Efficient numerical modelling and imaging practices for aiding marine acquisition design and interpretation

Milos Cvetkovic[1*], Carlos Calderón-Macías[1], Paul Farmer[1] and Giles Watts[2] present robust seismic modelling and imaging practices for assessing survey design parameters and how these affect velocity model building, imaging and interpretation.

Seismic modelling constitutes an important part of seismic exploration and field development workflows as it helps geophysicists better understand data, models and algorithms through controlled seismic experiments. These are of great value both for reducing risks in exploration and increasingly for providing the highest quality datasets for use in field development and maximizing recoverable reserves. Both incremental and step-change advances in acquisition, processing and model-building technologies have been preceded by well-designed seismic modelling studies. Much wave equation and Reverse Time Migration (RTM) research and development has been done using the SEG/EAGE 2D and 3D synthetic salt models. BP's modelling and illumination work for Mad Dog and Atlantis fields in the Gulf of Mexico led to the development of both the Wide Azimuth Towed Streamer (WATS) and Wide Azimuth (WAZ) node-based acquisitions. These new generation 3D marine acquisition geometries provide better azimuthal sampling leading to improved multiple suppression, enhanced illumination (Regone, 2007), and better tomographic model update. Anisotropic salt models presented by Billette and Brandsberg-Dahl (2005) were used for benchmarking VTI anisotropic velocity inversions and migrations, showing the benefits of steep dip imaging with RTM.

Interpreting seismic images in complex geological settings still remains a challenging task. Figure 1 shows a RTM image of synthetic 2D data with an imprint of a reflectivity section composed of a regular grid of semicircles. The image illustrates some of the problems observed in subsalt interpretation: poor illumination and a low signal-to-noise ratio resulting in a high level of uncertainty and wavefield distortion.

With modern computing capabilities and refinement of finite difference algorithms, creating high-fidelity synthetic data over large areas has become a preferred choice for modelling synthetic seismograms mimicking the real earth (Stork, 2013). Here we present a simple and efficient workflow that uses finite difference modelling and RTM for assessing acquisition geometries and for refining velocity

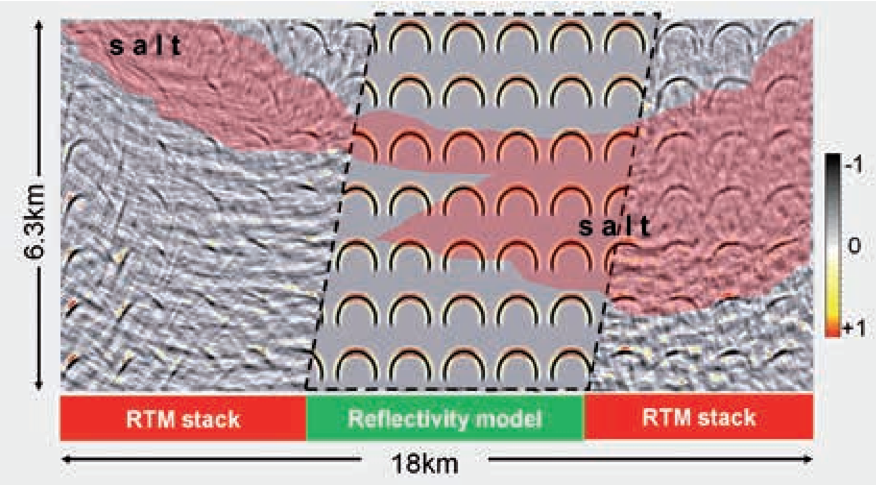

Figure 1 'Blended' display of reflectivity model and RTM stack of synthetic data, used to demonstrate combined effects of various acquisition parameters on subsalt imaging and interpretation ('How bad can it be?').

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model building practices for imaging and interpretation. Although our workflow can be applied in 3D, we often utilize fast turnaround 2D modelling and imaging which suffices for assessing some of the parameters that are most important for acquisition design, with the advantage that many scenarios can be explored in a relatively short computing time. Analysis of these results may lead to a full 3D modelling and imaging workflow that would then focus on 3D aspects.

After describing our workflow, we show an example of modelling as a tool for efficient acquisition design followed by a synthetic study for aiding interpretation in the presence of complex salt bodies.

Efficient seismic modelling workflow

Our workflow uses acoustic finite differences with constant density for both the modelling and the imaging phases (Figure 2). For some of the tests we use single scattering theory for computing synthetic seismograms thus simplifying the interpretation of the imaged results. In our implementation of this type of modelling (also described as Born modelling), the wave field is modelled using a finite difference acoustic propagator and a gridded reflectivity model. This single scattering modelling approach avoids generation of internal multiple reflections and is consistent with the basic single scattering theory of standard migration algorithms. Because our propagator supports two-way wave field propagation, our method also allows more complex propagation than one-way wave equation or ray-based modelling such as high-angle propagation and multi-path arrivals. This type of modelling is particularly suitable for illumination and acquisition design studies as the reflectivity is decoupled from the velocity model. For more realistic simulations where there is a tighter relationship between velocity complexity and reflectivity we use full acoustic finite differences modelling (Figure 3).

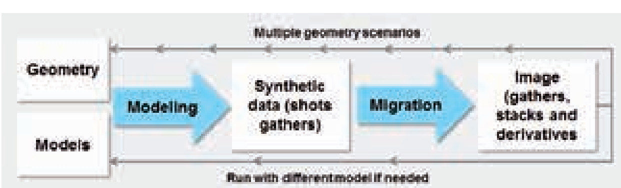

Figure 2 Modelling and migration workflow. In 2D, several geometry designs can be tested by analyzing migrated images and common angle gathers. Models may also be modified for evaluating different scenarios.

In all the test results shown here, synthetic shots are migrated with RTM. For analyzing and interpreting synthetic results both RTM full images and angle gathers are generated (our angle gathers are derived from time-shift gathers (Sava and Fomel, 2006)). As we are interested in evaluating geometries for integrated seismic exploration experiments we consider partial images to be a crucial part of the workflow for velocity interpretation work.

In our proposed workflow we use velocity models derived from field data and/or synthetically built velocity models. To obtain general survey design metrics we use relatively simple models in 2D. Recently L'Heureux and Etgen (2013) and Thatcher et al., (2013) have introduced computational geology and geo-statistically driven high-resolution synthetic models with reservoir scale stratigraphic features. For the case of targets with reliable a priori information such as basins in a development phase, the synthetic model should include this information but trying not to bias the selection of parameters on a high level of detail that might not be realistically achievable.

Modelling studies to aid survey design

The usefulness of our approach is first illustrated on a shallow marine illumination study that we used to recommend a real data acquisition survey. Here the main objective was to determine critical acquisition design parameters in terms of limitations of previously acquired inline OBC geometry. For most illumination studies we use an isotropic model as default. The model was derived from reflection tomography

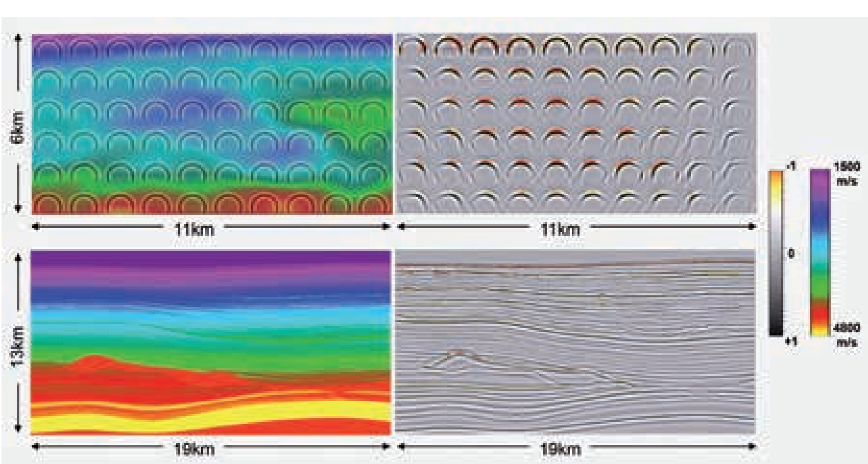

***Figure 3** Parts of modelling and migration workflows. Born modelling (top): Velocity model overlaid with reflectivity models (left) used at the modelling stage to create synthetic data which is then migrated with RTM to generate stacked section (right). Finite difference modelling (bottom): Velocity model (right) used for both modelling and RTM stack image result (right).*

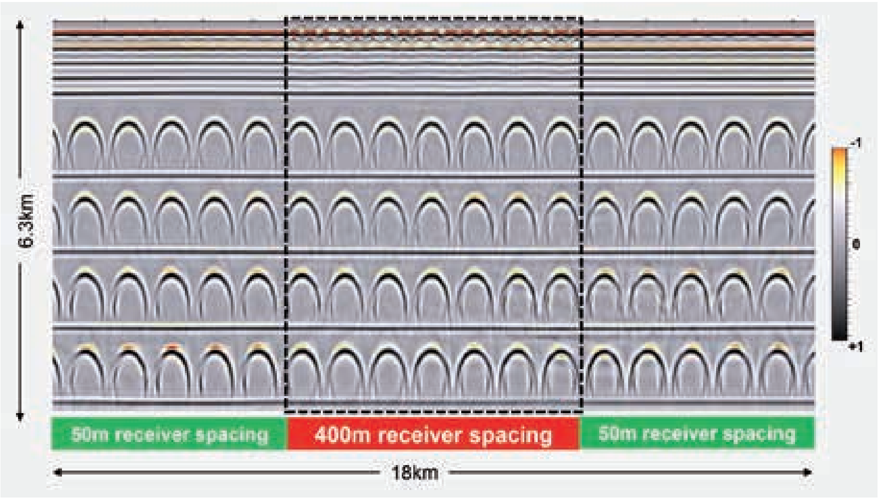

Figure 4 *'Blended' display of RTM final images from two different acquisition scenarios. Middle section correspond to 400 m receiver spacing (outlined with dashed line rectangular) while the rest of the section is RTM stack generated with 50 m receiver spacing. Coarser receiver sampling produces a poor image of the shallow set of reflectors while deeper imaging is almost identical.*

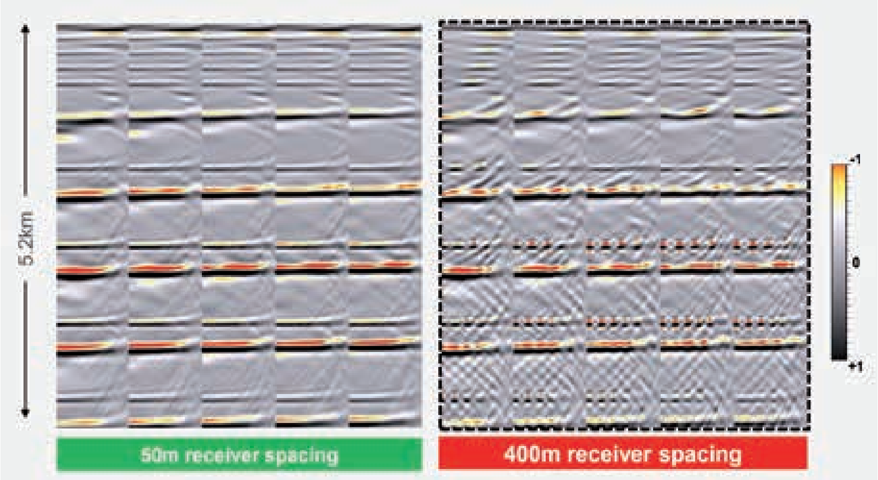

Figure 5 *RTM angle gathers from two different acquisition scenarios. Left display corresponds to 50 m receiver spacing while right section is from 400 m receiver spacing geometry (outlined with dashed line).*

performed on a real dataset around the project area. In this test we use Born modelling. The reflectivity is made up of a set of semi-circular bodies and flat reflectors with the intention of evaluating near-surface illumination as well as angle coverage throughout the model. Half-circles are convenient for analysing illumination as they can provide information about imaged dips from 0° at the top to 90° at the edges. The radius of the half-circles is 250 m, which is appropriate for the expected resolution being addressed in the project.

Because of the quick turnaround of modelling in 2D, we simulated multiple variations of surface marine geometries. We tested different geophysical and operationally realistic and unrealistic values of acquired maximum offsets, lack of near offsets, source and receiver sampling, record lengths, as well as simultaneous shooting and suitability of the data for regularization and interpolation algorithms (Cvetkovic et al., 2013). Figure 4 shows a blended display of RTM final images from two different acquisition scenarios. The display in the middle corresponds to a receiver spacing of 400 m while the panels at the edges use a receiver separation of 50 m. From the figure we observe that a coarser receiver sampling produces a poor image of the shallow reflectors but as depth increases the coarser sampling approaches the image quality of the 50 m receiver separation case. But if we further analyse the partial image result in the form of RTM angle gathers (Figure 5) we see that the coarser receiver spacing shows a strong acquisition footprint in both shallow and deep reflectors that would present problems for velocity estimation and for amplitude-related analysis.

Based on the findings of this study we selected a crossline receiver separation of 200 m as a cost-effective solution that did not compromise model building and imaging. These and other 'tuned' parameters from the 2D analysis were then used for a 3D modelling test to design OBC and OBN geometries over the full area of interest.

Our second test case mimics a North Sea geological setting with the main objective of optimizing an acquisition design that produce adequate images of mini-basins beneath a high-velocity thin and rugose chalk fast velocity layer (Lie et al., 2011; Jones, 2013). The model incorporates P-wave sonic logs and several interpreted target horizons. We extrapolated velocity profiles along the 3D horizons to produce a laterally heterogeneous model. We then used a very detailed water bottom horizon to insert the water layer. Deeper parts of the model (>2000 m) were based on regional trends for those depths. As we are interested in deep structural imaging, several faults within the basement were added (Figure 6). Vertical and lateral variations representing structural and stratigraphic features introduced in the model are useful for studying frequency content of migrated images.

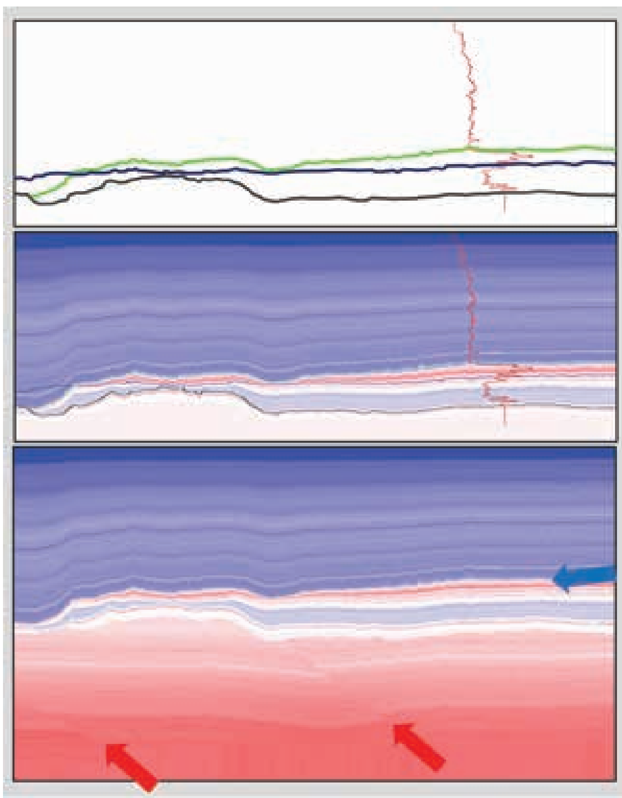

***Figure 6** Steps in building a realistic 2D North Sea velocity model. Top display shows P-sonic well log (red curve) and three key horizons (green – top of chalk, dark blue – base of chalk and black – basement); middle panel shows velocity model created from available well data and interpretation; bottom panel displays full P-wave velocity model with 'artificially' inserted velocity trends and structures in the deeper section. The blue arrow indicates rugose top chalk while red arrows point to basement faults inserted to add realism.*

We model the data with finite difference acoustic modelling followed by RTM imaging. Effectiveness of various source and receiver spacing and maximum offsets useful for velocity model building are evaluated by analysing full and partial RTM images. Figure 7 shows the effects of data sampling on imaging where it is observed that the noise and footprint levels increase with greater receiver separation. We modelled and processed receiver spacing values from 50 m to 400 m with a 25 m increment (15 geometry scenarios). Based on the quality of the final image and angle gathers we estimated that receiver separations from 200 m to 250 m to be optimal for preserving continuity of the stratigraphic features of the model, which we use to set up a limit of a hypothetical cross-line receiver cable separation. Receiver separations that exceeded 300 m resulted in final images with a poor quality in the shallow section. A source spacing of 50 m produced very similar results to those obtained with 25 m spacing, with very similar amplitude spectra (not shown for brevity). For model building and imaging, 4000 m of maximum offset is recommend in this investigation as a smaller maximum offset in the range of 2000 m to 3000 m damages the deeper parts of the section with consequences for velocity interpretation. Longer inline offsets do not contribute to an improved image at the target depth but could increase the depth range in particular for model building. By using 2D modelling and imaging with realistic complexity of the model the proposed scheme for survey design surpasses simpler metrics such as fold and coverage maps (Stork, 2011).

Salt interpretation case study

An important application of seismic modelling with finite differences corresponds to gaining experience for interpreting migrated images in complex geology such as subsalt exploration in the Gulf of Mexico. For this purpose we have modified the SEAM model (Fehler and Keliher, 2011) to test a number of scenarios for salt interpretation. We combined several inline and crossline sections from the original SEAM 3D model to produce a regional 2D seismic line of 248 km length. The 2D model contains several salt bodies alternating with smaller and larger sedimentary basins (Figure 9). We modified the top and base of the salt from the original model by introducing a more rugose

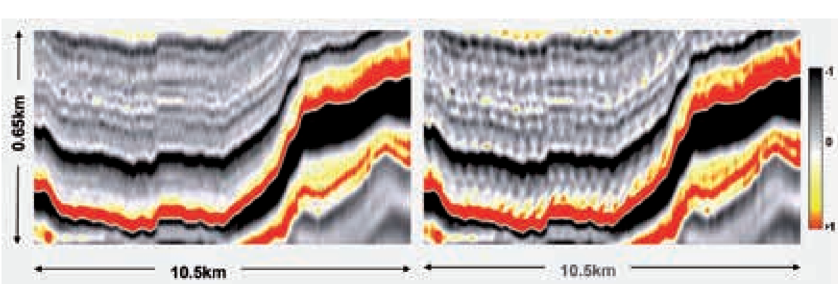

***Figure 7** RTM image of synthetic data simulated with the 2D North Sea velocity model. Comparison between 200 m (left) to 350 m (right) receiver spacing. The coarser sampling noticeably compromised imaging*

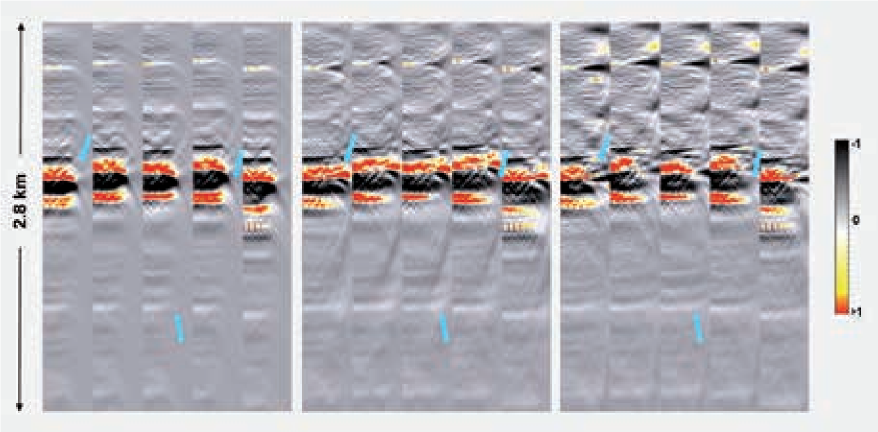

Figure 8 *RTM angle gathers of synthetic data simulated with a 2D velocity model. Comparison between 2000 m (left), 4000 m (middle) and 8000 m (right) of maximum acquired offset.*

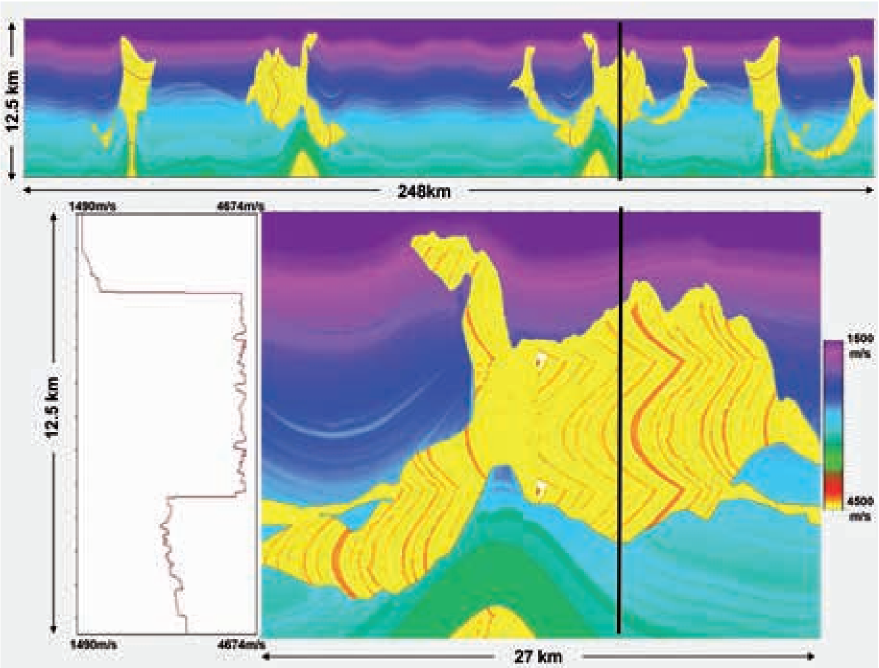

Figure 9 *SEAM 2D LONG model. Top display shows full 2D velocity model modified from original SEAM 3D model while bottom displays are enlarged section of the model (right) and velocity profile (left) from location indicated by black line.*

detail in the interface. We also introduced variations in the salt velocities reported in the literature (Haugen et al., 2009) and in production projects of the Gulf of Mexico. To better correlate with real problems and create a low illumination subsalt image problem (Stork et al., 2011; Cvetkovic et al., 2011) we also reduced subsalt velocity from the original model by 40% in accordance to well log information.

In this experiment, we compute synthetic seismograms with Born modelling with a reflectivity composed of half-circles of 250 m radius regularly distributed in the model. We then migrated synthetic shots with a set of incorrect velocity models in which we perturb the salt-sediment interface that might hypothetically result from an inaccurate velocity model. The acquisition geometry in this case is an 'ideal' geometry with a dense receiver and source sampling.

Based on past experiences and published work (Etgen and Albertin, 2012; Jones, 2012) it is known that accuracy in salt interpretation is arguably the most sensitive part in the model building flow. Figure 10 shows cases of erroneous salt interpretation. In line with similar studies in velocity model building (Etgen and Albertin, 2012) we find that an erroneous top of salt interpretation damages the image from shallow to subsalt depth. Our modelling studies show that errors in position of salt flanks have the largest detrimental impacts on the subsalt image. Accurate positioning of salt flanks can be directly related to velocity and anisotropy errors (Figure 10).

In a second test, we incorporated anisotropy in the salt and studied the effect of imaging the data with an isotropic salt, in accordance with analysis of salt outcrop samples and recent efforts for incorporating salt anisotropy for

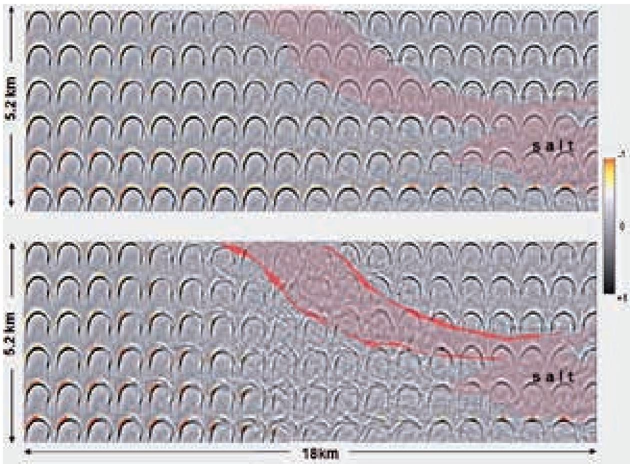

Figure 10 Effects of errors in salt body interpretation. RTM stack with true velocity model (top) and RTM stack with errors in salt flanks interpretation (bottom). Parts of the salt body in dark red represent incorrectly interpreted flanks.

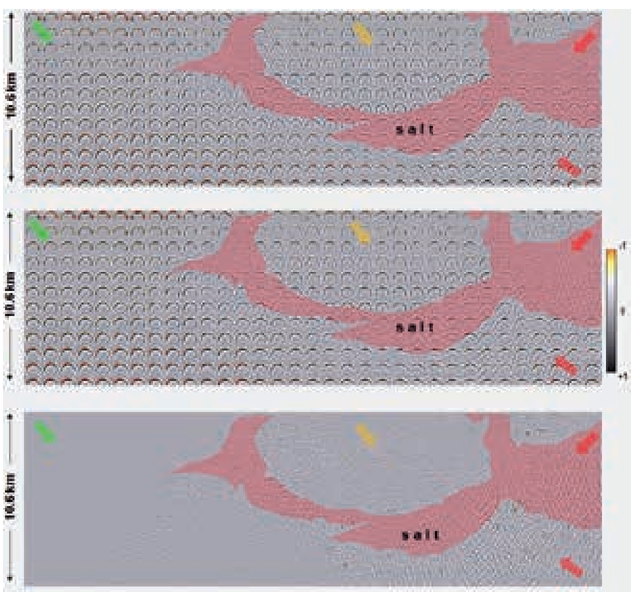

Figure 11 Effects of salt anisotropy. RTM stack with anisotropic salt body, true models used in migration (top), RTM stack with incorrect model (isotropic salt) used in migration (middle) and the difference between the two (bottom). Note that the only part of difference section that is not showing influence of assuming isotropic salt is a large sediment basin (green arrow). An intra-salt sediment basin still shows some amplitude in difference section (orange arrow).

imaging (Landro et al., 2011). We used a VTI anisotropy with a negative delta value (-4%) and positive epsilon (4%) for salt, and assume isotropy for sediments in the model. Figure 11 displays the migrated image with the true model (top), the case of imaging assuming an isotropic salt (middle) and the difference between the two (bottom). We clearly see that the RTM image with an isotropic salt model is not well focused and that the subsalt reflectivity is noticeably compromised. Distortion of the image is dominant within and below the salt but it is interesting to observe that as far as 15 km from the salt interface, residuals are observed between the two images. As we want to image deep subsalt targets the maximum offset employed in this test is 20 km for undershooting the salt.

Conclusion

Seismic modelling and subsequent processing and imaging is a powerful tool for guiding acquisition design, benchmarking processing algorithms and workflows as well as for guiding interpretation in complex geological settings. A way to speed up this process but still using a wave equation for a more realistic simulation is to consider 2D modelling as a very efficient tool for testing several scenarios. In the case of geometry design, source and receiver spacing and offset range can be tested for illumination, coherency of events and angle coverage by computing partial and final images. In the examples presented we first perform modelling and analyze full and partial images to derive source-receiver spacing that can result in optimal cross-line separations. These analyses can be tested subsequently with 3D modelling and some a priori information of lateral heterogeneity in the model. In our modelling workflow, Born modelling is a preferred tool for testing illumination as it is possible to decouple a smooth background velocity model from hypothetic features that can be distributed throughout the model. We have used this kind of modelling as an interpretation aid for salt body interpretation, where a catalogue of cases can be built with a relatively small computational effort.

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References

Billette, F. and Brandsberg-Dahl, S. [2005] The 2004 BP velocity benchmark. 67th Annual International Conference and Exhibition, EAGE, Extended Abstracts, **B035**.

Cvetkovic, M., Zhou, Z. and Farmer, P.A. [2011] Beyond WAZ: A Modeling-based Evaluation of Extensions to Current Wide Azimuth Streamer Acquisition Geometries. 73rd EAGE Conference & Exhibition incorporating SPE EUROPEC 2011, Expanded Abstract, **E012**.

Cvetkovic, M., Farmer, P.A. and Bloor, R.I. [2013] The Effects of Marine Data Acquisition Practices on Imaging in Complex Geological Setting – Modeling Study. 75th EAGE Conference & Exhibition incorporating SPE EUROPEC 2013, Expanded Abstract, **F007**.

Etgen, J. and Albertin, U. [2012] Reflection tomography: failures of conventional wisdom. SEAG/EAGE Summer Research Workshop, Velocity Model Building in Complex Geology.

Fehler, M. and Keliher, P.J. [2011] SEAM Phase I: Final Report - Challenges of Subsalt Imaging in Tertiary Basins, with Emphasis on Deepwater Gulf of Mexico. SEG.

Haugen, J.A., Mispel, J. and Arntsen, B. [2009] Seismic Imaging Bellow "Dirty" Salt. 71st EAGE Conference & Exhibition incorporating SPE EUROPEC 2013, Expanded Abstract, **U008**.

Jones, I.F. [2012] Tutorial: Incorporating near-surface velocity anomalies in pre-stack depth migration models. *First Break*, **30**(3), 47-58.

Jones, I.F. [2013] Tutorial: The seismic response to strong vertical velocity change. *First Break*, **31**(6), 43-54.

Landro, M., Puigdefabregas, C. and Arntsen, B. [2011]. Anisotropy in the salt outcrop at Cardona, Catalonia – implications for seismic imaging. *First Break*, **29**, 41-45.

L'Heureux, E. and Etgen, J. [2013] Building better models for seismic simulations with stochastic stratigraphy. 83rd Annual International Meeting, SEG, Expanded Abstracts, 3320-3324.

Lie, J.E., Daniesen, V., Kolbjornsen, K., Jorstad, A., Jones, N. and Toomey, D.R. [2011] The Luno Discovery, Imaging Outside the Mute Zone. 73rd Annual International Conference and Exhibition, EAGE, Extended Abstracts, **E025**.

Regone, C.J. [2007] Using 3D finite-difference modeling to design wide-azimuth surveys for improved subsalt imaging. *Geophysics*, **72**, 231-237.

Sava, P. and Fomel, S. [2006] Time-shift imaging condition in seismic migration. *Geophysics*, **71**, 209-217.

Stork, C. [2011] Seismic acquisition is moving from a "CMP Fold" perspective to a "Wavefield Recording" perspective which has significant implications on acquisition design. 81st Annual International Meeting, SEG, Expanded Abstracts, 157-162.

Stork, C., Compton, S. and Heuermann, P. [2011], RTM images from SEAM data show interesting features. 81st Annual SEG International Meeting, Expanded Abstracts, 3196-3200.

Stork, C. [2013] Eliminating Nearly All Dispersion Error from FD: Modeling and RTM with Minimal Cost Increase. 75th Annual International Conference and Exhibition, EAGE, Extended Abstracts, **F007**.

Thacher, C., Stefani, J., Wu, C., Nihei, K., Sydora, L., Chou, T., et al. [2013] Subsalt imaging and 4D reservoir monitoring evaluation of Tahiti field, Gulf of Mexico. 83rd Annual International Meeting, SEG, Expanded Abstracts, 4876-1879.