LEAST-SQUARES KIRCHHOFF PSDM WITH A LOCAL BASED INVERSION APPROACH AND COMPENSATION FOR LIMITATIONS IN MODELING.

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Summary

Reliable seismic amplitudes are crucial for the estimation of rock properties. In conventional depth imaging, amplitudes and resolution will be influence by propagation effects in the imaging model. These limitations origin from the formulation of the migration operator, implemented as the adjoint rather than the inverse of modeling. Least-squares migration (LSM) tries to eliminate these effects and resolve the real reflectivity model.

In this study, we make use of a newly developed local calibrated image-domain Kirchhoff least-squares migration to deconvolve the system response from the depth migrated gathers. We demonstrate how the inversion de-blurs the image and adjusts the prestack amplitude response, following better the expected response from well synthetic. The method is demonstrated on a North Sea dataset from the Viking Graben area, covering the Verdandi/Lille Prinsen discovery.

Introduction

Reliable seismic amplitudes are crucial for the estimation of rock properties. In conventional depth imaging, the migration is formulated as the adjoint of modeling. As a consequence, the migrated image may suffer from irregular amplitude variations and have limited resolution. Imaging with an exact earth model, and the most advanced migration operator, will still be affected by propagation effects from acquisition, aperture and overburden complexities. Azimuthal rich acquisitions will improve the illumination below complex structures but the seismic amplitudes will still be influenced by focusing and de-focusing effects as the energy propagates through velocity anomalies. Alternatively, or in combination with a better acquisition design, the imaging step can be formulated as an inversion process to provide more reliable seismic attributes.

In this paper, we make use of a least-squares migration with a Kirchhoff modeling/migration operator (LSM-Kirchhoff) to balance the illumination, improve prestack attributes and resolution of the underlying conventional Kirchhoff PSDM. The case study was performed over the Verdandi/Lille Prinsen discovery and Ivar Aasen field in the Norwegian North Sea. Calcite cemented sands are widespread in the area and can lead to shadow zones and illumination artefacts during imaging.

Methodology

Least-squares migration addresses the imaging step as an inversion rather than a migration process, (Nemeth et al., 1999), and can be implemented in either the image- or data-domain. The data-domain implementation minimizes the residuals between observed and modeled data in an iterative and linearized inversion process (Lu et al., 2017). The image-domain approach can be seen as a multi-dimensional deconvolution of the image based on the measured system response (Valenciano, 2008). The system response is typically measured with point-spread-functions (PSFs), a two-step process of modeling and migration, with a known reflectivity model (scatter points), the acquisition geometry and the migration velocities. The velocity model is assumed to be known and exact for both approaches, and it is not updated during the inversion process, meaning only the reflectivity model is inverted for.

In this paper we utilize an image-domain implementation to deconvolve the depth migrated gathers based on PSFs computed with a Kirchhoff modeling/migration operator. The PSFs measure the Hessian of the cost function at discrete locations in the model space, and the inversion process seeks the reflectivity model, $\boldsymbol{r}$ that minimize the following equation:

$$\|\boldsymbol{m} - \boldsymbol{H}\boldsymbol{r}\|^2. \quad (1)$$

where $\boldsymbol{m}$ is the migrated data and $\boldsymbol{H}$ represents the interpolated PFSs. The inversion can be extended to the prestack domain by expanding the PSFs dimensionalities to the angle or offset domain (Valenciano et al., 2019). For a single azimuth acquisition, the PSFs becomes a 7-dimentional matrix, where each PSF has its own 3-dimention local space in addition to its spatial positon in the model and the extended axis along the angle or offset dimension. Figure 1 shows the PSFs along the crossline direction for a common offset class (1780 m) and a PSF offset gather for the location marked with the yellow box. As illustrated, the PFSs are non-stationary in the model space and along the offset axis. The offset dependent global reflectivity model is iteratively updated for with a linear solver (conjugate gradient or least-square) that seeks to minimize the misfit between the migrated data and the forward modeling (reflectivity convolved with the PSFs) in equation (1).

Imaging results from Kirchhoff least-squares migration

We have applied LSM-Kirchhoff on a narrow azimuth North Sea data set to correct the prestack attributes in a challenging geological regime where shallow features degrade the imaging result. Figure 2 shows a comparison between LSM-Kirchhoff and Kirchhoff PSDM with the associated Frequency-Wavenumber (FK)-spectra. The deconvolution process improves both the vertical and lateral resolution, helping reveal thin layers and providing better fault imaging. This reduces the effect of seismic tuning and improve the ability to identify the targets. The Verdandi/Lille Prinsen discovery is annotated with the yellow ellipse. The inversion further balances the amplitude response and creates better event continuity by correcting for the uneven illumination from the acquisition and velocity variations.

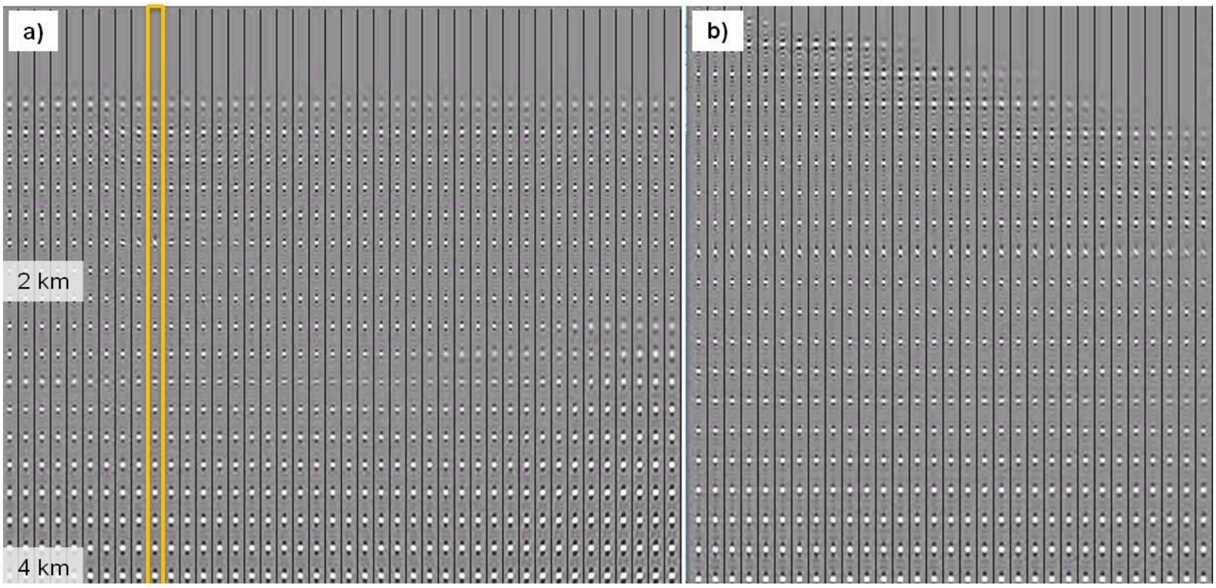

Figure 1. *PSFs along the crossline direction for offset 1780 m (a) and the PSF offset gather (b) for the image point marked with the yellow box. The PSFs are non-stationary in the model space and in the prestack domain.*

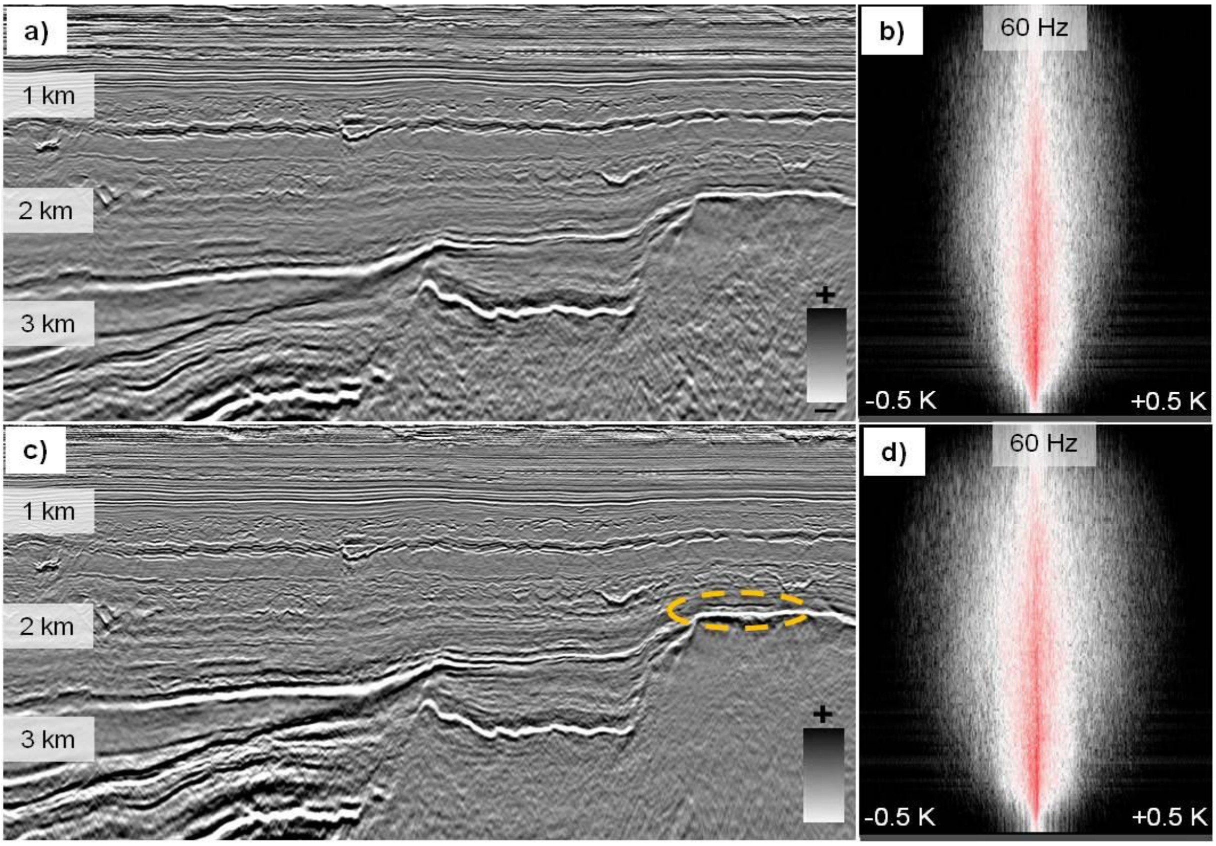

Figure 2. *Kirchhoff PSDM stack (a) and corresponding FK-spectrum (b) compared to LSM-Kirchhoff PSDM (c) and (d). The yellow ellipse indicates the area with gas and oil discovery Verdendi/Lille Prinsen.*

To achieve the desired image corrections with LSM-Kirchhoff, an accurate velocity model is crucial. Velocity anomalies need to be correctly captured in the model, before the propagation effects experienced during the seismic acquisition can be measured correctly and compensated for in the inversion process. Figure 3a shows the velocity model overlaid on the seismic image and Figure 3b shows the associated stacked illumination. The illumination from source to receivers is represented through the diagonal of the Hessian (***H***) of the cost function in equation (1). Figure 3b shows how the illumination follows the large scale velocity variations and the shadow zones originating from the small scale cemented sands, annotated with black arrows. The velocity model was generated with Full Waveform Inversion combined with reflection tomography and automatic detection/scaling of the cemented sand bodies (Korsmo et al., 2017). Figures 3c and 3d shows the corresponding migration and inversion results. Improvements in resolution and amplitude fidelity is achieved with LSM-Kirchhoff, and the image corrections follow the illumination pattern measured in Figure 3b. The imaging at the reservoir level over Ivar Aasen field, annotated with black ellipse in Figure 3d, is improved with LSM-Kirchhoff when compared to Kirchhoff migration.

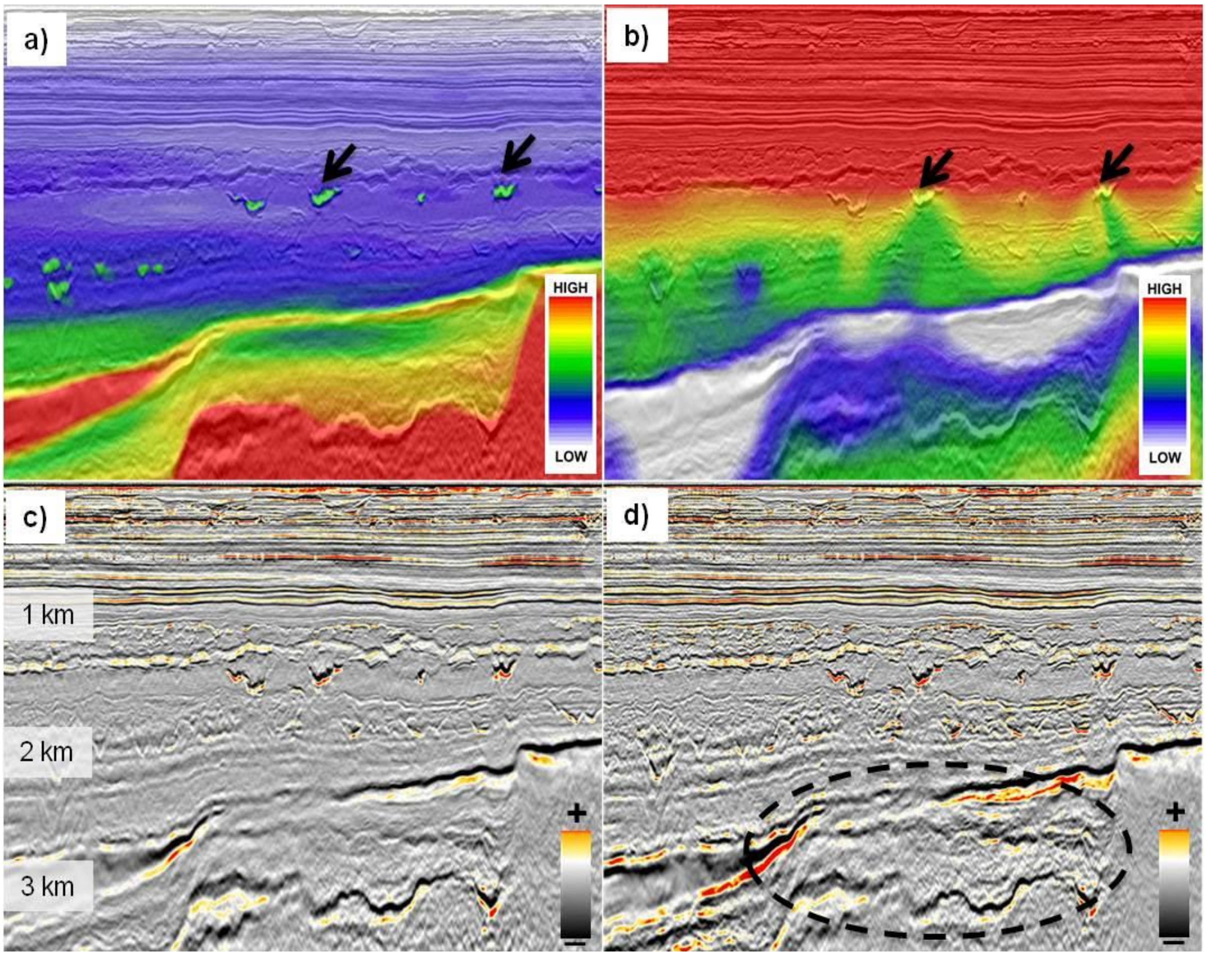

Figure 3. *Velocity model used in the Kirchhoff modeling/migration (a) and the corresponding stacked illumination from PSFs (b). Kirchhoff PSDM image (c) and the LSM-Kirchhoff PSDM (d). The black ellipse indicates the Ivar Aasen field, where LSM-Kirchhoff has increased the resolution and the amplitude fidelity by compensating for the complex overburden and limitations in the acquisition design.*

LSM-Kirchhoff was applied in the prestack domain, where each offset was convolved with different deblurring operators. Figure 4a shows the depth and offset dependent illumination pattern for three gather locations, and the corresponding migrated and inverted gathers in Figures 4b and 4c. The figure illustrates how the velocity variations in the overburden and the acquisition design influence the prestack amplitudes in conventional imaging.

Conclusions

We have applied LSM-Kirchhoff on a narrow azimuth acquisition to improve the prestack attributes in a challenging geological regime, where cemented sands degrade the reservoir image quality at the Utsira High in the North Sea. The inversion process provides better event continuity in both the prestack and poststack domain and increased resolution through the multi-dimensional deconvolution process. Our implementation is performed in the image-domain where the migrated gathers are deconvolved with PSFs that represents the explicit calculation of the Hessian in the least-squares objective function.

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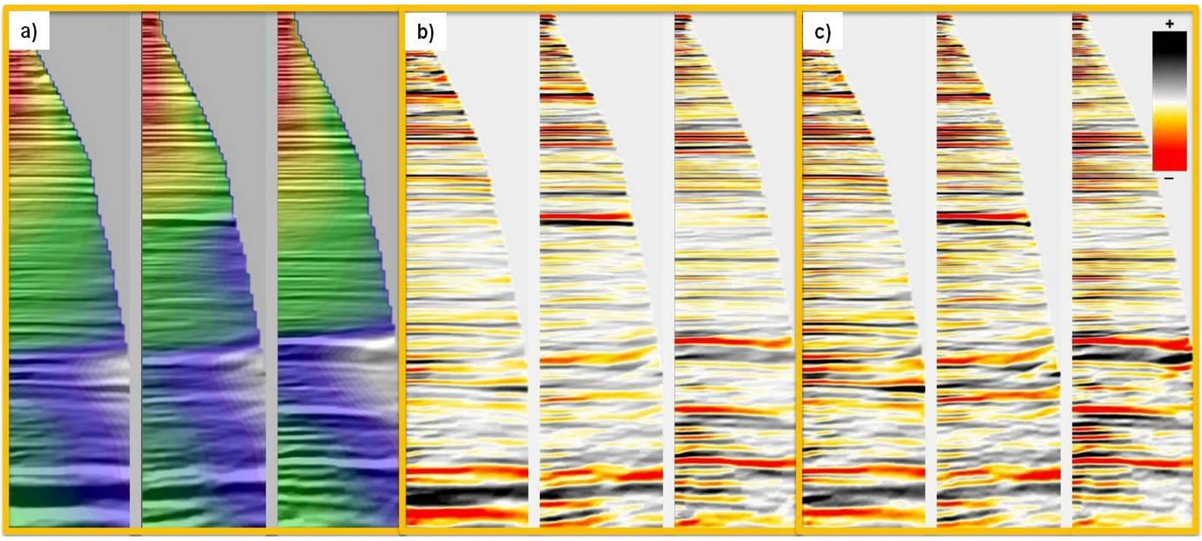

Figure 4. *Prestack illumination from PSFs (a) overlaid on the depth migrated gathers, Kirchhoff PSDM gathers (b) and the LSM-Kirchhoff gathers (c). The illumination and image corrections with LSM-Kirchhoff are non-stationary in all dimensions.*

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