Abstract

Wave-equation migration (WEM) has been shown to produce an improved image over Kirchhoff migration in sub-salt areas of the Gulf of Mexico (Sun et al., 2001). However, it has not yet been shown to be of benefit in the North Sea. Using generic models of the North Sea, this paper examines if WEM can provide a substantial advantage for imaging hydrocarbon reservoirs. We show that the North Sea places demands upon imaging algorithms that standard Kirchhoff migration cannot fulfill in complex geology.

Introduction

The Kirchhoff algorithm is a standard tool for imaging subsurface structures. These methods are efficient, versatile and can produce accurate images in moderately complex geology. As the drive to image hydrocarbon reservoirs moves to increasingly complex areas, the limitations of Kirchhoff algorithms become evident. Typically, these limitations include: use of single-arrival travel times, ray-paths computed with a high-frequency approximation, anti-alias filters that can only be correct for a single dip angle. These limitations further complicate the demanding problem of preserving the amplitude response. The Kirchhoff algorithm can be enhanced; for example using multiple-arrival travel times or using band-limited travel times. However, such improvements can only incrementally improve the image quality and at great cost to algorithmic efficiency.

WEM uses a conceptual model that is closer to the geophysical reality than Kirchhoff methods. For this reason, many of the problems faced with a Kirchhoff algorithm are handled naturally by WEM. Improved technology has recently enabled these methods to be routinely used for imaging in the Gulf of Mexico: the benefits are seen in imaging beneath tabular salt, where multiple arrivals are a persistent problem for Kirchhoff methods.

North Sea geology also poses severe demands upon Kirchhoff imaging. Although of a different character from the Gulf of Mexico, WEM may be a considerable asset. To study this, several complex geological structures were examined that are typical of North Sea hydrocarbon reservoirs. Geological models were built to emulate a Southern Gas Basin reservoir, a Central Graben gas reservoir and tilted Rotliegend blocks beneath a salt and faulted cover.

Southern Gas Basin

Figure 1a shows a schematic cross-section through a model from the southern North Sea gas basin. The gas filled structure is immediately below a salt diapir. Figure 1b shows the associated velocity model in colour (where blue is slow and red is a fast velocity) and a fan of rays traced through a smoothed velocity. The rays were traced from a single surface location at regular increments in surface-incidence angle. The ray-paths illustrate several features we may expect a seismic wave-front to exhibit:

- Divergent ray-paths suggest a wave-front that is spreading and dissipating energy; this effect can clearly be seen within the salt diapir. Conversely, convergent rays suggest a wave-front that is being focused; this occurs below the base chalk to the right of the salt diapir. Note that a small change in the shape of the base chalk can have a large effect upon the focused wave-front, and hence the illumination, below this region.
Multiple arrival wave-fronts will be shown as overlapping ray-paths. This condition can be seen to occur when rays approach the edge of the salt diapir. The high velocity contrast between salt and sedimentary velocity will cause rays to be refracted back into the sediment.

Figures 1c and 1d show a zero-offset impulse response using a Kirchhoff algorithm and WEM around the gas region, respectively. The Kirchhoff migration algorithm used will image the most energetic ray-path and makes no amplitude correction due to ray-path divergence. The WEM image shows several wave-fronts forming around the base of the salt diapir; the ray-paths indicate that several arrivals should be seen here. Additionally the WEM image shows an amplitude response that is consistent with the focusing of the ray-paths. The image in the gas reservoir has a different character between the two impulse responses.

**Central Graben Gas Reservoir**

A typical Central Graben hydrocarbon reservoir was modelled, as with the previous example. This model is shown in figure 2a with the associated velocity model shown in figure 2b. Figure 2b also shows a fan of rays traced from a surface location. The hydrocarbon reservoir lies near the base of the salt diapir within the Puffin Sandstone layer.

Figures 2c and 2d show impulse responses from the Kirchhoff migration and WEM around the gas reservoir, respectively. Figure 2b shows that rays refracted from the right-hand edge of the salt diapir are focused into the gas reservoir. Since these rays have less divergence than the direct arrivals, the Kirchhoff algorithm will preferentially image these refracted rays. This creates a gap in the Kirchhoff image of the gas reservoir where the Kirchhoff algorithm alternates between imaging the direct and highly refracted arrivals. Additionally, the Kirchhoff impulse response has a mis-positioned contact between the gas reservoir and the salt diapir. The WEM impulse response has both a smooth wave-front and shows a clear discontinuity at the edge of the salt diapir. Also, as with the previous example, the WEM image shows multiple-arrivals due to the salt diapir.
Fault Block Beneath Faulted Chalk and Salt Pillow

Figure 2a shows another typical southern North Sea scenario with a tilted Rotliegend block beneath a fault. A hydrocarbon reservoir lies within the fault block. Figure 2b shows the velocity model with a fan of ray-paths from a surface location. The ray-paths show considerable focusing beneath the fault.
Figure 3c and 3d show impulse responses using a Kirchhoff migration and WEM around the Rotliegend blocks, respectively. The Kirchhoff impulse shows a smooth and continuous wave-front. The WEM impulse response shows significant differences with a strong amplitude response where the ray-paths focus beneath the fault, a weak amplitude response where ray-paths diverge through the left-hand side of the fault, as well as a refracted wave-front to the right of the fault.

![Figure 3c. Kirchhoff Impulse Response.](image1) ![Figure 3d. WEM Impulse Response.](image2)

**Imaging of Real Seismic Data in Complex Geology**

A Kirchhoff algorithm was used to create a velocity model using real seismic data acquired above a North Sea reservoir. Figures 4a and 4b show migrated images using a Kirchhoff migration and WEM at the edge of a salt diapir, respectively. The figures show the WEM is a superior structural image than the Kirchhoff result. Analysis of the velocity model suggests that multiple arrivals cause the greatest problem for Kirchhoff migration in this model.

![Figure 4a. Kirchhoff imaging of real data.](image3) ![Figure 4b. WEM imaging of real data.](image4)

**Conclusion**

The study of ray-paths through complex geological models shows the problems with Kirchhoff imaging are primarily due to amplitude and multiple-arrival problems. This paper has shown three representative North Sea scenarios where Kirchhoff migration would fail to accurately resolve a hydrocarbon reservoir. Wave equation methods have been demonstrated to image the subsurface in a manner that is consistent with the ray-path analysis. The benefit of WEM over Kirchhoff migration in the North Sea has clearly been shown using a real data example.

**References**