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Reliable Seismic Amplitudes in Sub-salt Imaging Through Wave Equation Inversion

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SUMMARY

To mitigate the irregular illumination problem in the subsalt area, we propose a wave equation reflectivity inversion (WEI) method. The method poses depth imaging as least squares problem with explicit computation of the Hessian through the use of point-spread functions. WEI not only removes the illumination imprint on the seismic amplitudes, it also enhances the wave number content, improving the overall resolution of the migrated image.

We will show how applying WEI ensures that reliable amplitude can also be extracted in sub-salt/pre-salt areas. Compared to a conventional migration, WEI recovers the amplitudes in the subsalt shadow zone and improves the sharpness of the reflectors.

Introduction

Incomplete acquisition geometries and complex overburden cause illumination variations distorting the seismic amplitudes on the migrated image. To alleviate this problem, innovative acquisition configurations such as Multi-azimuth (MAZ), Wide-azimuth (WAZ), or Full-azimuth (FAZ) have been proposed. However, non-uniform illumination remains a challenge particularly below salt bodies and other complex geological structures. It leads to uncertainty when analysing amplitudes sub-salt or in estimation of rock properties from the migrated volumes. The variable illumination creates significant amplitude variations that are unrelated to the lithology.
To mitigate the irregular illumination problem in the subsalt area, we propose a wave equation reflectivity inversion (WEI) method. The method poses depth imaging as least squares problem (Nemeth et al., 1999) with explicit computation of the Hessian through the use of point-spread function (PSF) (Valenciano et al., 2006). First, we estimate the Hessian in the target area, and then solve a linear system of equations to deconvolve the multidimensional PSFs from the migrated image. WEI not only removes the illumination imprint on the seismic amplitudes, it also enhances the wave number content, improving the overall resolution of the migrated image.
We will illustrate the benefits of WEI with examples from synthetics and field data. The 3D field data examples all utilize data recorded with a dual-sensor streamer that ensure pre-stack compliance in the deghosted amplitudes. To ensure that these amplitudes can also be used in areas with complex geology such as in sub-salt areas, the effects of varying illumination and incomplete acquisition geometries need to be corrected before amplitude extractions and further analysis. We will show how applying WEI ensures that reliable amplitude can also be extracted in sub-salt/pre-salt areas. Compared to a conventional migration, WEI recovers the amplitudes in the subsalt shadow zone and improves the sharpness of the reflectors.

Theory

We adopt the standard linear model for seismic data, where the data **d** can be described as the result of a linear modelling operator **L**, applied to a reflectivity model **m**:

$$\mathbf{d} = \mathbf{Lm} \quad (1)$$

To invert for the reflectivity model **m**, we use a least-squares approach where we estimate the reflectivity model $\mathbf{m}_{est}$ from the observed data $\mathbf{d}_{obs}$ by minimizing the objective function:

$$\mathbf{J} = ||\mathbf{d} - \mathbf{d}_{obs}||^2 = ||\mathbf{Lm} - \mathbf{d}_{obs}||^2 \quad (2)$$

The solution can be expressed directly in terms of the modelling operator **L** and its adjoint, or migration operator **L'**. The reflectivity $\mathbf{m}_{est}$ that minimizes the objective function is given by:

$$\mathbf{m}_{est} = (\mathbf{L'L})^{-1}\mathbf{L'd}_{obs} = \mathbf{H}^{-1}\mathbf{m}_{mig} \quad (3)$$

where $\mathbf{m}_{mig} = \mathbf{L'd}_{obs}$ is the migrated image, and $\mathbf{H} = \mathbf{L'L}$ is the Hessian matrix. This matrix can be formed by a cascade of modelling and migration, but it can also be interpreted as the response of a point scatterer through the imaging system, or the point spread function (PSF). It contains information about acquisition geometry and earth properties. The action of equation (3) amounts to a multi-dimensional deconvolution of the seismic image that yields a direct estimate of reflectivity by correcting for the transfer effects of the seismic system, including acquisition and illumination related effects. The diagonal of the Hessian matrix is a measure of the illumination. It is possible to compensate for some of the blurring and distortion effects on the image once the PSFs are known (Gelius et al., 2002).
We estimate the PSFs by modelling the response of a set of point scatterers distributed over the earth model, then migrating the resulting data. The computed PSFs are interpolated to the imaging grid before the inversion. Finally, we iteratively solve a linear system of equations to deconvolve the multidimensional PSFs from the image.

Field data examples

We applied the wave equation reflectivity inversion workflow to a subset of a FAZ dataset from the Gulf of Mexico (Long et al., 2014). Figure 1 displays the illumination map computed from PSFs in the subsalt area. The illumination changes rapidly along the reflectors due to the focusing and defocusing of the seismic energy by the rugose base of salt.

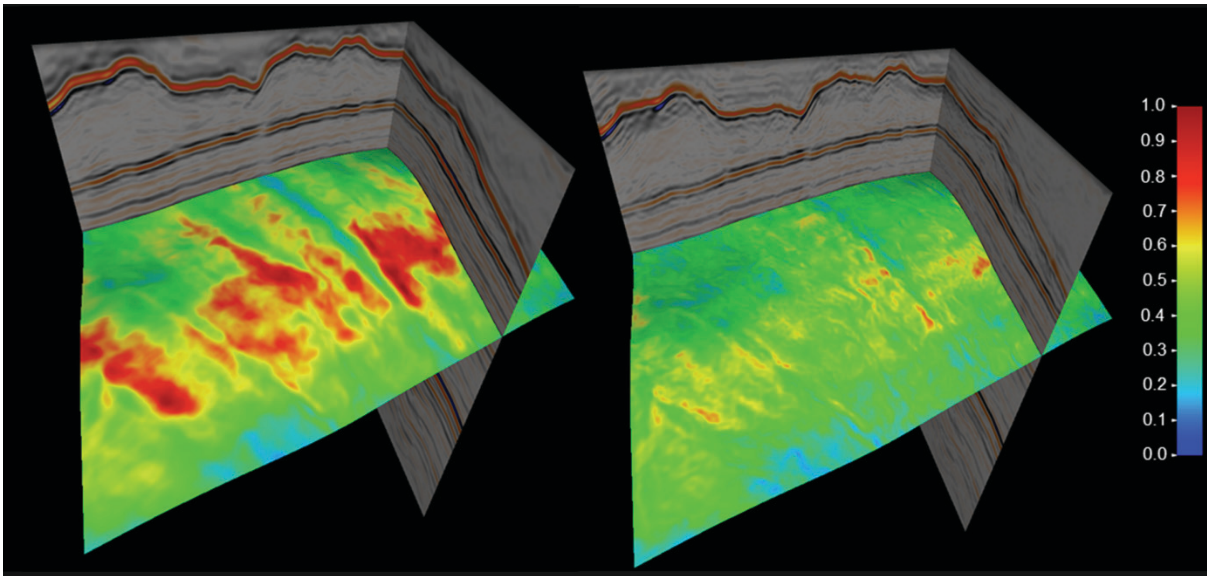

Figure 1 *Amplitude extraction along a target horizon sub-salt at about 9km depth. The image on the left is from a migration where the sub-salt amplitudes are severely affected by illumination effects. The WEI image on the right shows how that these effects are corrected for such that reliable amplitudes can be extracted along the target horizon.*

Conclusions

The point spread functions capture illumination variations beneath the salt bodies. This information is used in the wave equation reflectivity inversion workflow to alleviate the effects of irregular illumination. A field data example shows improvements of the subsalt reflectivity and spatial resolution after inversion.

References

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