteration, the velocity update is guided by the velocity update resulting from a migration/inversion process.*

For MVA we propose to use non-linear slope tomography (Guillaume *et al*., 2008), which exhibits the advantages of a non-linear update while using densely picked locally coherent events. For the computation of the guide we propose to use ray+Born inversion (Thierry *et al*., 1999), which allows producing a good approximation of the velocity perturbation in terms of phase and amplitude.
Starting from a given velocity model, $v_n(x)$, each iteration involves four steps:

1) Computation of waveform residuals for velocity model $v_n(x)$;
2) Computation of a velocity perturbation by ray+Born migration/inversion of waveform residuals to be used as a guide for the tomographic update, $g_n(x)$;
3) Computation of the scaling of the velocity guide, $\alpha_n(x)$, to derive a velocity update improving focusing of ray based tomography, $\Delta v_n = \alpha_n g_n$.
4) Addition of the scaled velocity perturbation to the previous velocity model, $v_{n+1} = v_n + \Delta v_n$

Clearly, the quality of the guide is very important for the success of the process. First, it should contain wavelength components of the velocity model that affect the MVA, i.e. it should contain wavelength components within the overlapping area in Figure 1 (typically below 6 Hz). Second, in this area the guide's wavelength components should not overlap with those of the background model.
At the end FWI-guided MVA guarantees that the velocity model follows the structures, since the added velocity perturbation does, and that the focus of the migrated image is maximized, since it uses a MVA criterion for the assessment of the velocity model.

Real data application

We present an example of the FWI-guided MVA on a 2D real dataset. It is a broadband (2.5 to 100 Hz) marine 48 km long dataset acquired offshore Australia. We used 2479 shots with a maximum offset of 4 km. The source and receiver spacings are 18.75 m and 12.5 m, respectively.
The initial velocity model is obtained by non-linear slope tomography, starting from a 1D model with a constant gradient in depth. The resulting initial model is shown in Figure 3. The guide is computed by a ray+Born inversion using this initial velocity model and frequencies from 2.5 to 8 Hz (Figure 4).

It is very similar to a low frequency migrated image (with, in particular, good structural conformity), but it represents velocity perturbations instead of reflectivity. Note that even if the process used to compute the guide is said to be "preserved amplitude", we cannot fully trust the amplitude of the resulting velocity perturbation, which is relevant for structures but not for absolute amplitudes which are determined by source strength. Hence these require, at least, a proper scaling, computed through the FWI-guided MVA. This is due to the lack of an accurate source wavelet and the constant density acoustic approximation. Figure 5 shows the velocity after FWI-guided MVA. The scaling is computed in such a way as to reduce the average residual move-out of the picks. The (x,z) B-splines grids are: (250m, 250m) for the background model, (100m, 20m) for the guide and (2000m, 500m) for the scaling function. We see that the process significantly improves resolution of the velocity model while improving the flatness of CIGs (Figure 6).

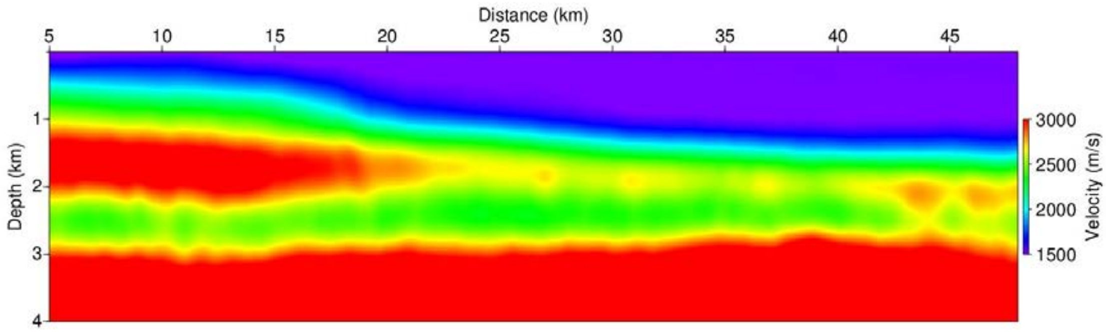

Figure 3 *Real data application: the initial model is obtained through a non-linear slope tomography.*

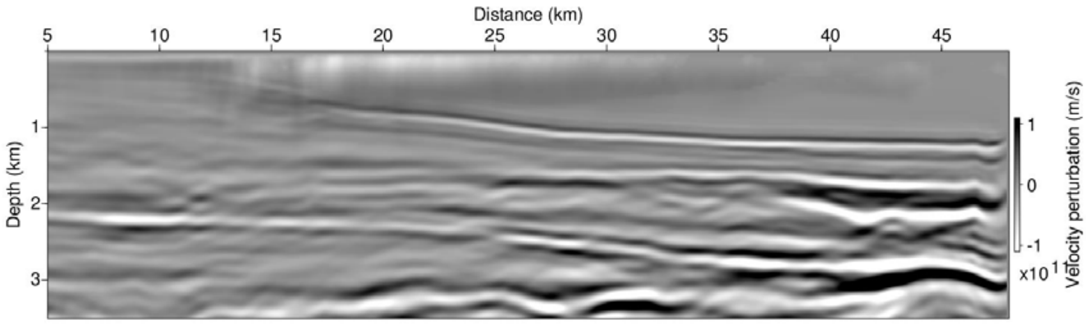

Figure 4 *Real data application: the velocity guide is computed through a ray+Born inversion.*

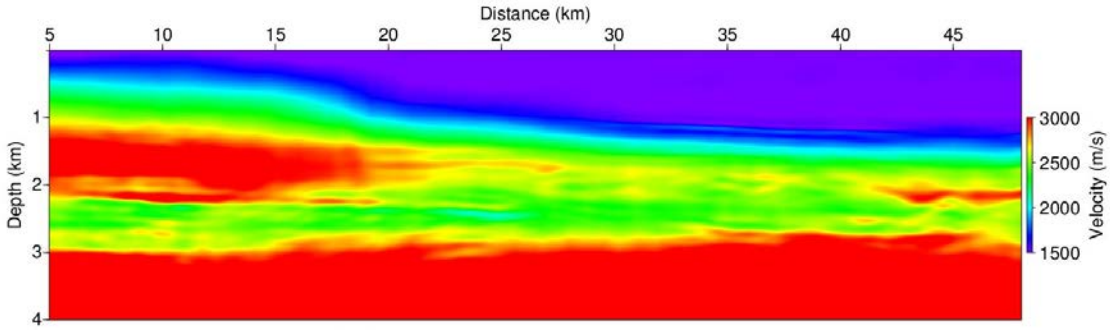

Figure 5 *Real data application: FWI-guided MVA computes the proper scaling which allows adding the velocity perturbation to the initial velocity, thus producing a higher resolution velocity model.*

Conclusions

FWI-guided MVA has been proposed by Allemand and Lambaré (2014) to combine, in an efficient way, FWI and MVA in order to obtain high resolution structurally conformable velocity models while improving flattening of migrated gathers. It works in the area of the mid-frequency overlap (Figure 1) and is based on the MVA cost function, while the high wavenumber part is included as a constraint in the tomographic inversion. For the first time an application to a 2D marine broadband real dataset is shown with promising results.

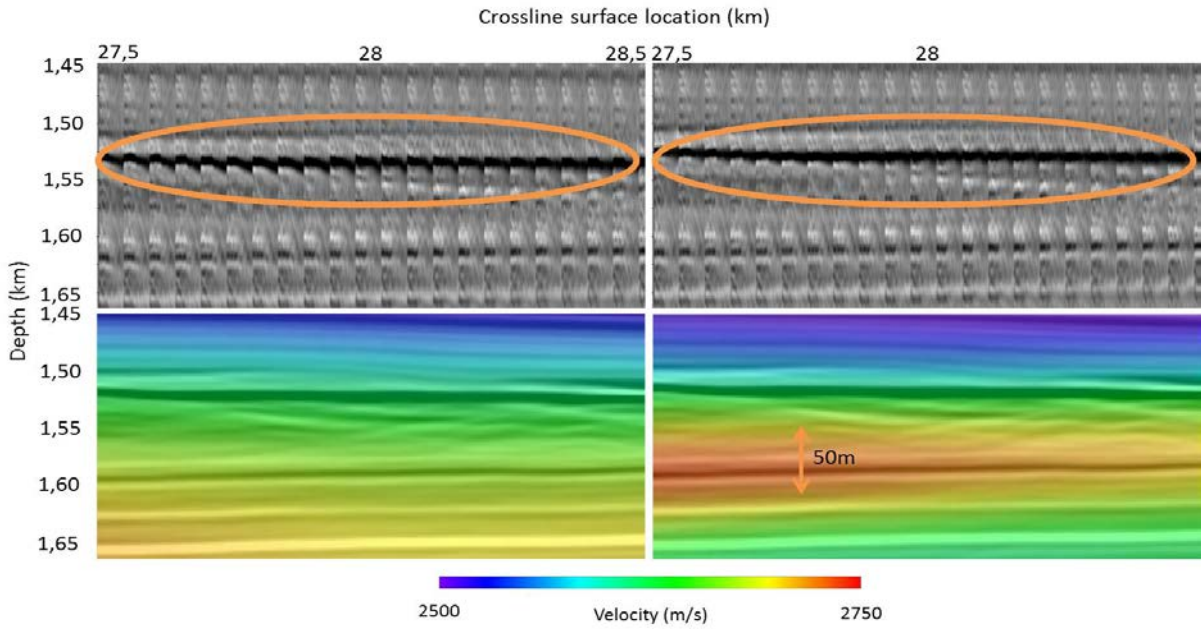

Figure 6 *Real data application: CIGs and stacks before (left) and after (right) FWI-guided MVA. The gather flatness is improved by the process. The offset range spans 2 km.*

Acknowledgments

We thank CGG for permission to publish this work and for providing the dataset. We thank our colleagues Ronan Sablon and Diego Carotti for their help in processing the data, and Andrew Ratcliffe and Hongbo Bi for providing helpful comments.

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