3D Migration of a Simulated Wide-Azimuth Towed Streamer Survey

A. Guitton (3DGeo Inc.), B. Kaelin (3DGeo Inc.) & F. Ortigosa (Repsol YPF)*

Summary

A 3D synthetic wide-azimuth towed-streamer (WATS) dataset is migrated with different migration techniques. These migration techniques are suited for imaging complex overburden. First, a wave-equation method based on a one-way propagator is used. Second, a two-way method that utilizes one-way propagators for the wavefield extrapolation downward and upward is tested. Finally, a method based on the solution of the two-way acoustic wave equation, also known as Reverse Time Migration (RTM) is selected.

We compare the migration results in 2D and 3D and show that the best results are obtained when more information is incorporated in the imaging process, e.g., turning and/or prismatic waves. In practice, the selection of a migration algorithm is based on computational and geophysical considerations. For instance, the complexity of the subsurface tells us if turning waves are needed or not. Our ability to estimate an accurate velocity model helps us to decide which method will produce the best results. Finally, computing resources could present challenges when large datasets need to be migrated, especially for advanced imaging techniques such as RTM.

Introduction

Obtaining accurate images of the subsurface when complex velocity structures are present remains a challenging undertaking. This challenge must be tackled from the acquisition side as well as from the processing side. For instance, wide azimuth geometries show promise by attenuating undesirable artefacts caused by multiples in the migration, and by overcoming illumination issues. On the imaging side, the processing flow should be such that the primary reflections are kept intact and imaged properly by our migration algorithms.

To better understand the effects of acquisition and imaging for complex overburden, 2D and 3D synthetic WATS data were generated on the MareNostrum supercomputer in Barcelona (Kaelin et al., 2007). The modelling was conducted as a collaborative effort between 3DGeo Inc, Repsol YPF, and the Barcelona Supercomputing Center (BSC) as part of the Kaleidoscope project.

The modelled data were then migrated with advanced imaging techniques suited for handling complex wavefield propagations. We decided to focus on three migration techniques. All of them use shot profiles for input data. The first migration technique utilizes a 1-way propagator for the wavefield propagation (SPM 1-way). This propagator, which incorporates a Fourier Finite-Difference operator with optimized coefficients, is accurate for steep dips. The second migration technique is a two-pass migration, where the down-going wavefield is saved and used as a source for the up-going wavefield (SPM 2-way). This technique has the ability to migrate overturning waves. Last, we use a 2-way propagator based on the acoustic wave equation. This last technique is also known as Reverse Time Migration (RTM). These techniques have their pros and cons, which we analyze and compare in the following sections.

This abstract starts with a short description of the synthetic WATS data. Then we present briefly each migration method used for imaging. Finally, we show imaging results in 2D and 3D which compare the different migration strategies.

Modelling results

For the modelling effort, 4,047 wide-azimuth shots were created. The shots are separated by 536 m in each direction (X and Y). The recording aperture is 20 km inline, and 12 km crossline. In addition, 18 s of data are recorded to capture events coming from the deepest parts of the model. Two datasets were created: one 2D and one 3D datasets. Both are migrated here.

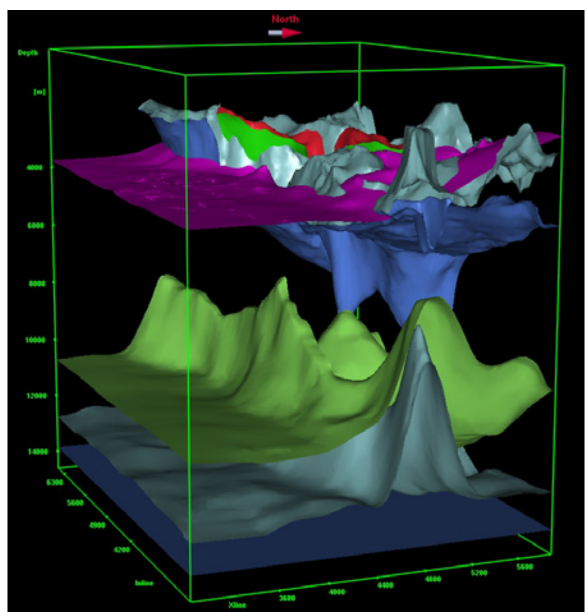

Figure 1: Geological model provided by Repsol-YPF with salt bodies (blue) and other structures.

Figure 1 displays a geological model that was later on used to generate the final velocity model of Figure 2. More details on the modelling of these datasets are available in a companion abstract by Kaelin et al. (2007). The final velocity model is showed in Figure 2 and the migration result using SPM 1-way in Figure 3.

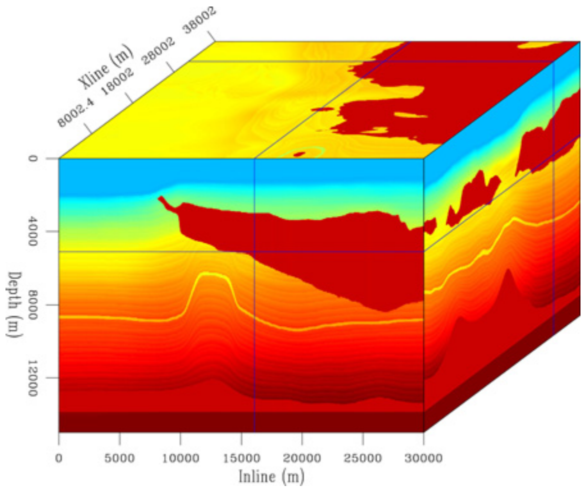

Figure 2: Velocity model used to create the 2D and 3D synthetic data.

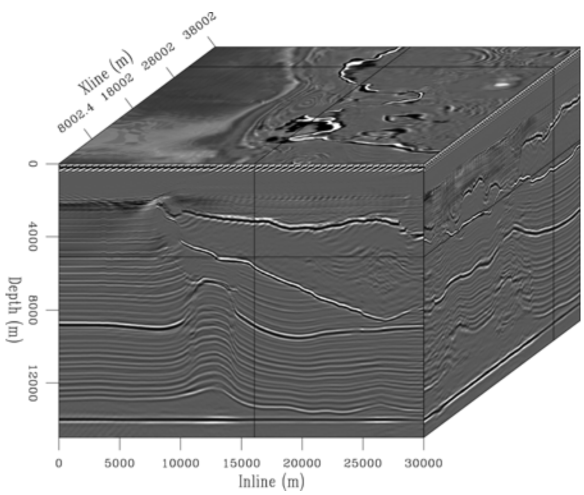

Figure 3: 3D Migration results of shot gathers using SPM 1-way.

Three Migration Algorithms

Here we present the migration techniques used to image the 2D and 3D datasets. All of them produce accurate images of the subsurface, but each of them has limitations in terms of velocity sensitivity, imaging accuracy and computing requirements. We opted for the migration of shot profiles with different propagators that we present below:

1. One-way acoustic propagator in the ω-x domain:

$$\left(\frac{\partial}{\partial z} - i\sqrt{\frac{\omega^2}{v^2} + \Delta}\right) P^+ = 0 \qquad (1)$$

where v=v(x,y,z) and $P^+=P^+(x,z,w)$ is pressure for a 3D earth and Δ the Laplacian operator in x and y. We call this migration SPM 1-way.

For the SPM 1-way algorithm, we use a FFD method to approximate the square root for complex velocity profiles. In addition, we use optimized velocity-dependent coefficients to improve the accuracy of the propagator further. This operator is accurate for steep dips.

2. Two-way acoustic propagator: this algorithm is a simple extension of the SPM 1-way. We call it SPM 2-way. In the 2-way method, the wavefield obtained during the 1-way propagation is saved in memory and used as a source for the up-going wavefield. The two-way acoustic wave equation in the ω-x domain becomes (Zhang et al., 2005):

$$\left(\frac{\partial}{\partial z} - i\sqrt{\frac{\omega^2}{v^2} + \Delta}\right) P^- = \Gamma P^+ \qquad (2)$$

where Γ is, in some sense, equivalent to a reflection coefficient and P^- is the up-going wavefield.

3. Full two-way acoustic wave equation propagator: this algorithm is based on the solution of the two-way wave equation with, for instance, finite differences.

$$\left(\frac{\omega^2}{v^2} + \frac{\partial^2}{\partial z^2} + \Delta\right) P = 0 \qquad (3)$$

This technique is the most accurate of the three, but requires more computing resources. This technique is known as Reverse Time Migration (RTM).

Comparing imaging algorithms

SPM 1-way is a fast algorithm which can image complex structures as long as the energy does not overturn. This limitation is overcome in SPM 2-way and in RTM. However, having a limited sensitivity to steep dips, SPM 1-way has the advantage of being less sensitive to velocity errors.

3D Migration of a Simulated WATS Survey

The two way algorithm, being based on the 1-way propagator (going either up or down) is limited in its ability to correctly propagate events travelling close to 90 degrees in complex areas. This can produce events that are not position correctly in depth. Because SPM 2-way can model up- and down-going events, artefacts similar to those seen with RTM will be created. These artefacts come from the cross-correlation of undesired events, such as head-waves. Fortunately, these events can be attenuated by either looking at different images formed by the cross-correlation of up- and down-going events in the receiver and source wavefields separately, or by adapting the Γ operator in equation (2) to exclude these artefacts.

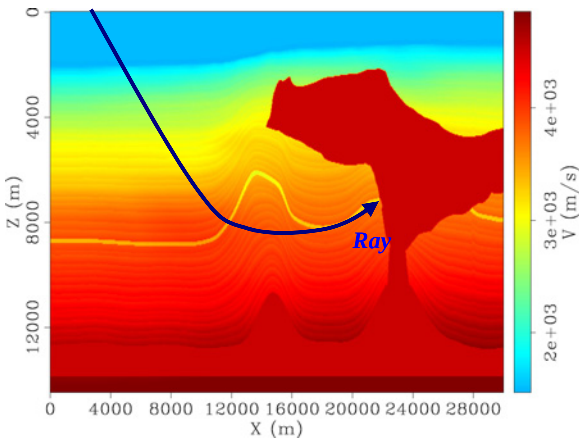

Figure 4: Velocity model showing an overturning ray (in blue).

RTM is the most accurate technique since the entire wavefield is used for imaging. Being the most accurate, RTM is also the most sensitive to velocity errors. In addition, the removal of the artefacts created at the imaging stage is not a trivial task (Kaelin and Guitton, 2006; Fletcher et al., 2006; Guitton et al., 2007).

In terms of computing, RTM, especially in 3D, requires a large amount of storage and is slower than either SPM 1-way or 2-way. The SPM 2-way is almost twice as expensive as SPM 1-way. This is because in essence, the migration is run twice. Also, SPM 2-way requires the storage of the receiver and source wavefields going downward before they can be used going upward.

2D and 3D imaging results

We show migration results for the 2D and 3D datasets.

- **2D results**

Figure 4 shows the velocity model for the 2D line. A ray (in blue) shows that the steep flanks on the deep root of the salt body can only be imaged with overturning events. Figure 5 shows the SPM 1-way result. The propagator is accurate enough to image the steep flank at z=4000 m but the deep salt root is missing. Figure 6 and 7 show the imaging results for the SPM 2-way and RTM techniques.

The SPM 2-way image shows the deep root pretty well, but not with the same accuracy as the RTM in Figure 7. The difference stems partly from the accuracy of the SPM propagator close to 90 degrees. A better propagator may result in a better image, but would also increase the cost significantly. Contributing to the difference is the fact that the same kernel is used in the modelling as well as in RTM. The noise level is slightly higher in the SPM 2-way result due to the presence of internal multiples that are not properly imaged.

- **3D results**

We display in Figure 8 a volume extracted from the 3D velocity model for which the migration is done. This volume embeds the 2D section of Figure 4. As pointed by the red arrows, the SPM 1-way result in Figure 9 shows missing reflectors that the RTM in Figure 10 is able to image properly. Note that the deep salt root visible in 2D in Figure 7 is not imaged with RTM. The reason for this is simple and symptomatic of 3D RTM: due to limited computing resources, the migration aperture had to be reduced, thus excluding some parts of the model in the final image.

Conclusions

A 2D and 3D WATS surveys were modeled and migrated with three different migration algorithms, the goal being to investigate the effect of each imaging algorithm on the final image.

SPM 1-way is the fastest imaging algorithm amongst the three but cannot image overturned events. SPM 2-way can image steep dips but might have accuracy issues if the waves overturn in a complex area. On the other hand, RTM can image the entire wavefield but is more expensive in terms of computing cost and storage. RTM is also very sensitive to velocity errors.

Using one or another method should be based on our geophysical goals, computing resources and ability to estimate (or not) an accurate velocity model.

Acknowledgments

We thank 3DGeo Inc. and Repsol-YPF for permission to publish this work. The simulations have been done in the supercomputer MareNostrum in Barcelona Supercomputing Center – Centro National de Supercomputacion (The Spanish National Supercomputing Center).

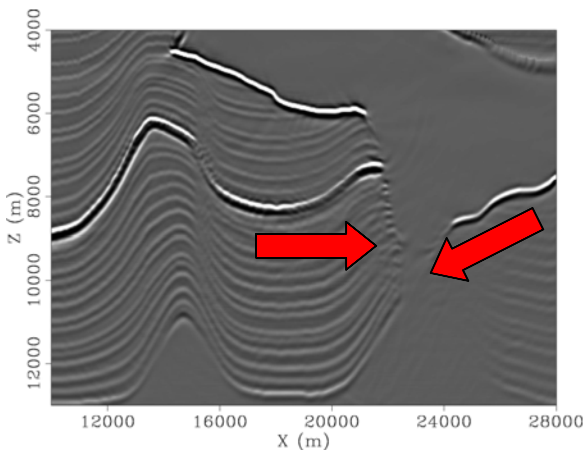

Figure 5: 2D Migration result using SPM 1-way. The salt root is not imaged (red).

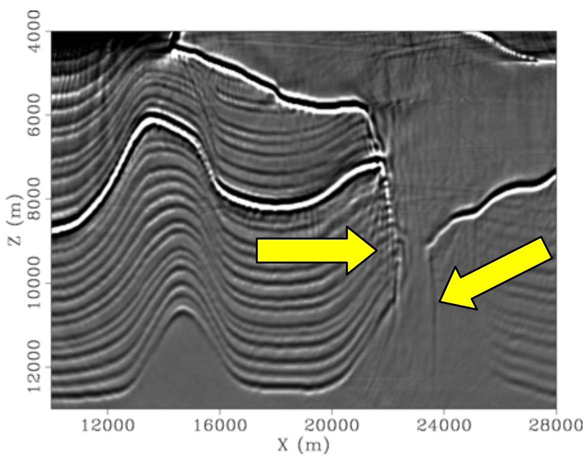

Figure 6: 2D Migration result using SPM 2-way. The salt root is now imaged.

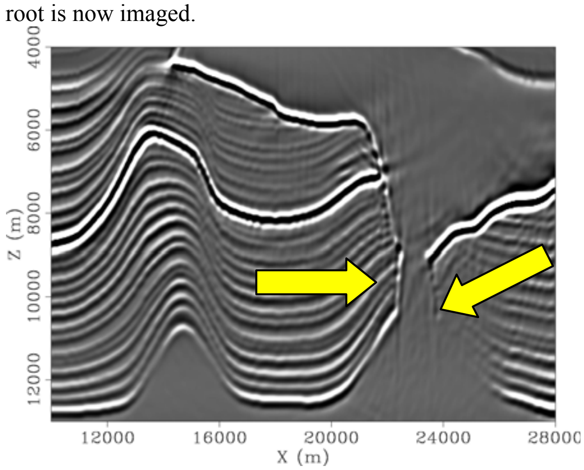

Figure 7: 2D Migration result using RTM.

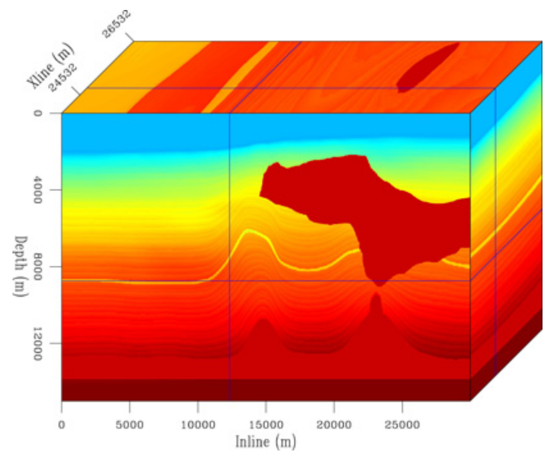

Figure 8: Close-up of the velocity model in Figure 1

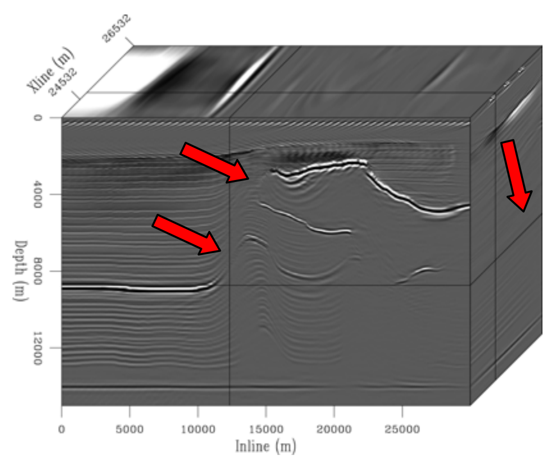

Figure 9: 3D Migration result using SPM 1-way.

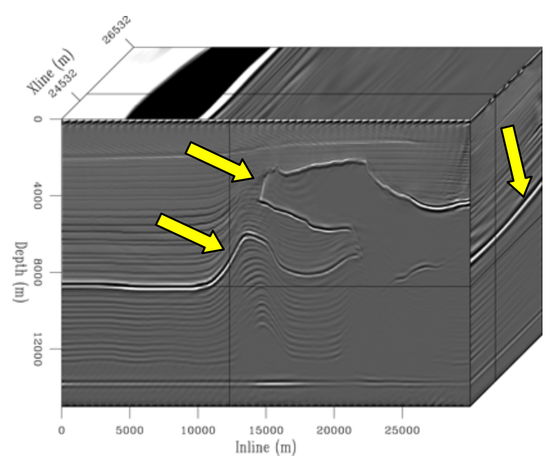

Figure 10: 3D Migration result using RTM.

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2007 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Fletcher, R. P., P. J. Fowler, P. Kitchenside, and U. Albertin, 2006, Suppressing unwanted internal reflections in prestack reverse-time migration: Geophysics, 71, no. 6, E79–E82.

Guitton, A., B. Kaelin, and B. Biondi, 2007, Least-squares attenuation of reverse-time-migration artifacts: Geophysics, 72, no. 1, S19–S23.

Kaelin, B., and A. Guitton, 2006, Imaging condition for reverse time migration: 76th Annual International Meeting, SEG, Expanded Abstracts, 2594–2598.

Kaelin B., J. Higginbotham, C. A. Fernandez, F. Ortigosa, B. Fontecha and J. M. Cela, 2007, Modeling of wide-azimuth towed-streamer surveys with high performance computing: 77th Annual International Meeting, SEG, Expanded Abstracts, this issue.

Zhang, Y., S. Xu, and G. Zhang, 2006, Imaging complex salt bodies with turning-wave one-way wave equation: 76th Annual International Meeting, SEG, Expanded Abstracts, 2323–2327.