Application of Anisotropic 3D Reverse Time Migration to Complex North Sea Imaging

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Following completion of model building, amplitude preserving 3D depth migration is usually performed using a Kirchhoff scheme for modest structural problems with steep dips. For structures where multi-valued ray-paths exist (e.g. complex salt bodies), we generally use a one-way Wavefield Extrapolation (WE) algorithm instead. However, more recently, full two-way solutions of the wave equation, such as Reverse Time Migration (RTM) have become commercially available:- these are suited for highly complex environments, where both steep dips and multi-pathing are an issue.

Standard shot-based one-way WE preSDM techniques image the subsurface by extrapolating the source and receiver wave-fields for each shot. The imaging condition is invoked by cross correlating these two wave-fields at each depth level, and then summing the contributions from all shots in the aperture to form the image. One of the assumptions made in using this technique is that the wave-fields travel along the direction of extrapolation only in one direction: downwards for the source wave-field, and upwards for the receiver or scattered wave-field.

In practice, each of these wave-fields will generally travel both up and down when the velocity model is complex, when turning (diving) raypaths are involved, or when multiples are being generated. In addition, approximations in the extrapolation techniques usually limit the dips present in the final image to less than seventy degrees. Steeper dips, and turning rays are usually imaged using Kirchhoff techniques, but these fail to deliver acceptable images once we have a multi-pathing problem. One technique which can address all these issues is migration using the two-way wave equation. Here, we have used an anisotropic RTM algorithm to achieve this. RTM properly propagates the wave-field through velocity structures of arbitrary complexity, correctly imaging dips greater than 90 degrees. It even has the potential to image with internal multiples when the boundaries responsible for the multiple are present in the model.

We will show anisotropic RTM examples from the North Sea, and other environments, outlining the potential benefit of migrating with the full acoustic two-way wave equation.

Introduction

During the past 5 years as computer costs have become less of an issue, we have seen much interest in one-way WE preSDM. Wavefield extrapolation implementations of the one-way scalar wave equation are relatively simple to write compared to a Kirchhoff scheme, but in principle are more costly; the extra cost may be prohibitive if many iterations are needed for construction of the velocity model. With Kirchhoff migration, it is routine to output the data sorted by surface offset (resulting in familiar-looking migrated CMP gathers). For shot domain wavefield extrapolation techniques, preserving the surface offset of the data is prohibitively expensive, and thus pre-stack output must be created in some other domain. Common azimuth approaches, such as delayed-shot, can address this issue cost-effectively, but rely on a limiting common azimuth assumption.

That being said, with a WE approach we have a better approximation to the true amplitudes of wave propagation, especially in heterogeneous velocity media than with Kirchhoff methods (Jones & Lambaré, 2003), and the algorithms are readily extendable to two way schemes. Wavefield continuation approaches are best known for their inherent ability to addresses the multi-pathing issue (unlike a Kirchhoff scheme). Recently, we have seen renewed interest in the two-way wave equation both with reverse time migration (Baysal, et al, 1983, Whitmore, 1983, Yoon, et al, 2003, Bednar et al, 2003, Farmer, 2006, Zhou, et al, 2006,) and other wavefield extrapolation techniques (Zhang et al, 2006).

An intermediate route to addressing turning wave energy using a one-way WE scheme is to employ the two-pass one-way scheme. In this approach we first downward continue using one of the square root solutions, (and saving the evanescent wavefield that corresponds to the complex square root solution). We then migrate the saved complex root terms reversing the direction of propagation. With such a scheme (using roughly double the CPU time of a one-way scheme), we can image turning waves and prism waves (double bounce arrivals: Bernitsas et al, 1997). However, it cannot handle multiple bounce events.

Using RTM, which we consider here, we have a full solution to the acoustic two-way wave equation. The version used in the case study shown here involved an 8^{th} order solution in space, and incorporated VTI (Zhou, 2006). RTM has the potential to migrate all multiples, although some consideration must be given to the boundary conditions. Although the theory dictates that recordings should be made on two (vertical) levels (Mittet, 2006), practice shows that multiples can be profitably handled, giving enhanced images of the subsurface. This may be of particular use for VSP imaging.

However, in our routine data pre-processing we still strive to remove multiple energy, primarily because in order to image multiples, we would need a very detailed and accurate representation of the velocity contrasts associated with them, in our model (i.e. the model would need to include all interfaces that generated significant multiple reflection energy). Such detail is not always possible (or practical) to achieve: consequently, we still strive to suppress multiple energy prior to migration.

Results

The North Sea data considered here show one of the classic mushroom shaped salt domes typical of parts of the North Sea. The otherwise flat-lying chalk beds are upturned during deposition as the salt piercement continues contemporaneously with sediment deposition (Davison et al, 2000, Thomson, 2004). The commercial WE project had recently been completed, so we had a 'final' model available, as well as comparisons of the usual one-way WE and Kirchhoff images.

Using this conventionally derived final model (figure 1), we ran an RTM, limiting the modelling frequency to 17Hz. The results of the RTM clearly indicated the inadequacies of the conventional model building route, and we proceeded to attempt to refine the model based on iterative RTM model update.

Figures 2 and 3 show respectively a WE preSDM, and an RTM using the 'final' model through a crestal line from the commercial project. We see from the RTM that we have very steep salt flank arrivals (perhaps from an upturned chalk interface). From a ray trace study, we concluded that it is likely that these steep events come from prism wave illumination (Bernitsas et al, 1997). The salt interpretation in this model, made on the basis of the one-way WE results, look like they are incorrect near the edges of the salt. The RTM result indicates that the salt is probably a bit less wide, with near-vertical edges. Also, the RTM result indicates that the top Balder and top Chalk events probably turn-up sharply to abut the salt, rather than 'rolling through' the model with a gentle anticlinal shape, as was used here.

Two sediment flood models were then employed to assess the potential of the RTM imaging for model update. The first was a sediment-only model with only the moderate shallow velocities present (no top balder of top chalk, etc). The second flood model contained the top Balder (the first major velocity increase) and the subsequent chalk layers. The geometry of these high velocity layers below the position of the salt, was left as a gentle anticline.

In the 'sediment only' flood RTM result (figure 4) we saw a good top salt image, but no steep events, as the flat-lying velocity contrasts required for the prism wave imaging are absent from the model at this stage. However in the 'sediment+chalk' flood RTM results, we clearly see these steep events. This is an indication that the steep events are prism wave arrivals, incorporating a bounce from the flat lying top Balder and/or top Chalk horizons, and then reflecting from the steep salt (or sediment) flanks.

Such sediment floods will help delineate the steep events with ray paths that travelled through the sediments only. Salt floods may also help in delineating a salt base using energy that has traveled through the salt.

Conclusions

Complex bodies such as salt domes are illuminated by many wave paths that cannot be imaged by conventional on-way propagators. Significant improvement can be achieved both in the model building and final migration by employing a two-way wave equation.

The first of these points is perhaps the most significant: if we cannot derive an accurate velocity model of the subsurface, then our final imaging step will not produce a meaningful image.

It is the combination of model building and migration that is the key to successful imaging. We have shown in this work that iterative application of RTM can help delineate the correct salt geometry, whereas a one-way method failed to do so.

Subsequent imaging of the body shows enhancements to steep and overturned flanks, most likely illuminated by prism waves (double bounce arrivals).

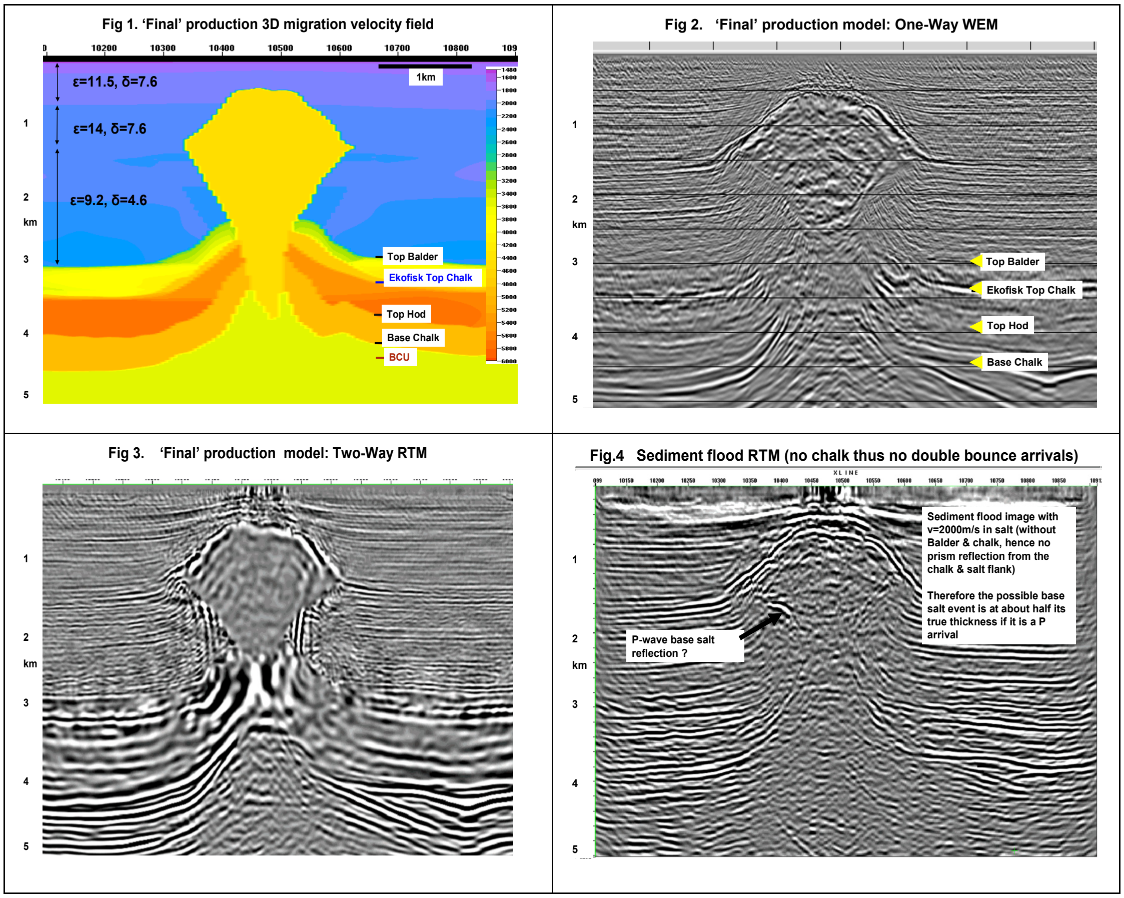

Figure 1. 'Final' production model used for images in figs 2 & 3. Figure 2, SSFPI WE preSDM. Figure 3, RTM. Figure 4, RTM using sediment only flood model

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