Successful application of joint reflection/refraction tomographic inversion in a shallow water marine environment

Sergey Birdus
CGG
38 Ord St., West Perth,
WA, 6005, Australia
Sergey.Birdus@cgg.com

Dean Criddle
Rialto Energy
Level1/34 Colin St,.
West Perth, WA, 6005, Australia
Dean.Criddle@rialtoenergy.com

Alexey Artyomov
CGG
38 Ord St., West Perth,
WA, 6005, Australia
Alexey.Artyomov@cgg.com

Qingbing Tang
CGG
38 Ord St., West Perth,
WA, 6005, Australia
Qingbing.Tang@cgg.com

SUMMARY

We show how refraction tomography (also called first arrival travel time tomography) helps to produce more accurate and detailed depth velocity models below a shallow seafloor. We do not use refractions by themselves to build a complete shallow velocity model. In our proposed workflow, refraction tomography complements standard reflection tomography and the priority remains with the reflections to guarantee stability of the solution and to avoid uncertainties associated with refracted or diving waves in complex media.

We use wave equation modelling to calculate synthetic gathers and estimate the travel time mismatch between real and synthetic first arrivals. It leads to a robust workflow which can be easily introduced into production depth-velocity processing.

We show how this joint reflection/refraction velocity inversion works using a real 1000sq.km 3D marine seismic dataset acquired in an area where the water depth varies from 20m to 1100m.

Key words: velocity modelling, refractions, tomography.

INTRODUCTION

Standard depth-velocity modelling, which uses reflections, can be challenging for the upper part of the section in shallow water marine environment (water depth up to few hundred meters). Problems are caused by the limited number of offsets that are available for analysis and the wide-spread presence of strong multiples. Seismic acquisition is designed for an optimal illumination of much deeper target intervals. Very often it does not allow accurate velocity estimations in the shallow part of the section. However all deeper target reflections travel through the upper part of the model, so having an accurate velocity model right from the seafloor is important.

In this paper we show how refraction tomography (also called first arrival travel time tomography) helps to produce more accurate and detailed depth velocity models below a shallow seafloor. We do not use refractions by themselves to build a complete shallow velocity model. In our proposed workflow, refraction tomography complements standard reflection tomography and the priority remains with the reflections to guarantee stability of the solution and to avoid uncertainties associated with refracted or diving waves in complex media.

Our joint reflection/refraction tomography has two major objectives. Firstly, refracted and diving waves carry valuable information about the shallow velocities. When these waves come to first arrivals, their travel times can be measured with high accuracy and reliability. First arrival travel time tomography can complement the industry standard reflection tomography and lead to more accurate and reliable depth-velocity models and seismic images.

Secondly, in recent years we have seen a fast advance of Full Waveform Inversion (FWI) which represents the next generation of velocity modelling and imaging techniques. FWI primarily uses diving waves. So, the transition from the standard reflection tomography to FWI means not only changes in the processing algorithms and software but also a shift from reflections to diving waves. In practice, the standard reflection tomography provides starting velocity models for FWI. The use of different wave types can explain some reported cases when such models did not lead to convergence in FWI. From this point of view, the inclusion of refracted tomography into production depth-velocity modelling workflows can be seen as an important step towards future wide practical implementation of FWI.

REFRACTION TOMOGRAPHY AS A PART OF JOINT REFLECTION/REFRACTION VELOCITY INVERSION

Robust application of first arrival travel time tomography in depth-velocity processing can be impeded by the fact that very often the first arrivals (diving and refracted waves) do not continuously illuminate the upper part of a section. These effects depend on complexity of real velocities. First arrivals usually correspond to relatively high velocity layers and intervals with positive vertical velocity gradients. To solve this problem we (a) use refraction tomography as a part of joint reflection/refraction velocity inversion and (b) calculate synthetic gathers (not only the first arrival travel times) to compare with real seismic data, get understanding what really happens with the first arrivals and set optimal parameters for tomographic velocity inversion.

We use refracted tomography after the normal initial depth-velocity modelling and a couple iterations of standard reflection tomography (Figure 1).

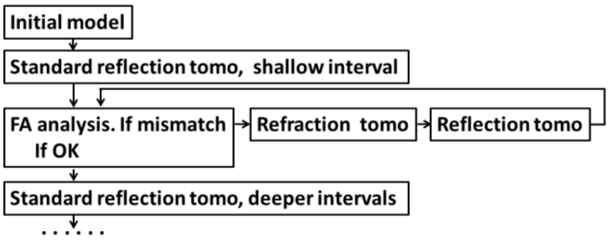

Figure 1. Joint reflection/refraction tomography workflow.

Then we employ 3D finite-difference wave-equation modelling to calculate a grid of synthetic gathers corresponding to the current velocity model (Figure 2B). We pick the synthetic first arrival travel times and compare them with the first arrival travel times measured on real seismic data (Figure 2A). The mismatch between real and synthetic travel times (red line on figure 2B) is caused by velocity errors in the current model. The current model has been built by the reflection tomography alone. We can see how refracted and diving waves highlight some velocity errors that could not be detected by the reflected wave analysis, especially in the shallow part of the section.

We know seismic ray paths for the current velocity model (Figure 3). Similar to standard reflection tomography (Zhou et al. 2003), refraction tomography (Zhu et al. 2000 and Taillandier et al. 2011) back propagates observed mismatches along the ray paths and inverts these mismatches into velocity perturbations. The new updated velocity model reduces the travel time differences. This can be validated by another round of synthetic modelling (Figure 2C). Several iterations of refraction tomography can be performed until we accept the achieved mismatch level and proceed with standard reflection tomography to deeper intervals. In order to make sure that the refraction tomography does not cause any dis-balance to our primary reflections, each iteration of refraction tomography is followed by an iteration of reflection tomography (Figure 1).

The actual refraction velocity inversion uses only travel times. Unlike the majority of refraction tomography techniques, we do not calculate the synthetic first arrival travel times, instead we pick these travel times on synthetic gathers created by wave-equation modelling. From practical perspective, the direct comparisons of real and synthetic gathers (Figure 2) assists in understanding the nature of the observed mismatch, setting optimal parameters for the inversion (such as offset and depth ranges) and controlling the results. This is especially important if we meet localized anomalous zones, effects of thin high velocity layers, velocity inversions etc. Interactive software allows us to simultaneously analyse real and synthetic gathers, current seismic sections and velocity models. It leads to a robust workflow which can be easily introduced into production depth-velocity modelling. Also, working this way we are one step closer to FWI.

APPLICATION TO A REAL SEISMIC DATASET

Figures 2 to 5 illustrate results that we obtained with the joint reflection/refraction tomography on a large (~1000sq.km) 3D marine dataset. Water depth varies from 20m to 1100m within the project area. Ten cable acquisition with 100m intervals between the cables means that the shortest offset with nominal regular coverage is near 450m (Figure 4A). In the shallow water areas, it was difficult to pick reliable and consistent velocities using reflections within the first 500m of sediments (Figure 4B).

We applied refraction tomography after two iterations of standard reflection tomography. Figure 5A shows PSDM section and interval velocities that correspond to this stage.
Shallow geology varies within the project area. When we compared real first arrival travel times with synthetic travel times corresponding to the current PSDM velocity model we observed that in some areas the misfit between the real and synthetic data was minimal (velocities were good). In other areas the mismatch was large and obvious (significant errors in the shallow velocities). Figures 2A-B show an example of data with a large mismatch where the travel times differ by more than 120ms (more than 12%). Refraction tomography reduced the mismatch to less than 10ms (figure 2C).

The velocities and PSDM section after two iterations of joint reflection/refraction tomography are shown in figure 5B. We got significant, up to 10%, changes in the shallow velocities. These changes are consistent with the geology. Effective RMS velocities for deep target reflections remain unchanged but their average velocities change as refraction tomography introduces more details into the shallow interval velocity model. In our case, this resulted in a noticeable tilt to all deep structures.

It is also interesting to note that the velocity model before refraction tomography was smoothed and synthetic modelling did not generate any visible reflections (figure 2B). Refraction tomography introduced velocity gradients and these gradients created some reflections in the corresponding synthetic wave field (marked by the green pointer on figure 2C). In general, these reflections match reflections on the real gather (figure 2A).

We used refracted waves for an additional illumination and better velocity estimations in the very shallow part of the model which consists of soft unconsolidated low velocity sediments. Normally, such sediments are isotropic or exhibit negligible anisotropy. In our case, we did not notice any anisotropy dealing with the first arrivals and some anisotropy was later introduced within deeper intervals based on well information and non-parabolic moveout observed on reflected seismic data.

As we used only the first arrival travel times for velocity inversion, we limited the maximum frequency in synthetic modelling to 40Hz. This minimized required computer resources. The differences in wavelets were compensated by a constant shift applied to synthetic travel times to match real travel times for near offsets and in the deep water area.

CONCLUSIONS

We show how refraction tomography makes 3D depth velocity modelling more detailed and accurate in a shallow water marine environment.

Joint reflection/refraction velocity inversion and the use of wave equation modelling to calculate synthetic gathers and estimate the travel time mismatch lead to a robust workflow which can be easily introduced into production depth-velocity processing.

ACKNOWLEDGMENTS

We thank Rialto Energy and CGG for permission to present these results.

REFERENCES

Zhu T., Cheadle S, Petrella A., Gray S. [2000] First-arrival tomography: method and application. 70th Annual International Meeting, SEG, Extended Abstracts, 2028-2031.

Taillandier C., Deladerrière N.,Therond A. and Le Meur D.[2011] First Arrival Traveltime Tomography – When Simpler Is Better. 73rd EAGE Conference & Exhibition, Extended Abstracts, I034.

Zhou H., Gray S.H.. Young J., Pham D., Zhang Y.[2003] Tomographic Residual Curvature Analysis. 73rd Annual International Meeting, SEG, Extended Abstracts, 666-669.

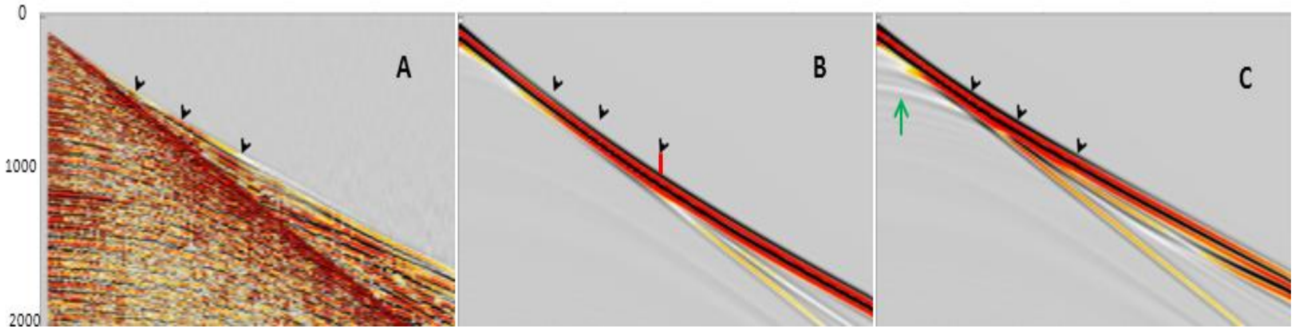

Figure 2. Examples of a real gather (A), corresponding synthetic gathers before (B) and after (C) refraction tomography. Black ticks mark position of first arrivals picked on the real gather.

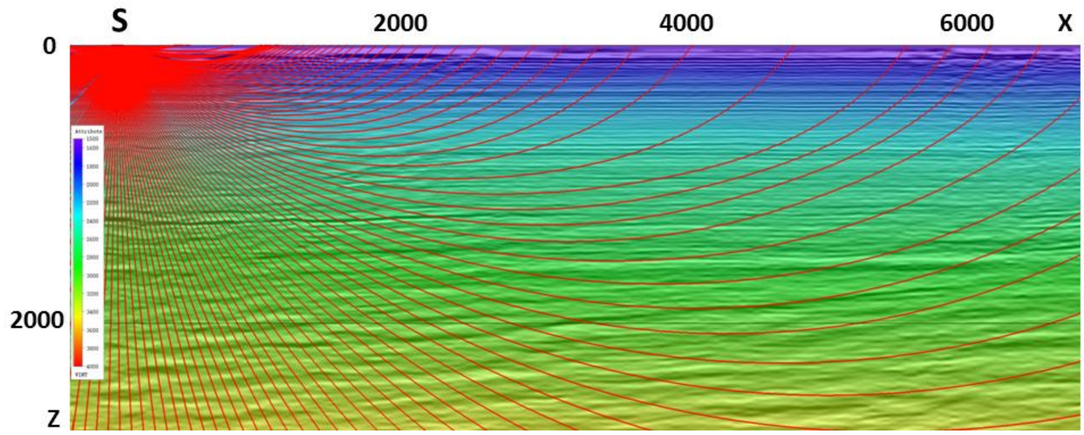

Figure 3. Ray tracing through the initial velocity model. Depth scale, real aspect (X:Z=1:1). Diving waves that come to first arrivals will be used to check and update the velocities.

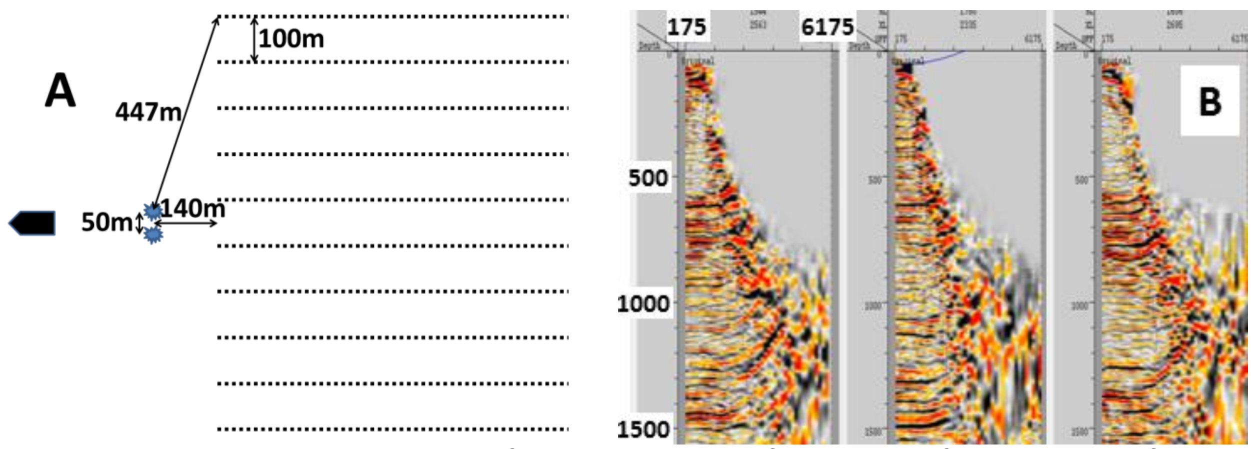

Figure 4. A- Ten cable dual source acquisition configuration. B- examples of PSDM gathers for the upper part of the section in area with shallow seafloor.

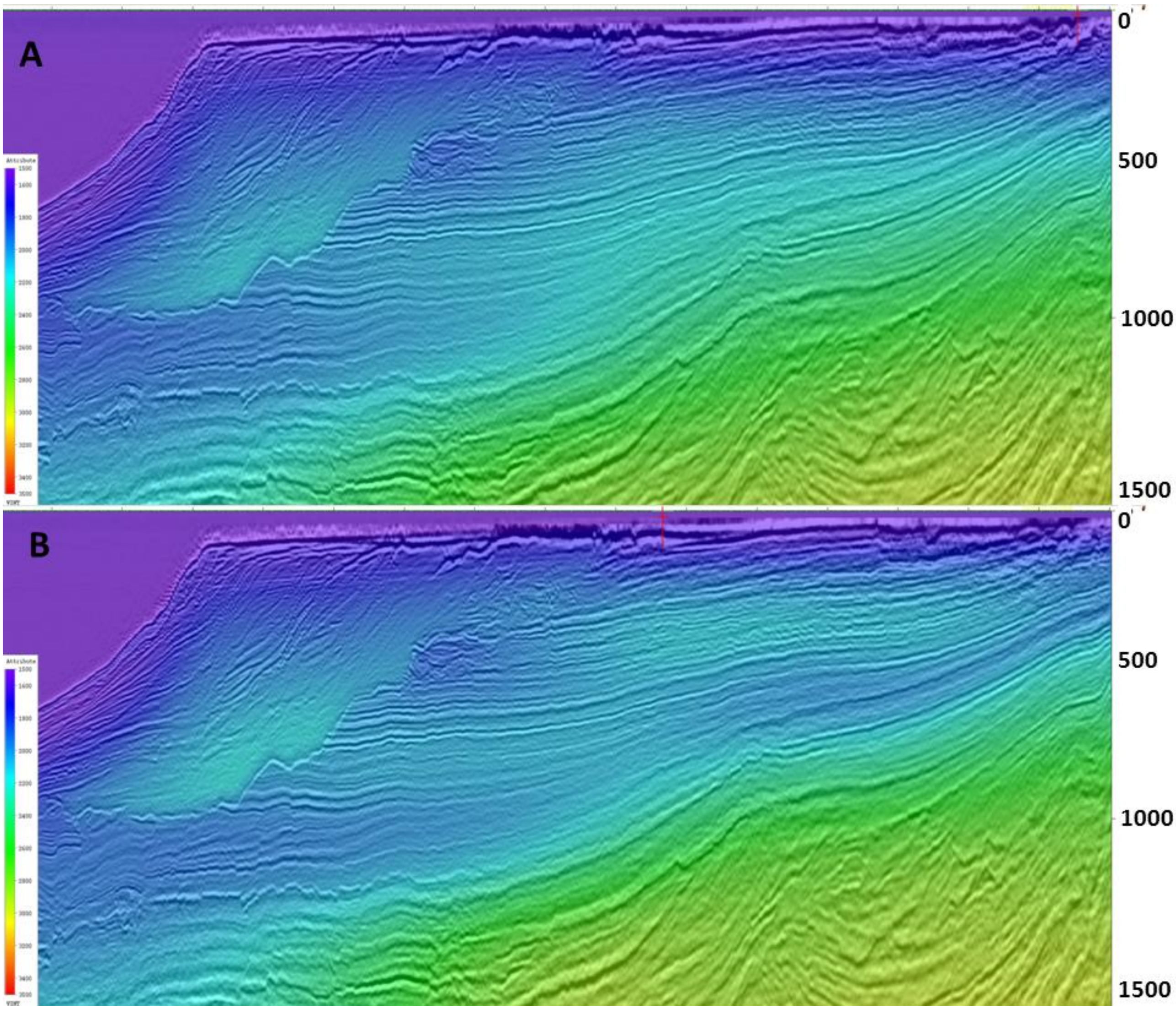

Figure 5. PSDM sections and interval velocities before (A) and after (B) refraction tomography. Data courtesy Rialto Energy.