Tu_P03_01

Optimized and Cost-Efficient Visco-Acoustic Iterative Least-Squares Migration

Ø. Korsmo[1]*, A. Osen[2], A. Pankov[1], O.A. Sandstad[2]

[1] PGS; [2] AkerBP

Summary

Iterative least-squares migration is an expensive process that requires several passes of migration and de-migration. In this paper we focus on how an optimized initial reflectivity model combined with a deconvolution imaging condition can ensure faster convergence. We also incorporate the visco-acoustic effects in the de-blurring process to improve image corrections across and below Q-anomalies. This workflow is demonstrated on a dual-azimuth North Sea dataset, where the aim is to improve the understanding of the Frosk and Bøyla fields, which are characterized by complex and steeply dipping sand systems and areas of weak reflectivity.

Introduction

Least-squares migrations (LSM) have recently received increased attention as the new high-resolution standard in seismic imaging. This technology suggests that imaging should be posed as an inversion rather than a migration process, to correct for amplitude variations related to propagation effects and to balance the wavenumber content in the migrated image.

Here, we discuss how an optimized initial reflectivity model combined with a deconvolution imaging condition (IC) can reduce the cost of iterative LSM. Image corrections are achieved by utilizing an accurate background model. In addition to velocities, we incorporate visco-acoustic effects to resolve image corrections across and below Q-anomalies.

In this case-study we have used a dual-azimuth North Sea dataset, where the aim is to improve the understanding of the Frosk and Bøyla fields. These target structures are characterized by a complex and steeply dipping sand system and areas of weak reflectivity due the low impedance contrast compared to the background sediments.

Methodology

In conventional migration, the adjoint operator is used instead of the true inverse operator of modeling. Consequently, the migrated image can be a blurred representation of the earth reflectivity, with biased illumination and limited wavenumber content. The image resolution at a given depth is controlled by the migration operators, the acquisition parameters (source signature, frequency bandwidth and acquisition geometry), the earth properties at the reflector depth and the overburden (velocity and attenuation). These limitations and their associated side-effects in the migrated image can be addressed by posing the imaging problem in terms of least-squares migration (Nemeth et al., 1999).

Both image and data-domain implementations exists, with curvelet domain matching filters, Point Spread Functions (PSFs) and the full iterative LSM (Guitton, 2004; Valenciano, 2008; Lu et al., 2017). In this study we use a visco-acoustic anisotropic one-way wave-equation operator (Valenciano et al., 2012), which integrates the one-way operator with a fast, linear inversion solver in an efficient migration/de-migration workflow (Lu et al., 2017).

Increased efficiency - Deconvolution Imaging Condition

Conventional wave equation migration algorithms use a cross-correlation IC. We can consider LSM to be a 3D deconvolution process to de-blur the migrated image. This process requires several passes of migration and modeling. Our implementation of LSM use a 1D deconvolution IC (equation 1) to calculate the seismic image function I_i, where the back projected received wavefield, U_i is divided frequency by frequency by the forward propagated source wavefield, D_i

$$I_i(\bar{x}) = \sum_{\omega} \frac{U_i(\bar{x},\omega) D_i^*(\bar{x},\omega)}{D_i(\bar{x},\omega) D_i^*(\bar{x},\omega) + \varepsilon} \qquad (1)$$

where the index i denote the iteration number, and ε is a stabilization factor. The 1D deconvolution IC can remove some propagation effects and broaden the wavenumber spectrum and hence represents a step toward the full 3D deconvolution process achieved with LSM. For a flat layer model, a one pass migration using 1D deconvolution IC can provide images comparable to the iterative LSM. The advantage of using deconvolution IC in LSM is faster convergence, requiring fewer iterations and therefore a reduction in cost.

Importance of the initial reflectivity model

We should ensure that we start the inversion with the best available migrated section (Korsmo et al., 2018). In principle, any imaging algorithm could be used for the initial reflectivity. Events that are not imaged in the initial migration will not be modeled in the first de-migration step and would contribute as large data residuals in the initial iterations of LSM. Figure 1 compares LSM results from two initial reflectivity cubes using the same background velocity model. One is a Kirchhoff migration whereas the other one is a wave-equation migration (WEM) and we show the corresponding results after a few iterations of LSM. Even though the two initial reflectivity cubes are quite different in character, the inverted results appear similar. A closer look show that the shallow faulted structure (ellipses) and the steep dipping event (arrows) are better resolved using the WEM image as the initial reflectivity model. These dipping structures are already better imaged in the initial WEM compared to the Kirchhoff PSDM. Figure 2 shows an observed shot point and initial data residuals for the two corresponding initial models. In this example we see less initial data residual when we start the inversion using the WEM.

These observations indicate that we should optimize the migrated image before entering LSM. The benefit will be faster convergence and reduced cost (Korsmo et al., 2018).

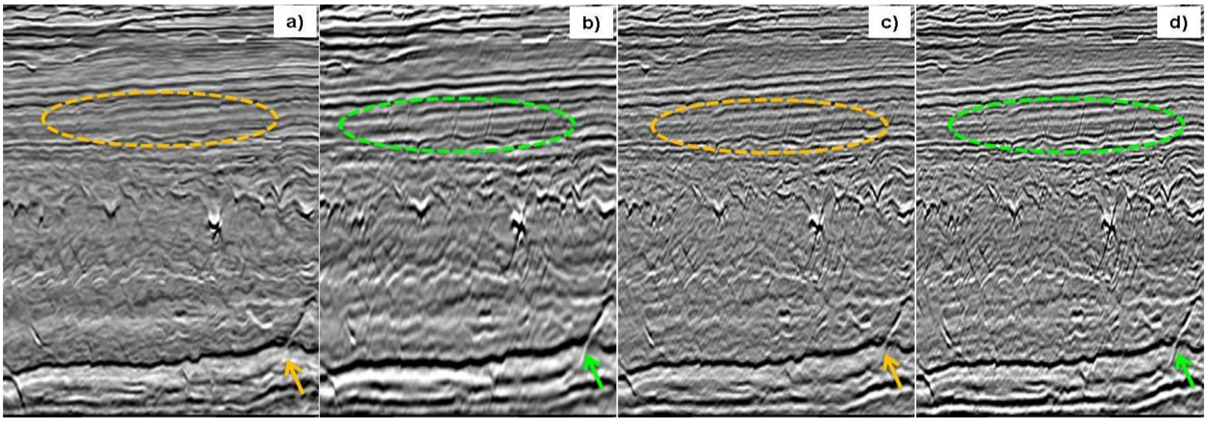

Figure 1. *Kirchhoff PSDM (a) one-way wave equation migration (b) LSM with initial reflectivity model from Kirchhoff PSDM (c) and LSM with initial reflectivity model from WEM (d).*

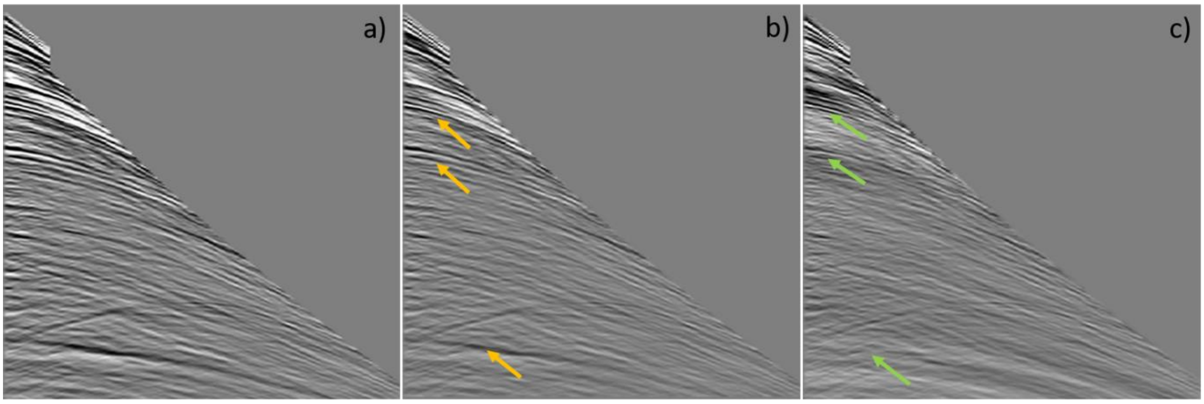

Figure 2. *Observed shot point (a) and the corresponding initial data residuals based on a Kirchhoff migration (b) and a WEM (c) as the initial reflectivity model. As indicated by the arrow, less initial residuals are observed with WEM.*

Visco-acoustic effects – allowing more physics in the wave field propagation

Migration with 1D deconvolution will not correct for attenuation and dispersion effects, where anomalies in the Q-model will distort the migrated image. These visco-acoustic effects will only partly be corrected for in the migration as long as we use the adjoint operator, not the true inverse of modelling. For this reason, we should include the Q-model in LSM process when we have access to reliable measurements.

Inversion results over the Frosk and Bøyla fields, Norwegian North Sea

To ensure rapid convergence and a minimum number of iterations required with LSM, we start by optimizing the initial reflectivity model. The model was based on an existing Kirchhoff PSDM and a WEM image. The Kirchhoff PSDM had benefited from regularization prior to migration, followed by a full post-migration processing sequence. Some of the steepest dipping target events were, however, better imaged with the WEM. For this reason, a weighted stack of Kirchhoff PSDM and the WEM was used as the starting reflectivity model for LSM. This initial reflectivity model provided a focused image, where most of the acquisition footprints had already been addressed.

In the legacy processing a 3D Q-model had been generated based on the FWI velocity model. This Q-model contains lower Q-values inside some shallow channels, and this helps in healing the dimming and distortion for events below. The Q-model was utilized in our LSM to further improve the image corrections. Figure 3 shows the comparison between the Kirchhoff PSDM image and the LSM results for an arbitrary line that goes through the Frosk and Bøyla fields and in addition a few other challenging structures. Two of these features are below or at the edge of the shallow channels. Clear structural improvements and focusing of small scale details are achieved with LSM compared to the Kirchhoff image. In addition, there are clear signal enhancements with LSM, especially for areas characterized by low impedance contrasts between the target sands to the background sediments.

Figure 4 shows two target depth slices at 1780 and 2050 m depth comparing Kirchhoff PSDM and LSM – and showing an overly of the corresponding relative acoustic impedance. Mapping the steeply dipping sand systems (indicated by the arrows in Figure 4b) improves significantly with LSM compared to migrations. The same observations can be seen over the Bøyla field, indicated by the ellipse in Figure 4d. These details provide critical information required to understand the extent and complex geometry of the target structures.

Conclusions

In this case study we have utilized a visco-acoustic least-squares migration to improve and focus an already high-quality Kirchhoff PSDM image over the Frosk and Bøyla fields. These structures form two complex and challenging fields, consisting of steeply dipping sands and areas of weak reflectivity. To ensure a cost-efficient inversion through rapid convergence, we have optimized the initial reflectivity model by combining a final processed Kirchhoff PSDM and WEM. Furthermore, our 1D deconvolution imaging condition contributed to an accelerated convergence and the 3D Q-model optimized the image corrections across and below the Q-anomalies. The inverted images reveal much more detail in these complex targets compared to migration results.

Acknowledgements

We thank AkerBP and their partners Lundin Norway and Vår Energy for the permission to present this work. Furthermore, we thank Alejandro Valenciano, Nizar Chemingui and Grunde Rønholt for valuable discussions and support.

References

Guitton, A. [2004] Amplitude and kinematic corrections of migrated images for nonunitary imaging operators. *Geophysics, **69**(4), 1017-1024*
Korsmo, Ø. and Valenciano, A. [2018] Iterative Least-Squares Migration in Practice, Application to a Narrow Azimuth North Sea Dataset. *First EAGE/SBGF Workshop on Least-Squares Migration*.
Lu, S., Li, X., Valenciano, A., Chemingui, N. and Cheng, C. [2017] Least-Squares Wave-Equation Migration for Broadband Imaging. *79th EAGE Conference and Exhibition.*

Nemeth., T., Wu, C., Schuster, G.T. [1999] Least-squares migration of incomplete reflection data. *Geophysics*, ***64****(1), 208-221*
Valenciano, A.A. [2008] Imaging by wave-equation inversion. PhD thesis, Stanford University.
Valenciano, A.A. and Chemingui, N. [2012] Viscoacoustic imaging: tomographic Q estimation and migration compensation. *82nd SEG Annual Meeting*, Expanded Abstracts, 1-5.

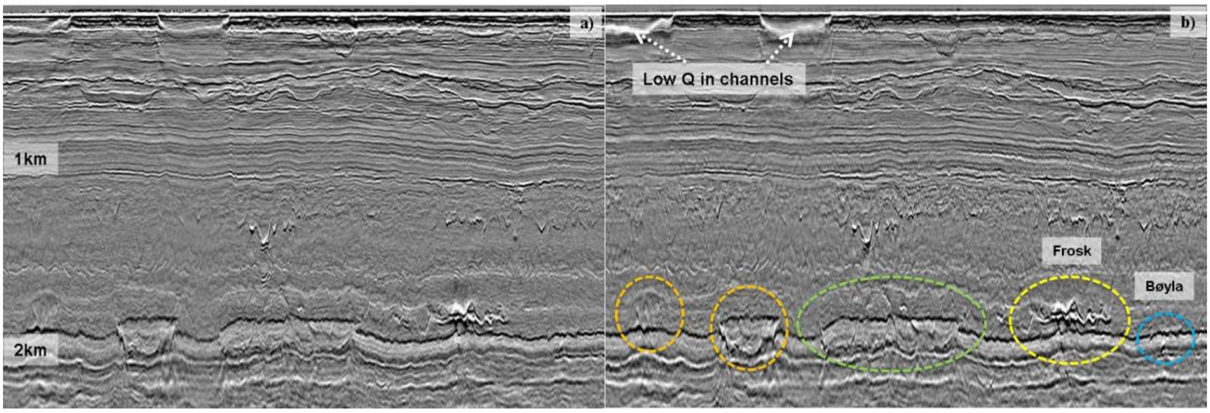

Figure 3. *Kirchhoff PSDM (a) and the LSM (b) through the Frosk and Bøyla fields, and in addition, a set of similar complex sand systems indicated by the green and orange ellipses. The green ellipse shows identify a potential new drilling target.*

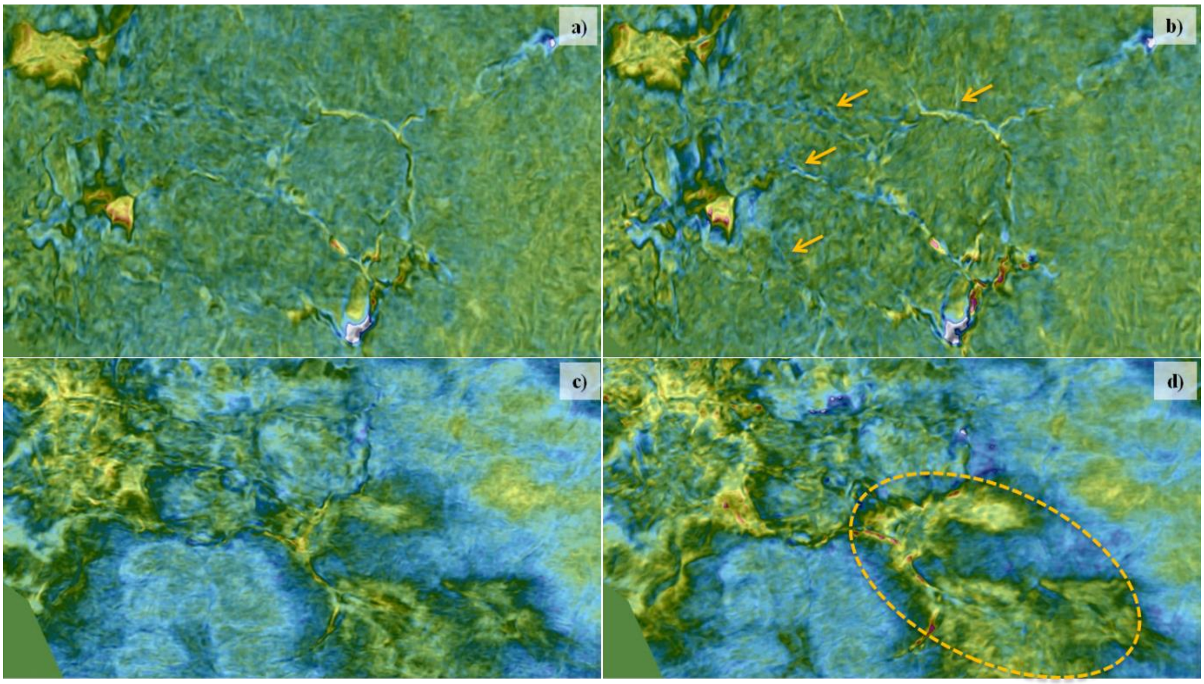

Figure 4. *Depth slice of Kirchhoff PSDM (a) and LSM (b) image at 1780 m depth with the corresponding relative acoustic impedance overlaid. The yellow arrows show how the sand feeder systems have been better resolved with LSM compared to the Kirchhoff PSDM. The same illustration is shown at 2050 m depth with the Kirchhoff PSDM (c) and the LSM (d). The yellow ellipse shows the Bøyla field which stands out much clearer with LSM.*