High Resolution Imaging by Wave Equation Reflectivity Inversion: A MAZ Case Study from Jequitinhonha Basin, Brazil

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Abstract

Wave Equation Reflectivity Inversion (WEI) is a powerful Least-Squares imaging technology that enhances the wave number content of the depth migrated images and mitigates the illumination problem due to incomplete or inadequate acquisition. In practice, we explicitly compute the Hessian matrix, also known as resolution function, or point spread function (PSF), by wave equation modelling and migration of discretely sampled point scatterers distributed over the earth model. The computed PSFs are then interpolated to the imaging grid before inversion. Finally, we iteratively solve a linear system of equations to deconvolve the multi-dimensional PSF from the migrated image. Application of WEI to the BM-J4/5 MAZ TTI PSDM volume in the Jequitinhonha Basin offshore Brazil demonstrates the improvements in spatial resolution and illumination after WEI.

Introduction

The ultimate goal of seismic imaging is to create high fidelity and high resolution images of the earth's interior, particularly at the subsurface target level. Several factors limit our ability to achieve this goal. While the image fidelity is mainly controlled by the accuracy of the earth model and the imaging algorithm used, the image resolution at a given depth is controlled by the acquisition parameters (source signature, frequency bandwidth, acquisition geometry), the earth properties at the reflector depth, and the overburden (velocity, illumination and attenuation).

Recent technology developments in data acquisition and seismic processing enabled the recording and generation of data with broader bandwidth (e.g., Carlson et al., 2007); as a result, stunning high-resolution images of the subsurface have been produced around the world using broadband data. Unfortunately, imaging with broadband data alone does not solve the image resolution problem completely. This is because most commercial broadband solutions are intended to remove the notches from the frequency spectra but they do not compensate for heterogeneities in the earth's interior and/or limitations of the acquisition geometry that could reduce the wave number content (lateral resolution) of the migrated image.

The problem is aggravated when the subsurface is complex. Propagation of seismic waves through complex media, combined with incomplete or inadequate acquisition geometries, can result in uneven illumination of potential targets. Consequently, amplitude information from migrated images can be distorted. A typical scenario is the presence of rugose salt bodies similar to the ones found in the Gulf of Mexico, offshore West Africa and Brazil. Salt bodies cause focusing and de-focusing of the seismic energy which results in uneven illumination of the underlying formations (sub-salt targets). Figure 1 shows a depth migrated image from a Full-azimuth (FAZ) dataset acquired in the Gulf of Mexico. The illumination map overlaid on the image demonstrates the distortions of the seismic wavefield propagated through a rugose base salt. The uneven illumination creates significant amplitude variations along the sub-salt formations that are unrelated to lithology (Klochikhina et al., 2016). Consequently, the reflectivity of these formations cannot be reliably used to estimate their corresponding rock properties unless the distortions are removed from the migrated image.

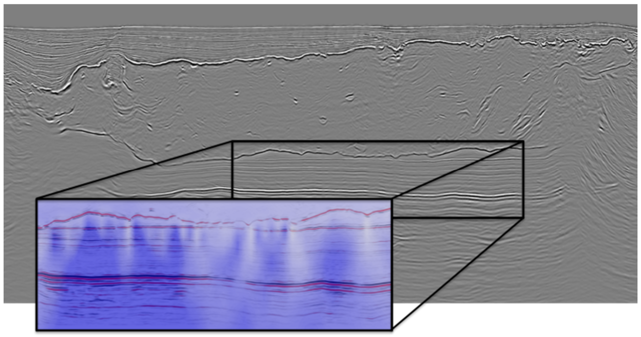

Figure1. Depth migrated image from a FAZ dataset in the Gulf of Mexico showing the seismic overlaid with the illumination map. The zoomed area focuses on the base salt and sub-salt formations. Dark blue color represents high illumination while light blue color corresponds to low illumination.

Here, we discuss a wave equation reflectivity inversion (WEI) method (Valenciano et al., 2006) that enhances the wave number content of the depth migrated images and mitigates the illumination problem. Examples from a Multi-azimuth (MAZ) dataset acquired in the Jequitinhonha Basin offshore Brazil are presented to demonstrate the improvements in spatial resolution and illumination after WEI.

Wave equation reflectivity inversion (WEI)

Valenciano et al. (2006) proposes a wave equation reflectivity inversion method that explicitly computes the wave equation Hessian, a matrix whose rows contain information about the acquisition geometry, the velocity model, and the bandlimited characteristics of the seismic data. This work is based on the idea that the imaging problem can be posed in terms of reflectivity inversion. The theoretical framework of the inversion is formalized in Tarantola (1987).

The algorithm can be summarized as follows. Given a linear wave equation modelling operator $\mathbf{L}$, compute synthetic data $\mathbf{d}$ using $\mathbf{d} = \mathbf{Lm}$ **,** where $\mathbf{m}$ is a reflectivity model. The quadratic cost function,

$$S(\mathbf{m}) = \|\mathbf{d} - \mathbf{d}_{obs}\|^2 = \|\mathbf{Lm} - \mathbf{d}_{obs}\|^2, \quad (1)$$

is formed, where $\mathbf{d}_{obs}$ denotes the recorded data. The reflectivity model $\hat{\mathbf{m}}$ that minimizes $S(\mathbf{m})$ is given by

$$\hat{\mathbf{m}} = (\mathbf{L}'\mathbf{L})\mathbf{L}'\boldsymbol{d}_{obs} = \mathbf{H}^{-1}\mathbf{m}_{mig} \quad (2)$$

where the migration operator $\mathbf{L}'$ is the adjoint of the modelling operator $\mathbf{L}$, $\mathbf{m}_{mig} = \mathbf{L}'\boldsymbol{d}_{obs}$ is the migration image, and $\mathbf{H} = \mathbf{L}'\mathbf{L}$ is the Hessian of $S(\mathbf{m})$, also known as resolution function, or point spread function (PSF). The Hessian can be interpreted as the response of a point scatterer through the imaging system as it contains information about the acquisition geometry and earth properties. The diagonal of the Hessian matrix is a measure of the illumination.

The main difficulty of solving equation (2) is the explicit computation of the inverse of the Hessian matrix because it can be quite large. It is often more feasible to compute the inverse of the Hessian as the solution of the linear system of equations

$$\mathbf{H}\hat{\mathbf{m}} = \mathbf{m}_{mig} \quad (3).$$

by using an iterative inversion algorithm (Valenciano et al., 2006). Equation 3 expresses the convolutional relation between the ideal reflectivity $\hat{\mathbf{m}}$ and the migrated image $\mathbf{m}_{mig}$. Therefore, equation 3 is the key to understand the fundamental imaging resolution problem: only a filtered version of the true reflectivity is recovered by migration. It follows that the solution is to estimate the Hessian (PSF). As a result, we can compensate for deficiencies in illumination (caused by the system) and increase the spatial bandwidth of the reflectivity (recover it).

In practice, we explicitly compute the PSFs by wave equation modelling and migration of discretely sampled point scatterers distributed over the earth model. The computed PSFs are then interpolated to the imaging grid before inversion. Finally, we iteratively solve a linear system of equations to deconvolve the multi-dimensional PSF from the migrated image. The implementation is efficient and effectively incorporates the spatial variability of the PSF.

Jequitinhonha Basin offshore Brazil

The Jequitinhonha Basin is a frontier offshore basin located off the northeastern coast of Brazil (Figure 2). The main potential reservoir units are post-salt Upper Cretaceous turbidites, pre-salt Jurassic to Barremian continental sandstones and, potentially, pre-salt Aptian limestones. Post-depositional salt deformation resulted in large and complex salt structures that affect seismic imaging of the underlying pre-salt succession. WEI is applied to the existing BM-J4/5 MAZ pre-stack depth migration (PSDM) volume with the objective to improve the imaging of both post-salt and pre-salt reservoir targets.

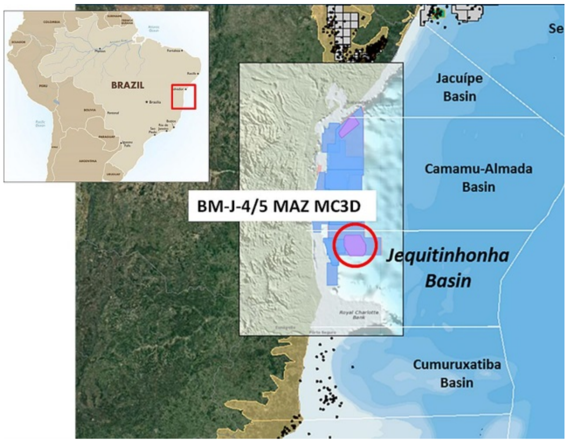

Figure 2. This image shows the location of the 3D MAZ survey over BM-J-4/5 in the Jequitinhonha Basin offshore Brazil.

BM-J4/5 MAZ acquisition and processing

In February 2006 a conventional 3D narrow azimuth (NAZ) survey was acquired over blocks BM-J4 and 5 in an east-west direction using a recording spread of 10 hydrophone only streamers towed at 9 m depth and 100 m separation. Streamer length was 6km. Processing and reprocessing of the data provided high quality images in the shallow section but the deeper pre-salt targets that had been identified subsequent to the acquisition proved challenging to image and interpret due to poor illumination and signal penetration.

In 2011 PGS overshot the original east-west survey with two new 3D surveys oriented in different acquisition directions: one in the north-south and the other at 30° counter clockwise of north-south (i.e., northwest-southeast), to complement the subsurface illumination of the legacy image. Most specifications were similar to the original survey but with some important differences. The new surveys were acquired using broadband dual sensor towed streamer technology, resulting in seismic data that are much richer in both low and high frequency content.

The three surveys were processed simultaneously. A series of processing steps including receiver-side de-ghosting and additional noise suppression were applied to the hydrophone only legacy data to allow the combination of all three datasets into a single MAZ data volume. Details of the MAZ time processing are documented in Burren et al., (2013). The new MAZ 3D anisotropic TTI depth migration resulted in significant improvements in the image quality, particularly at the pre-salt targets. Subsequent amplitude extractions along key target horizons, however, revealed remnant amplitude variations caused by the complex salt bodies. These variations required correction to enable reliable quantitative interpretation and rock property analysis.

Results

WEI is applied to a sub-set of the BM-J4/5 MAZ TTI pre-stack depth migration (PSDM) volume. The test area consists of 344 km^2 and it is located on the eastern section of the volume. Figure 3 shows the location of the test area and the sail line tracks from contributing surveys. As part of the exercise, the WEI process was applied to individual PSDM volumes from each acquisition azimuth. This allows for analysis of illumination and data quality of the individual surveys and combinations. Figure 4 shows the diagonal of the Hessian, representing the illumination, at 5,600 m depth for each of the PSDM volumes: Three azimuths, Azimuth I, Azimuth II and Azimuth III. Red color represents high illumination while light green color corresponds to low illumination. In this case the diagonal of the Hessian clearly shows the salt boundary and demonstrates that the pre-salt area is best illuminated by the North-South acquisition direction. The best overall illumination is obtained by the full MAZ acquisition and processing.

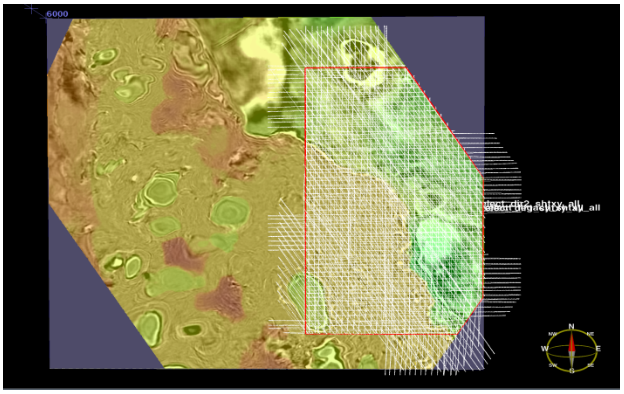

Figure 3. The red polygon represents the limits of the test area (344 km^2). White lines represent acquisition sail line tracks from contributing surveys.

Figure 5 compares the TTI migration with the WEI result for each of the depth volumes. The comparison demonstrates how WEI helps compensate for the illumination variations observed due to the different acquisition directions. The WEI images shown in the lower half of Figure 5 all exhibit more even illumination and resolving power compared to the PSDM images. The WEI results are easier to interpret and clearly show the geological features in the pre-salt and the radial faults emanating from the salt boundary. Figure 6 shows a crossline section through the center of the volume. The significant improvement in image resolution can be seen above the salt body marked in yellow in the WEI image. In the pre-salt section, image improvements are more subtle, but some of the fault boundaries have been imaged more clearly (red arrows).

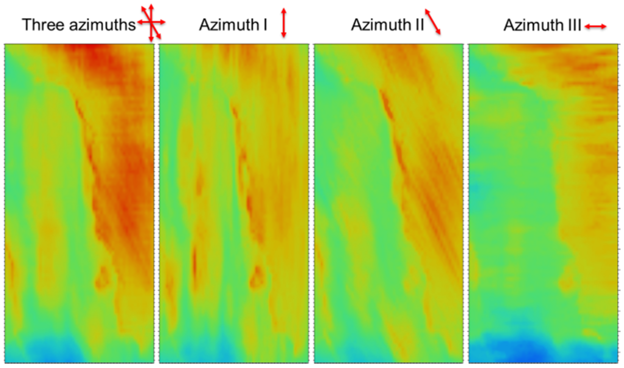

Figure 4. The diagonal of the Hessian matrix is a measure of illumination. This image shows the diagonal of the Hessian at 5,600 m depth for each of the azimuths and all three azimuths combined. Red blue color represents high illumination while light green color corresponds to low illumination.

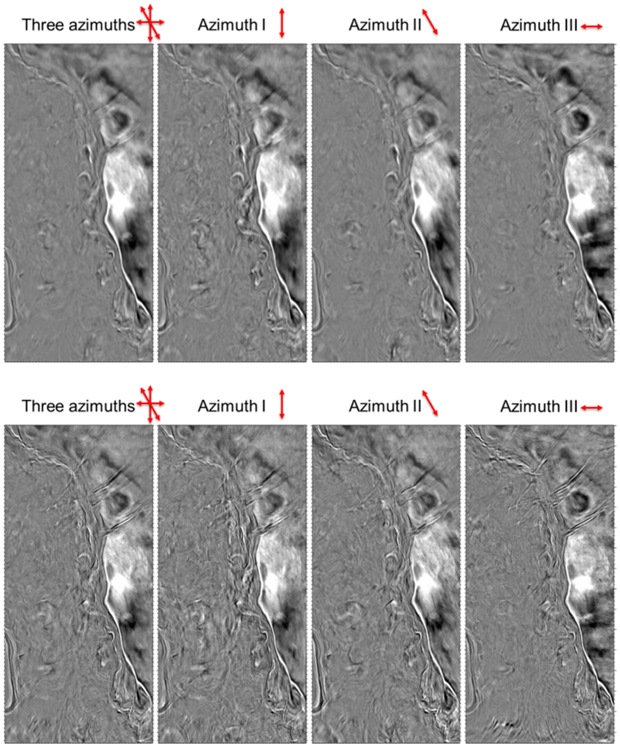

Figure 5. Images from a 5,600 m depth slice of the BM-J4/5 PSDM volumes: migration (top), and WEI (bottom).

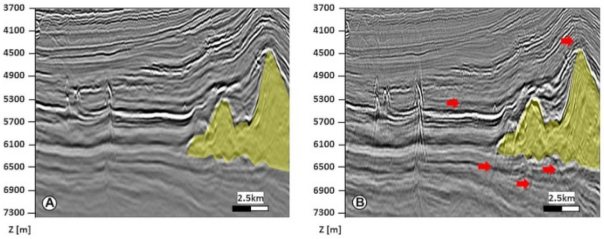

Figure 6. Crossline section from the BM-J4/5 MAZ TTI conventional migration (A) and WEI (B). Note the improvement in spatial resolution and interpretability.

Conclusions

We have introduced a novel Least-Squares imaging technology, that uses an explicitly formed Hessian operator computed using point spread functions, to compensates for the effects caused by irregular illumination and incomplete data. The resulting images are direct estimates of reflectivity where the effects of the wavelet and illumination variations are compensated for, providing a more balanced wavenumber content and overall higher resolution. This wave equation inversion (WEI) approach has many uses, but is particularly well suited for correcting for illumination effects below complex overburdens, such as in the Brazilian pre-salt. We illustrate this with examples from the BM-J4/5 MAZ TTI PSDM volume in the Jequitinhonha Basin offshore Brazil. By applying WEI to individual acquisition azimuths, we are able to optimally combine the datasets without having to go through tedious parallel processing and matching. Of the three surveys, two were modern broad band acquisitions acquired with a dual sensor streamer, but as WEI corrects for both wavelet (bandwidth) and illumination, we are able to combine the multi-vintage, multi-azimuth surveys in an optimal way, to create high resolution images of the complex geology in the area.

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