Wave Equation Migration - the Application for Subsalt Imaging

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SUMMARY

Prestack depth migration algorithms based on one-way wave equation extrapolation have been widely used in the oil and gas industry in recent years, especially in areas with complex salt structures. The methods are known to be amplitude friendly and can produce high-quality images, especially when triplication encountered in areas with complex salt structures where Kirchhoff migration becomes inadequate. Here, we implemented and applied the phase-shift-plus-interpolation (PSPI) method for imaging synthetic and marine field data.
Introduction

Deep water marine becomes an area of interest for aggressive petroleum exploration globally. Typically, the geology in the area is very complex, highlighted by ample of salt and subsalt structures. This presents big challenges for seismic imaging. Kirchhoff based depth migration appears inadequate for the job. Here, we investigated the feasibility of one-way wave equation based migration for subsalt imaging in deep water.

Wave equation migration based on downward continuation of the one-way wave equation has become a common practice for seismic migration in recent years. Many authors have developed a variety of algorithms in the last twenty years. Gazdag and Squazzero (1984) developed phase-shift-plus-interpolation (PSPI), Ristow and Ruhl (1994, 1997) introduced Fourier finite-difference and multiway splitting finite-difference algorithms, Fei and Etgen (2002) developed a full-implicit domain decomposition Fourier finite-difference algorithm. Ren et al., (2004, 2005), Fei and Liner (2008) applied finite-difference and Fourier finite-difference extrapolators for isotropic and anisotropic media. Etgen (1994) studied the stability issues of the explicit depth extrapolation methods. Here, to avoid the operator splitting error which exists in 3D finite difference and Fourier finite-difference extrapolation methods, we implemented the PSPI algorithm for 3D wavefield extrapolation and applied the method to both synthetic and field data from deep water.

Wave equation migration via PSPI

PSPI is a one-way wave-equation based migration operator. Here, we give a brief overview of the PSPI migration. The 3D acoustic one-way wave equation in the frequency-space domain is

\[ \frac{\partial P}{\partial z} = i \sqrt{\frac{\omega^2}{v^2} + \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}} \cdot P \]  

(1)

where \( i = \sqrt{-1} \), \( \omega \) is the angular frequency, \((x, y, z)\) are the space coordinates, \( v = v(x, y, z) \) is the velocity, and \( P = P(x, y, z) \) is the wavefield. For velocity that varies with depth only, the one-way wave equation can be transformed to wavenumber-domain via FFT, therefore, the wavefield extrapolator can be written as

\[ P(z + \Delta z) = P(z) \exp \left\{ i \omega \sqrt{1 - \left( \frac{v(z)}{\omega} \right)^2 \left( k_x^2 + k_y^2 \right)} \Delta z \right\} \]  

(2)

where \((k_x, k_y)\) are wavenumbers, and \( \Delta z \) is the depth interval. To handle the lateral velocity variations, we applied the PSPI approach developed by Gazdag and Squazzero (1984). The PSPI implementation is achieved by using a phase-shift operator expressed in equation (2) with multiple reference velocities, resulting in the reference wavefields. To obtain the final wavefield, the phase-shifted reference wavefields are then inverse transformed back to the space domain, followed by an interpolation using these reference wavefields. The migrated image is obtained by applying the imaging condition for all frequencies.
Examples
To test the PSPI algorithm, we used a 2D salt model (Figure 1a) to generate synthetic shot records. For this model, there are a complicated salt dome and two isolated salt bodies in the shallow area. A total of 250 shots are generated on the surface. The shot spacing is 100 m and the receiver spacing is 20 m. The maximum offset of the shot record is 8 km. Figure 1b shows the migration image obtained using PSPI. From the figure we can see both top of the salt and base of the salt, and the isolated salt bodies in the shallow area are well imaged. For the vertical salt boundary (red arrow), however, the one-way extrapolation method via PSPI does not produce ideal image. In the subsalt area, the gently

Figure 1 (a) Salt model showing the complex salt dome and two isolated salt bodies. The model is used to generate synthetic shot records. (b) Prestack depth migration using PSPI.

Figure 2 (a) Velocity model with complex salt structure from deep water. The velocity of the salt structure can be two times higher than the surrounding sediments. (b) Wave equation migration image via PSPI. The image shows well positioned top and base of the complex salt.
sloping reflectors, faults, and scatters are well imaged. But for the fault with steep dip, the imaging quality is not perfect (yellow arrow).

The 2D and 3D field datasets from deep water are also used to test wave equation migration via PSPI. Figure 2a shows the subsurface velocity model in deep water where the velocity of the complex salt structure can be two times higher than the surrounding sediments. Using PSPI migration, we obtained image as shown in Figure 2b. From the PSPI migration image we see that the top of the salt, the base of the salt and the dipping, faulted structures above the salt are well imaged. In subsalt area, some events can also be identified (red arrow).

Figure 3a shows a vertical slice of a 3D salt model from deep water. Below the salt, it is flooded with salt velocity. Figures 3b-3e show vertical and depth slices of the 3D image obtained by the PSPI migration. From the vertical slice (Figure 3b) cutting through the middle of the 3D image, we can see that the steep salt boundary on the left and the base of the salt dome are well imaged (red arrow positions). The image of the right salt boundary is inferior compare to the left boundary. These differences can be attributed to imperfections in the velocity model and data quality. In the subsalt area, certain events can be imaged. Figures 3c-3e show three depth slices of the migrated image with increasing depth respectively. Figure 3c, the depth slice cutting through salt at shallow, clearly shows the boundaries of the salt (two red arrows pointed). But at middle depth level, Figure 3d, only one side
of the salt boundary can be seen (red arrow position). Figure 3e shows a deeper section near the base of the salt, and a good image is obtained.

Conclusion
3D wave equation migration via PSPI has been implemented and tested on synthetic and marine field datasets. Test results demonstrate that wave equation migration via PSPI can provide high fidelity image for complex top and base of the salt structures and, therefore, can be used for subsalt imaging. For vertical and overturn structures, the PSPI migration algorithm has its limitations. Reverse-time migration is needed for imaging those events. Furthermore, obtaining the correct velocity in subsalt area is critical for the subsalt imaging.

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References


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