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Application of Iterative Least-Squares Migration in Different Geological Settings

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Summary

Least-squares migration has over the last few years become the new standard in high-end seismic imaging. In this paper we utilize iterative least-squares migration in different geological settings from shallow complex structures to deeper sub-chalk and sub-salt targets. We evaluate how least-squares migration can improve the wavenumber content, suppress illumination effects from acquisition design and velocity anomalies and reveal finer structural detail compared to conventional migration. By utilizing the one-way extrapolators, the inversions can be done for the full frequency range supported by the data at an acceptable cost.

Introduction

Least-squares migration (LSM) can overcome limitations of the imaging system and estimate an image that is closer to the earth reflectivity. This suggests that imaging should be posed as an inversion rather than migration process to correct for amplitude variations related to propagation effects (acquisition geometry, aperture, velocity anomalies) and to balance the wavenumber content in the migrated image. The process has over the last few years become the new standard in high-end seismic imaging.

A requirement is a numerically stable implementation, which is suitable and affordable for high frequencies. Our implementation uses a visco-acoustic anisotropic one-way wave-equation operator which allows us to run LSM in the data-space and get access to 3D deconvolved images. The inversion is based on the Born approximation, where the background model is kept unchanged between each iteration. This requires an accurate earth model, usually derived from Full Waveform Inversion (FWI).

In this paper we utilize iterative LSM and evaluate the ability (compared to conventional migration) to generate high resolution images in different geological settings from shallow complex structures and sub-chalk targets in the North Sea to deep pre-salt targets in the Santos basin offshore Brazil.

Methodology

Depth migration produces 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 artifacts in the migrated image can be addressed by posing the imaging problem in terms of least-squares migration (Nemeth et al., 1999).

Different implementations exists in both the image and data-space, with curvelet domain matching filters, Point Spread Functions (PSFs) and the full iterative LSM (Guitton, 2004; Valenciano, 2008; Lu et al., 2017). Our algorithm uses 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). Synthetic shots are created from Born modeling based on a reflectivity model, background velocity and the acquisition geometry. For each iteration imaging is achieved with a 1D deconvolution imaging condition and regularization is applied to control the variability of the model.

Linearized inversion in the data-domain

The iterative inversion in the data-domain implicitly solves the Hessian of the cost-function at every sample in the model space. This will require a numerically stable implementation and an accurate background model, usually derived with FWI. Over the last decade, FWI has become a standard tool in velocity model building, not only for the shallow sediments but in recent years also to build the entire imaging model. This has been possible by utilizing the tomography term of the FWI kernel (Ramos et al., 2016). Figure 1 shows an example where this has been applied for targeted intra-salt and pre-salt model updates between 3 km and 8 km depth in the Santos Bain, offshore Brazil. As indicated by the arrows, imaging with the FWI updated model, simplifies and improves the pre-salt structure. Optionally, further stabilization and correction for un-resolved velocity errors can be achieved with local time-variant shifts of the observed data to best match with the modelled shots (Korsmo et al., 2018).

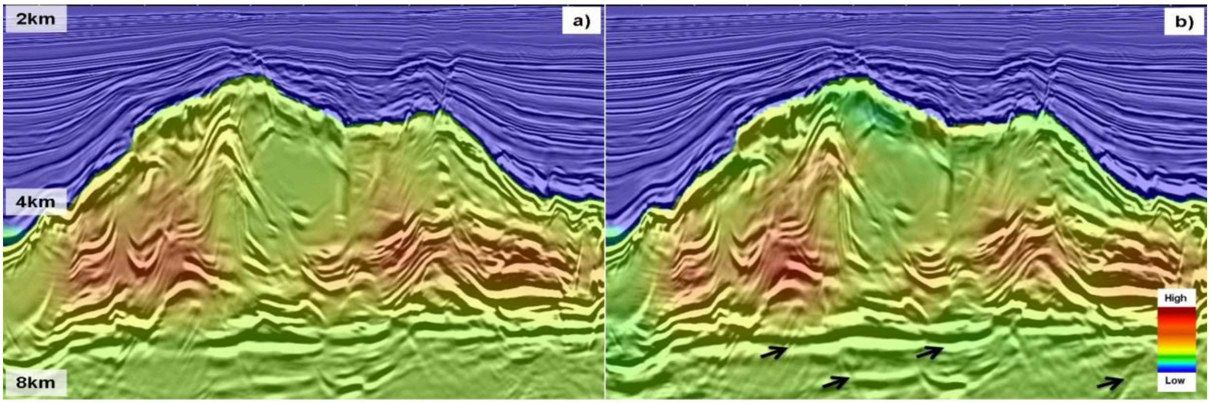

Figure 1 *Velocities and corresponding image before (a) and after (b) intra and pre-salt updates with FWI.*

High frequency inversion

LSM is an expensive process that requires several iterations of migration and modeling. By using a one-way wavefield extrapolator, whilst being aware of its limitations, we can estimate the true earth reflectivity. Other situations would of course require a two-way wavefield extrapolator, which comes with a much higher cost and is unlikely to be achievable for the full bandwidth supported by the data. As FWI is being extensively used as the main tomography engine and pushed towards higher frequencies, we need to be aware of the limitations of the imaging algorithm. It is well known that WEM handles complex velocity models with large contrasts better than ray-based methods. Iterative LSM with one-way wavefield extrapolators can be seen as a reasonable approach to achieve high-resolution inversion results suitable for complex velocity models.

Study areas

The first examples used in this paper covers shallow structures and prospects at around 2 km depth from the Viking Graben in the North Sea. These structures are characterized by complex and steeply dipping sand systems and areas of weak reflectivity due the low impedance contrast compared to the background sediments.

The following examples are from sub-chalk targets at 4 km depth in Moray Firth area of the UK sector of the North Sea and pre-salt carbonate prospects at 7-8 km depth in the Santos basin, offshore Brazil. Both of these deeper target examples sit below large velocity contrasts, which cause significant illumination variations and focusing/de-focusing effects as the energy propagates through the rugose high velocity layers.

Results

Structural mapping of the steeply dipping sand system was the main objective with LSM in the shallow data examples from the Viking Graben in the North Sea. Figure 2 shows an arbitrary line through both the migrated image and the iterative LSM; crossing the dim zone (yellow ellipse) and the target injectite sands system (blue ellipse). The sand system is more coherent and with finer details with LSM compared to conventional migration. There is better fault imaging (indicated by the arrows) and signal enhancements below a shallow poor illumination zone (yellow ellipse) with LSM compared to the conventional migration results. The dim zone could be caused by a combination of several effects, from shallow gas accumulations as well as scattering effects from near vertical carbonate pipes.

Figure 3 shows an inline, crossline, depth slice and FK-spectrum over the Moray Firth area in the North Sea. The 3D deconvolution process provides improvements in the wavenumber content as indicated by the spectrum and enhances finer details around the rotated fault blocks at 4 km depth.

The depth slice with regularized LSM shows attenuation of acquisition footprints and reveals more details within the target anticline structure. Also notice the suppressed migration swings and correction for incomplete acquisition in the crossline display (red ellipse).

Figure 4 shows an inline, a crossline and an amplitude map along the carbonate structure with LSM compared to a conventional migration. Again, LSM provides similar image improvements as for the other examples. Note the increased resolution and details with LSM compared to conventional migration along the carbonate structure around 7 km depth (amplitude map). The inversion was performed up to 55 Hz (full power) in this example and up to 60 Hz for the North Sea examples.

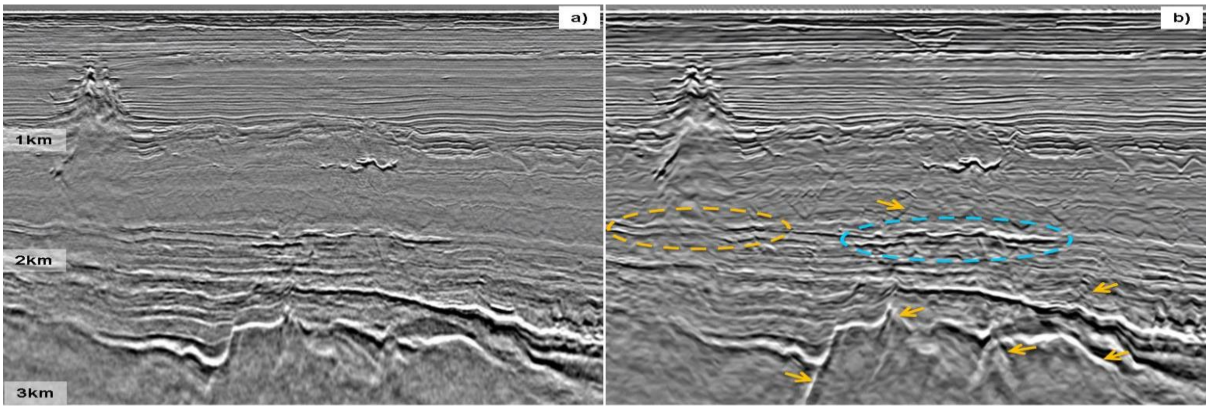

Figure 2 *Arbitrary line through the dim zone (yellow ellipse) and injectite sands (blue ellipse) with the conventional migration (a) and LSM (b). The LSM enhances the signal below the dim zone and reveal finer details within the target structure as well as improving the fault imaging compared to the conventional migration (arrows).*

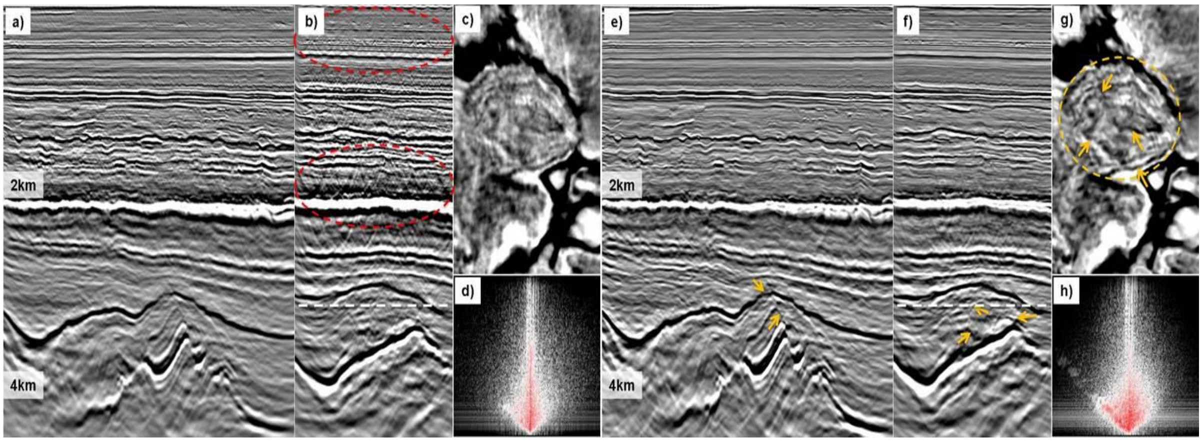

Figure 3 *Inline (a), crossline (b), depth slice (c) and FK-spectrum (d) with conventional migration and LSM (e, f, g, h). The white, dotted lines indicate the location of the depth slice. Comparing (b) and (f) within the red ellipse we notice how LSM with regularization suppresses noise from the high impedance contrast at the chalk (at 2 km depth) and corrects for incomplete acquisition in the shallow part of the crossline. Also noted are improvements in fault imaging, wavenumber content and details within the target structure (depth slice) with regularized LSM compared to conventional migration.*

Conclusions

In this paper we have utilized visco-acoustic least-squares migration to provide high resolution images for various geological settings and complex target structures; from shallow sand injectite systems to deeper sub-chalk & sub-salt targets. The data-domain implementation implicitly solve for the Hessian of the cost function at every sample in the model space. This can have significant advantages in areas of rapidly changing geology with associated velocity differences. The inverted results improve the wavenumber content in the images, suppress acquisition footprints, remove illumination effects from velocity anomalies and reveal finer structural details compared to conventional migration. By utilizing the one-way extrapolators we can run inversions for the full frequency range supported by the data for an acceptable cost compared to two-way extrapolators.

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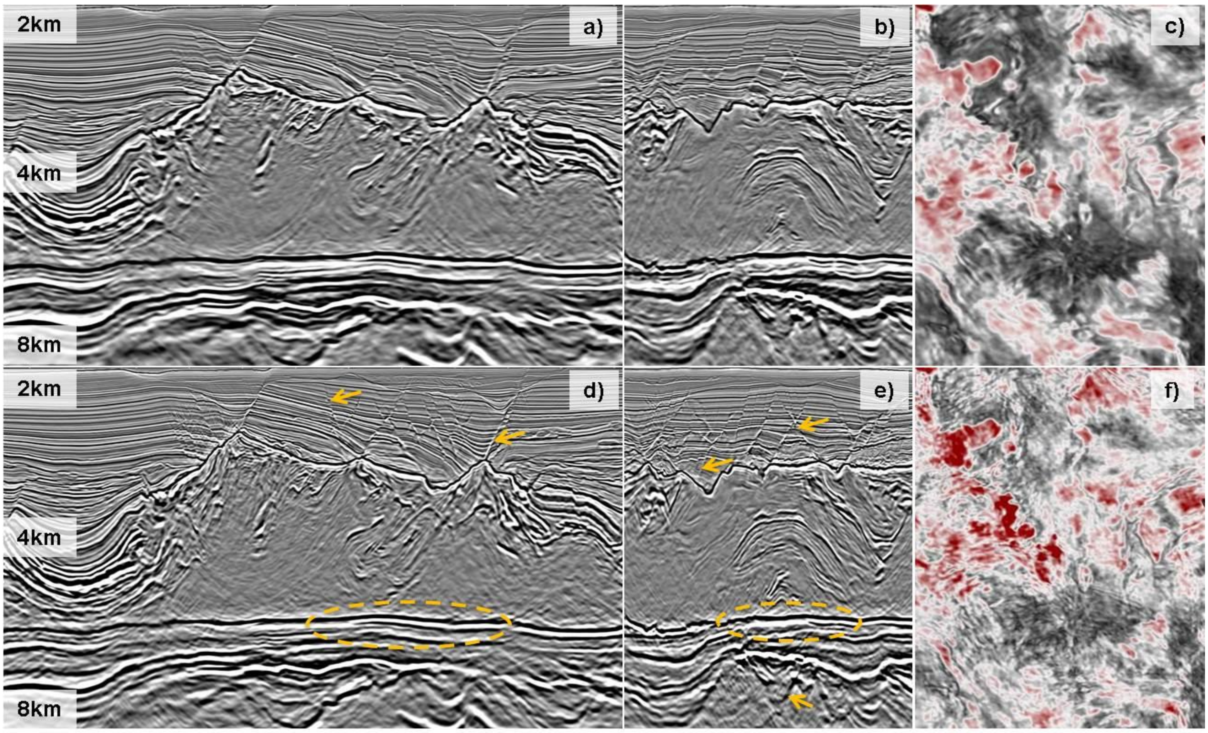

Figure 4 *Inline (a), crossline (b) and amplitudes extracted along the target reflector (c) with conventional migration and LSM (d, e, f). The yellow ellipses point to the target carbonate built-up. Notice the improved resolution, fault imaging and details along the carbonate structure with LSM compared to conventional migration.*