Th LHR4 08

Imaging through Mega Gas Clouds in Offshore Brunei

Y.N. Lin* (CGG), X. Wu (CGG), Y. Xie (CGG), J. Zhou (CGG), S. Sulaiman (Shell Deepwater Borneo), J. Turner (Shell Deepwater Borneo) & Z. Wei (CGG)

SUMMARY

The size and complexity of the mega gas clouds in offshore Brunei pose severe imaging problems to the structures underneath. We present a comprehensive technical package to tackle the complex wave propagation and anelastic energy losses associated with these gas clouds. We started by running FWI to resolve the velocity of the shallow gas clouds, followed by reflection tomography. We then conducted FWI-guided Q tomography to obtain a high-resolution absorption model. For the deep gas clouds, since their depth and the incurred low signal-to-noise ratio in the CMP gathers are beyond the limit of these geophysical methods, we moved on with geologically-guided scenario testing in intense collaboration with geologists. Finally, we carried out visco-acoustic TTI reverse time migration (Q TTI RTM) to better deal with the issues of multi-pathing and strong attenuation. This complete package brings significant uplift to the image as compared to the vintage QPSDM result, and therefore can serve as an effective option before turning to C-wave imaging.

Introduction

Seismic imaging under gas-obscured zones has long been a challenging task. The heterogeneous nature of gas-filled patches results in scattering, internal multiples, mode conversion during wave propagation, together with anelastic losses and wavelet distortion (Aki and Richards, 1980). Among all methods that aim to tackle the gas-cloud related issues, the C-wave processing is the ultimate solution for the problem, yet its high acquisition cost is a big concern especially to exploration projects. For P-wave processing, various approaches have been proposed to target different aspects of the problem (e.g., Liu *et al*., 2014; Zhou *et al*., 2014). In spite of a variety of methods, we need to answer a key question: have we extracted the last drop of information from the P-wave images? Where is the limit of P-wave imaging, and when should we turn to C-wave?

Figure 1 *Map of the Baram Basin (after Doust and Sumner, 2007).*

In this paper we present a comprehensive processing package for P-wave imaging in gas-cloud regions, using a special case of mega gas clouds in offshore Brunei. The survey is located within the Baram Basin (**Figure 1**), characterized by the siliciclastic sediments from the Neogene Baram delta and the complex structures including steep dips, growth faults and overthrusts (Doust and Sumner, 2007; Ghosh *et al*., 2010). In 2011 and 2013, two consecutive commercial 3D variable-depth streamer surveys were conducted to cover nearly the whole basin. The eastern part of the survey has particularly severe gas cloud problems. The 2013 broadband 3D PSDM survey (hereby the 2013 vintage survey) reveals two layers of gas clouds: the shallow gas clouds located within 500 m below the water bottom, and the deep gas clouds sitting between 1-3 km of depth. The shallow gas clouds form an extensive layer around the depth of 450 m (**Figure 2B**), while the deep gas clouds are dissected into several large patches (**Figure 2D**). A relatively gas-free zone of higher velocities forms a divide between the two gas cloud layers (**Figure 2C**). The vintage survey adopted a TTI model updated after 7 iterations of reflection tomography and visco-acoustic Kirchhoff migration (Xie, *et al*., 2009). Because of the complexity and the sheer size of the gas clouds (10 km in width and 20 km in length), however, the structures within and below the deep gas clouds are not well imaged. In 2015, we designed a new flow to tackle this mega gas cloud problem, aiming to explore the limit of P-wave imaging for gas clouds.

The new flow consists of the following steps: resolving the shallow gas velocity through FWI, updating the velocity of intermediate to deeper levels by reflection tomography, using FWI as the guide to obtain a high-resolution absorption model, building the deeper gas velocity through geologically-guided scenario testing, and migrating with visco-acoustic TTI reverse time migration (Xie, *et al*., 2015) method.

FWI: Resolving shallow gas velocity

The starting model for FWI is the smoothed version from the vintage TTI velocity model. We tested and decided that the 3-Hz frequency band had sufficient signal-to-noise ratio and could serve as the starting frequency to avoid cycle-skipping. We carried out inversions starting from 3 Hz and gradually increased to 8 Hz. After the final inversion both the cost function and the cross-correlation coefficient between the synthetic and the real shots show that the inversion had achieved convergence. The updated velocity has very high resolution in the shallow gas clouds (**Figure 2A-2B**), and delineates a relatively gas-free zone at around Z=1250 m (**Figure 2C**). The velocities and shape of deeper gas are also updated but the resolution is limited (**Figure 2D**).

In this area, most turning waves bend back by the depth of 2000 m, and therefore the update is mainly for the shallow gas clouds and the top of the deep gas clouds. Nevertheless, we want to emphasize that the accuracy in the shallow velocities plays a key role in providing a high-definition image to the deeper part. After FWI, we continue with several iterations of reflection tomography. The update extends all the way to the bottom of the survey.

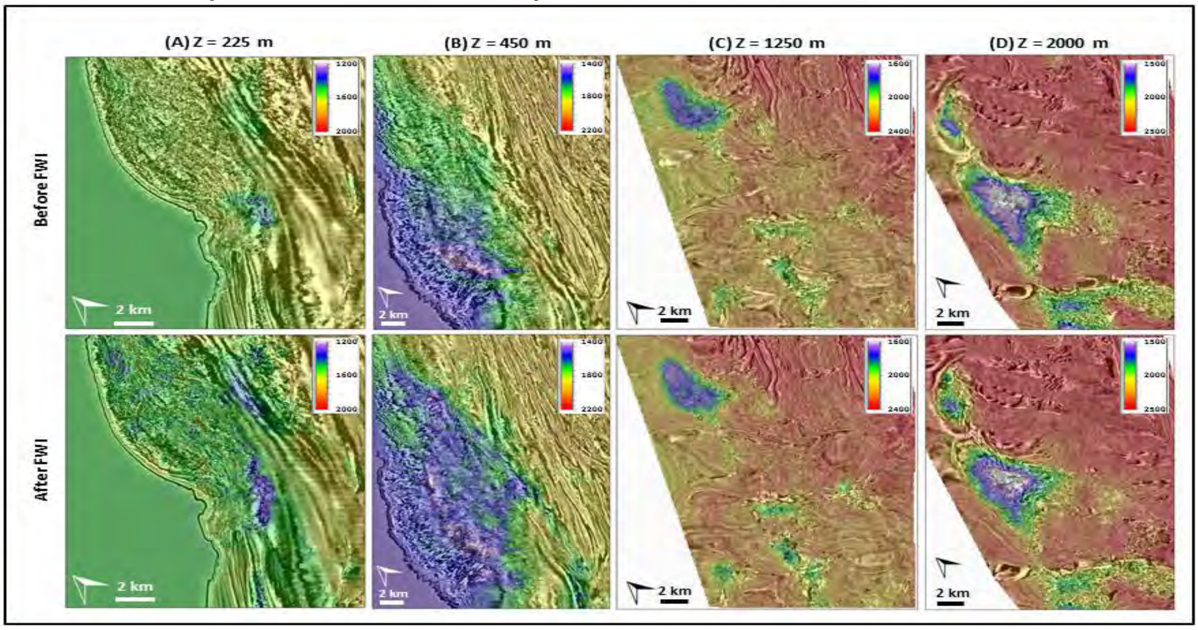

Figure 2 *Comparison of velocities at different depth slices between FWI input model (upper panel) and FWI output model (lower panel). Note that color scale and map view scale change with depth.*

FWI-guided Q tomography: Obtaining high-resolution absorption model

Several studies have demonstrated the success of incorporating a proper Q model to recover the energy losses and distorted wavelets (Teng *et al*., 2013; Zhou *et al*., 2014; Menzel-Jones *et al*., 2015). These real-case examples suggest that anelastic losses play an important role as elastic processes in the wipe-out effect, and therefore should be accounted for in processing. In this regard, we adopted the flow of FWI-guided Q tomography proposed by Zhou *et al*. (2014) to obtain a high-resolution absorption model. We extracted a gas cloud mask based on the velocity after FWI and tomography update, and used it in the TTI-based Q tomography algorithm (Xin and Hung, 2009). Through ray-tracing, the attenuation effect is accumulated and limited within the gas cloud mask, till a 3D attenuation model is achieved. The algorithm only inverts for the Q anomaly (background Q set to 170), and with the values restricted within the mask defined by FWI velocity, the Q model is geologically conformable.

Geologically-guided scenario testing: Building deep gas velocity

The deep gas clouds not only fall outside the update limit of FWI, but also significantly degrade the signal-to-noise ratio of the CMP gathers in the mid-to-far offsets, impairing the efficacy of reflection tomography. Indeed when it comes to gas bag problems, there exists an innate limitation for geophysics-based tools.

In that regard, we decided to turn to an entirely different approach – geologically-guided scenario testing, as inspired by the success in the Gulf of Mexico (Ritter, 2010). Scenario testing has been widely applied when it comes to the salt problems. The application of this method on gas cloud problems is not as common because of the time it takes and the opportunity cost of doing so when the gas clouds are relatively small. Now, when the gas clouds are huge and hinder the imaging of all key structures below, scenario testing may become a key solution for the problem.

Involvement of geologists is crucial in scenario testing. During the test cycles, model builders interact closely with geologists to determine the possible velocity structure within and below the gas clouds. Within the whole process, a good understanding of the regional geology is a must, and dynamically adjusting the interpretation with short turnaround time is the keystone to success. The main difference between scenario testing for salt bodies and for gas clouds is the significantly lower signal-to-noise ratio for the latter. It is therefore important to incorporate all available knowledge, experiences and even geological imaginations into the tests. A good tactic is to go to an extreme by assuming the lowest velocity within the gas clouds based on any nearby well (around ~1000 m/s in our case), and gradually retreat from there to achieve a geologically-valid 3D model (**Figure 3**).

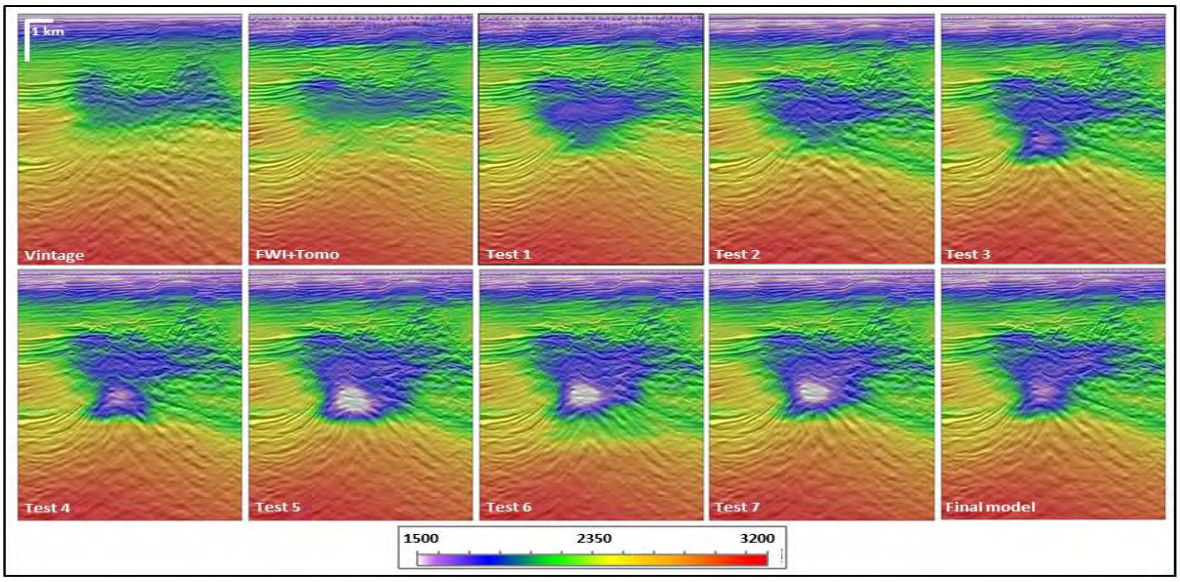

Figure 3 *Examples of gas bag scenario testing.*

Q TTI RTM: Imaging through the complex gas clouds

To image through and under the gas clouds, one needs to consider both the elastic effects such as multi-pathing and the anelastic effects including amplitude attenuation and phase distortion. An ideal migration algorithm to counter all these effects will be Q RTM. We adopted the method proposed by Xie *et al*. (2015), in which they started from the linear visco-acoustic wave equation in a TTI anisotropic medium, and proposed to use wavefields from both a conjugate medium and a lossless medium to compute the desired backward propagated receiver wavefield. This method resolves the instability issue associated with the frequency-dependent attenuation in time-reversal propagation, and deals with the multi-pathing effect that is observed around the base of huge gas bags in this area.

The migration result shows more coherent events within and underneath the gas clouds. In the final QTTI RTM result, the anticline geometry can be clearly defined, and the sediment package can be better identified as compared with the Q Kirchhoff TTI PSDM result (**Figure 4**). In other cases where the wave propagation field is further complicated by a juxtaposing fault, QRTM imaged more details such as the truncation point and the fault throw, which may be crucial to the interpretation of hydrocarbon migration process.

Conclusions

In this paper we present a comprehensive package for P-wave imaging through gas clouds by using a case study in offshore Brunei. The package consists of four parts: FWI for the velocity in the shallow gas clouds followed by reflection tomography, FWI-guided Q tomography for a high-resolution absorption model, geology-guided scenario testing for the velocity within the deep gas clouds, and Q TTI RTM for the multi-pathing and energy attenuation issues during migration. This flow brings significant uplift as compared with the vintage results. We believe that this package has achieved the limit of all available tool sets for P-wave imaging on gas cloud problems, may serve as an effective and economic choice to treat any existing gas-obscured prospects, and should be tested out before anyone turns to the costly C-wave imaging with OBC or OBN.

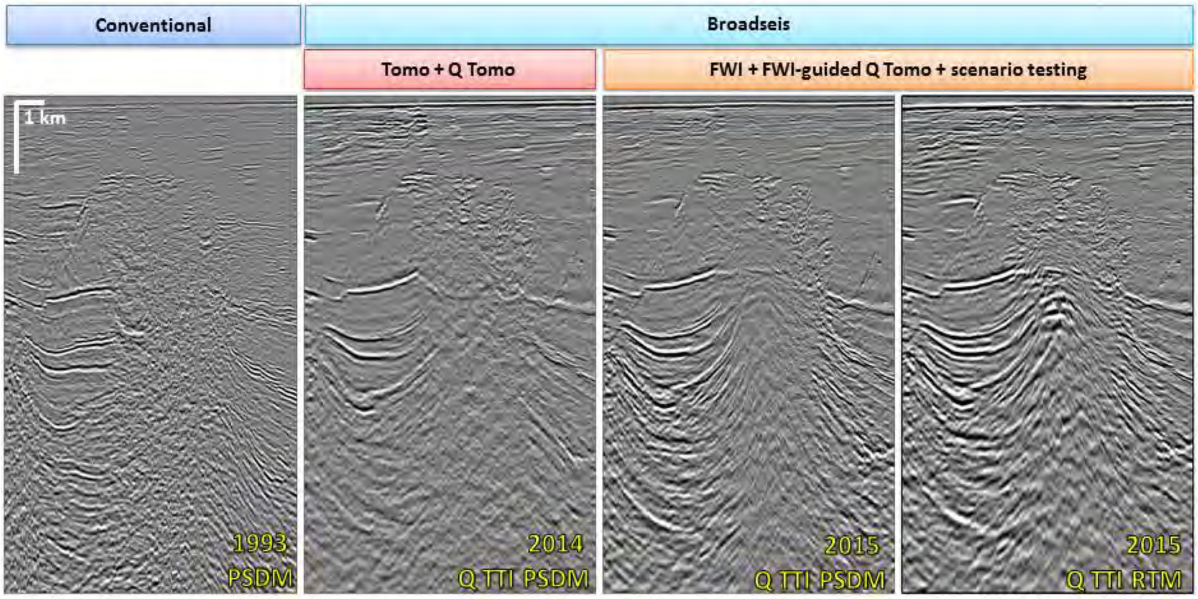

Figure 4 *Final result comparison. The advance from conventional (1993 PSDM) to broadband (2014 QPSDM) acquisition has increased the signal-to-noise ratio in the deeper part, forming a solid base for new model building flows (2015 QPSDM) and imaging technologies (2015 QRTM) to bring uplift to event coherency at depth.*

Acknowledgments

We thank CGG for permission to publish this work. We thank PETRONAS Exploration Technical Services (Exploration Geophysics) and Petronas Carigali Brunei Ltd (PCBL) geoscience team for their comments and suggestions throughout the course of this project. We also thank Brunei Shell Petroleum, Shell Deepwater Borneo, Petronas Carigali, Energy Division Prime Minister's Office (EDPMO) and Petroleum Brunei (PB) for granting the show right of the data used in this paper.

References

Aki, K. and P.G. Richards [1980] *Quantitative seismology – theory and methods*, Freeman.

Doust, H. and H.S. Sumner, 2007, Petroleum systems in rift basins – a collective approach in Southeast Asian basins. *Petroleum Geoscience*, **13**, 127-144.

Ghosh, D., M. Halim, M. Brewer, B. Viratno and N. Darman [2010] Geophysical issues and challenges in Malay and adjacent basins from an E & P perspective. *The Leading Edge*, **29**, 436-449.

Liu, Y., G. Chen, L. Hu, Y. Huang, M. Chang and C. Contrino [2014] Improving images below shallow gas clouds with adaptive data-selection FWI and Q-tomography: A case study at East Breaks, BOM. *84th Annual International Meeting, SEG*, Expanded Abstracts.

Menzel-Jones, G., J. Rndschwentner, C.H. Lim, S. Hydal and B.J. Lim [2015] Imaging through shallow gas: Integrating broadband acquisition, processing and high-end model building for improved imaging of deeper targets. *24th Annual International Meeting, ASEG-PESA*, Expanded Abstracts.

Ritter, G. [2010] Using interpretation-driven velocity model building to improve subsalt imaging. *80th Annual International Meeting, SEG*, Expanded Abstracts.

Teng, K.H., J. Zhou, X. Wu, Y. Zhou, T. Brothers, S. Bergler and C. Gibson [2013] Gas cloud imaging using variable-depth streamer data, a case study from offshore Brunei. *83rd Annual International Meeting, SEG*, Expanded Abstracts.

Xie, Y., K. Xin, J. Sun and C. Notfors [2009] 3D prestack depth migration with compensation for frequency dependent absorption and dispersion. *79th Annual International Meeting, SEG*, Expanded Abstracts, 2919-2922.

Xie, Y., J. Sun, Y. Zhang and J. Zhou [2015] Compensating for visco-acoustic effects in TTI reverse time migration. *85th Annual International Meeting, SEG*, Expanded Abstracts.

Xin, K., and B. Hung [2009] 3-D tomographic Q inversion for compensating frequency dependent attenuation and dispersion. *79th Annual International Meeting, SEG*, Expanded Abstracts.

Zhou, J., X. Wu, K. Teng, Y, Xie, F. Lefeuvre, I. Anstey and L. Sirgue [2014] FWI-guided Q Tomography for imaging in the presence of complex gas clouds. *76th Annual International Meeting, EAGE*, Expanded Abstracts.