Imaging challenges at Gulf of Papua (PNG) and their solutions through high-end imaging technology

Zongying Gong*[,1], Subhash Chandra[2], Xiaodong Wu[1], Yajing Li[1], Min Zhi[1], Michael Szczepaniak[2], Barry Hung[1]

[1]CGG, 9 Serangoon North Avenue 5, Singapore
[2]Oil Search, 1 Bligh Street, Sydney, NSW 2000

**Corresponding author: Zongying.Gong@cgg.com*

SUMMARY

Recently, there has been increasing interest in exploration of the Gulf of Papua (GoP), part of the Papuan Basin. This Basin has undergone a complicated structural and stratigraphic evolution related to its position on the north-eastern edge of the Australian plate. The presence of shallow absorbing anomalies, as well as complex tilted fault blocks and a mud volcano makes velocity model building and seismic imaging challenging. The image underneath such shallow gas anomalies suffers from considerable wavefield distortion and amplitude loss. There are also clear fault shadows and structural ambiguity underneath complex tilted fault blocks, as observed on the vintage PSTM seismic data. All these challenges are caused by the complexity of velocity and/or absorption (Q) fields.

To overcome these challenges, we need to focus on two major aspects. Firstly, we need to derive a high-resolution velocity model. Full Waveform Inversion (FWI) is the state-of-art technology used to resolve velocity anomalies caused by shallow gas pockets. Supplemented by multi-layer non-linear tomography, a high-resolution velocity model is obtained from shallow to deep. Secondly, we need to build a high-resolution absorption model. Frequency shift Q tomography and FWI guided Q tomography are applied to estimate the total absorption field, which is used in Q migration (QPSDM) to compensate for amplitude loss and phase distortion. A significant imaging uplift has been achieved by these technologies. The prominent improvement of interpretability of the new processed QPSDM seismic data will potentially enable a better understanding of hydrocarbon prospectivity in this area.

Key words: Gulf of Papua, FWI, fault shadow, shallow gas, tomography, QPSDM.

INTRODUCTION

Exploration in the Gulf of Papua, Papua New Guinea has mainly been onshore and near-shore. More recently, there has been an increasing interest in the gas potential in the unexplored offshore area. There have been three gas and condensate discoveries based on 2D seismic surveys (Andrew et al., 2012). In 2010, 4400 km^2 of conventional 3D streamer data was acquired by PGS in Gulf of Papua (PGS Solwara MC3D, Figure 1). This survey is characterized by shallow gas anomalies and NE-SW-trending extensional faults, revealed by vintage PSTM processing (Andrew et al., 2012). A large part of the survey has a water depth of around 100 m. The sea bottom gradually deepens to ~1000 m in the south-eastern direction. There are small gas bodies spread out in the shallow area, highlighted with purple arrows in Figure 2a.

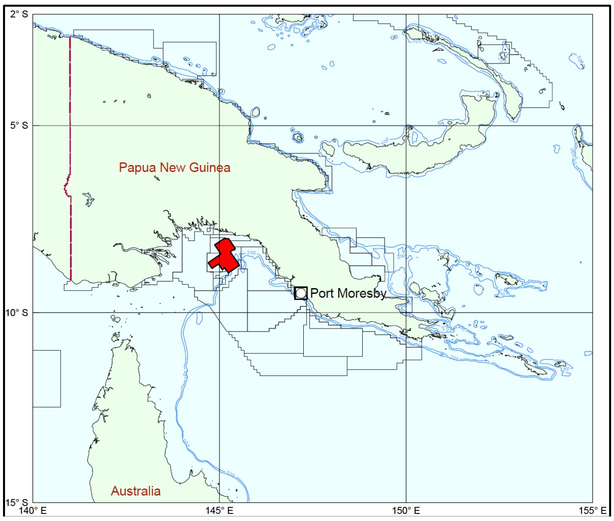

Figure 1. Solwara survey location (red).

The north-western part of the survey has multiple extensional faults starting from 250 m down to 5000 m in depth. These faults result in typical shadows in seismic images due to velocity variation across faults, creating significant structural distortions underneath the fault blocks. This issue is highlighted with a red arrow in Figure 2a. The fault shadow has significantly affected stratigraphic continuity and fault clarity in such a way that it makes horizon correlation across fault blocks challenging. In the middle part of the survey, there is a so called “mud volcano” developed in the area highlighted with the yellow rectangle in Figure 2a. It is characterized by slower velocity than its surroundings. Further to the southeast of the survey, a large zone of particularly poor imaging underneath the shelf edge is also observed with serious structural distortion and amplitude dimming. This is caused by a large diffuse gas cloud beneath the water bottom. The issue is highlighted with the blue dash lines in Figure 2a. It is essential to derive high resolution velocity/Q model in order to improve imaging.

To address all of these challenges, we adapted a comprehensive processing flow for high-resolution velocity and absorption inversion. For velocity, we first used Full Waveform Inversion (FWI) to resolve the shallow gas velocity. This was followed by non-linear tomography to update the velocity from the middle to the deep sections of the

whole survey. For the Q model, we used frequency-shift Q tomography (Xin et al., 2014) to invert the background Q and FWI guided Q tomography (Zhou et al., 2014) to obtain a Q anomaly model for compensating amplitude/phase distortion due to absorption.

BUILDING THE HIGH RESOLUTION VELOCITY

The starting model for FWI is from the 2010 vintage PSTM velocity converted to depth with proper smoothing. Here, diving waves are the main driver for the FWI. Special care has been taken to precondition the input data at the low frequency end: dipole sparse tau-p inversion was applied to attenuate the low-frequency noise. A reasonable signal-to-noise ratio can be seen for data from 5Hz, which was used as the starting frequency for FWI. To avoid cycle skipping, dynamic warping FWI (Wang *et al.*, 2016) was used. We carried out the inversion up to 7.5 Hz with a frequency step of 0.5Hz. A high resolution update of velocity has been achieved capturing all of the shallow gas bodies, faults and channels (Figure 3). It is revealed that the slowest velocity within the gas could be as low as 1400 m/s. In this survey with a streamer length of 6km, most diving waves bend upwards above 1250 m. Therefore FWI is used mainly for velocity updates at shallow sections. High resolution non-linear tomography was then used for deeper velocity update.

Non-linear tomography offers various solutions for velocity updates beyond diving wave FWI penetration (Guillaume, 2003). Compared to linear tomography, it has multi-layer update capabilities and kinematic de-migration/re-migration functions, which provides more effective and efficient velocity updates. As mentioned previously, there are large NE-SW trending extensional faults developed in this survey with a clear indication of fault shadows seen in the vintage PSTM data set. The key to address this issue is to derive a high resolution velocity model, which can resolve the velocity contrast across the fault. A dense grid of 50x50 m common image gathers (CIGs) was produced for curvature picking. Careful QC / high grading was done to ensure high quality RMO information was fed into the inversion engine. The inverted velocity has a very good correlation with the tilted fault block. A velocity contrast of up to 400 m/s can be observed across the faults. After several iterations of multi-layer tomographic inversion, we obtained sufficient velocity accuracy to resolve fault shadows and the final high resolution velocity model is shown in Figure 4b. Structural distortion underneath the faults has been corrected and event continuity improved as seen in the new seismic data (Figure 2b).

Another challenge we encountered is the mud volcano at around ~5 km deep which causes a push-down effect of the events beneath it as shown in the 2010 PSTM result (Figure 2a, highlighted in the yellow rectangle). Complex structures like these are usually associated with velocity anomalies. Recently, we have developed non-linear scanning tomography to update velocity anomalies in deep sections without much of manual interference (Gong *et al.,* 2018). We defined a scanning area inside the mud volcano. As we expected the velocity would be slower than the sediment velocity around it, we did a percentage scan of velocity inside the defined area from 70% to 105% with 5% intervals while keeping the velocity outside unchanged. We then performed CIG picking on each migration result with the different scanned velocities. These CIG picks were de-migrated kinematically to create the invariant files which include source-receiver locations, travel time etc. These pieces of information were then combined and fed into the non-linear tomography, which gave us a more reliable velocity model (Figure 4b). Migration with this velocity resulted in significant improvement of the continuity and event focus of the image (Figure 2b).

BUILDING THE ABSORPTION MODEL

For background Q estimation, we used the adaptive centroid frequency shift Q tomography developed by Xin et al. (2014). The method introduces an adaptive correction to the observed centroid frequency to account for any deviation from the explicit relationship. During tomography, these adaptively corrected centroid frequency shifts can then be back-projected along the ray path to reconstruct the attenuation distribution. The resulting background Q model can be used in the Q migration to compensate frequency dependent attenuation. The estimated background Q factor for this particular survey ranges from 100 to 200.

To image through the gas cloud, we also incorporated an Q anomaly model to compensate for the energy losses and phase distortion, in addition to the background Q. Inspired by previous successful cases (Lin et al., 2016; Zhou et al., 2014), we adopted the FWI-guided Q tomography for the anomaly absorption model. We first created a mask from the FWI velocity model according to its abnormal slowness. This mask was used as a constraint when we applied Q tomography (Xin and Hung, 2009). During the inversion process, the attenuation effect was accumulated within this mask. This technique has been working well in areas with shallow gas anomalies. An extremely low Q factor has been inverted just underneath the shelf edge due to the strong absorption effect. It is worthwhile to mention that another latest technology of absorption inversion called "QFWI" (Xiao et al., 2018) has also been tested at a small swath. The test result shows that both methods are able to produce consistent absorption models while the result from QFWI has higher resolution. Due to time constraint, QFWI has not been applied in full production on this project. The final total absorption model combining the background Q model and Q anomaly model is shown in Figure 4c.

With an accurate velocity and a total Q model, Q migration (Xie et al., 2009) was used for the final migration. The final imaging result shows significant uplift compared to vintage PSTM data. In the shallow section, gas bodies are better defined and more recognizable. The faults are better positioned and stratigraphic continuity of the events between faults is improved. In the deep section, the non-geological structure undulation is eliminated. The amplitude loss due to massive diffuse gas under the shelf edge is recovered. The new result leads to a more accurate interpretation across the whole survey from the shallow water environment to the deepwater area (Figure 2b).

CONCLUSIONS

We have presented a case study from the Gulf of Papua where a number of imaging challenges have been identified in the vintage PSTM data. Realizing that all of the imaging issues were attributed to the complexity of the velocity and Q fields, a tailored processing flow is applied. The flow includes technologies such as 1) a hybrid FWI / tomographic update flow to obtain a high-resolution velocity field from shallow to deep; 2) a combined frequency and amplitude analysis based inversion scheme to resolve an accurate Q model; 3) Q depth

migration to account for velocity complexity and absorption. It has been demonstrated that the new processed seismic data has corrected non-geological structure undulation and improved amplitude consistency. The newly processed data will potentially enables a better understanding of hydrocarbon prospectivity in this region.

ACKNOWLEDGEMENTS

We thank CGG for permission to publish this work. We also thank Oil Search and PGS MultiClient for granting the show rights for the data used in this paper, and for their suggestions throughout the course of this project.

REFERENCES

Andrew, B., Larry, E., and Amanda, H., 2012, Structural and Stratigraphic Evolution of the Gulf of Papua, Papua New Guinea: New Insights from a Modern 3D Seismic Survey: Search and Discovery Article, #10456.

Gong Z., Wu X., Lin, Y.N., Benfield N., and Alperin, P.J., 2018, Non-linear scanning tomography for velocity model building in seismic-obscured areas: SEG Technical Program Expanded Abstracts 2018: pp. 5128-5132.

Guillaume, P., 2003, Methods of tomographically inverting picked events on migrated seismic data: U. S. Patent 6 557 955 B2.

Hung, B., Wang, X., Phan Y.P., Alai, R., Xin, K., He, Yi., Rahman, N.N., and Tang W.H., 2015, Full broadband processing including total Q compensation in the presence of gas: SEG Technical Program Expanded Abstracts 2015: pp. 4080-4084

Lin, Y. N., Wu, X., Xie, Y., Zhou, J., Sulaiman, S., Turner, J., and Wei, Z., 2016, Imaging through Mega Gas Clouds in Offshore Brunei: 78th Conference and Exhibition, EAGE, Extended abstract, doi: 10.3997/2214-4609.201601350.

Wang, M., Xie, Y., Xu W.Q., Xin, K.F., Chuah, B.L., Loh, F.C., Manning, T., and Wolfarth, S., 2016, Dynamic-warping full-waveform inversion to overcome cycle skipping: 86th Annual International Meeting, SEG, Expanded Abstracts, 1273-1277.

Xin, K., and Hung, B., 2009, 3-D tomographic Q inversion for compensating frequency dependent attenuation and dispersion. 79th Annual International Meeting: SEG Technical Program Expanded Abstracts 2009: pp. 4014-4018.

Xin, K., Xie, Y., and He, Y., 2014, Adaptive Centroid Frequency Shift Q Tomography: 76th EAGE Conference and Exhibition 2014, doi: 10.3997/2214-4609.20141402

Xie, Y., Xin, K., Sun, J., Notfors, C., Biswal, K., and Balasubramaniam, M., 2009, 3D prestack depth migration with compensation for frequency dependent absorption and dispersion: 79th Annual International Meeting, SEG, Expanded Abstracts, 2919–2923.

Zhou, J., Wu, X., Teng, K., Xie, Y., Lefeuvre, F., Anstey I., and Sirgue, L., 2014, FWI-guided Q Tomography for imaging in the presence of complex gas clouds: 76th Annual International Meeting, EAGE, Expanded Abstracts, doi: 10.3997/2214-4609.20141081.

Xiao, B., Ratcliffe, A., Latter, T., Xie, Y., Wang, M., 2018, Inverting Near-Surface Absorption Bodies with Full Waveform Inversion: a Case Study from the North Viking Graben in the Northern North Sea: 80th Annual International Meeting, EAGE, Expanded Abstracts, doi: 10.3997/2214-4609.201800681.

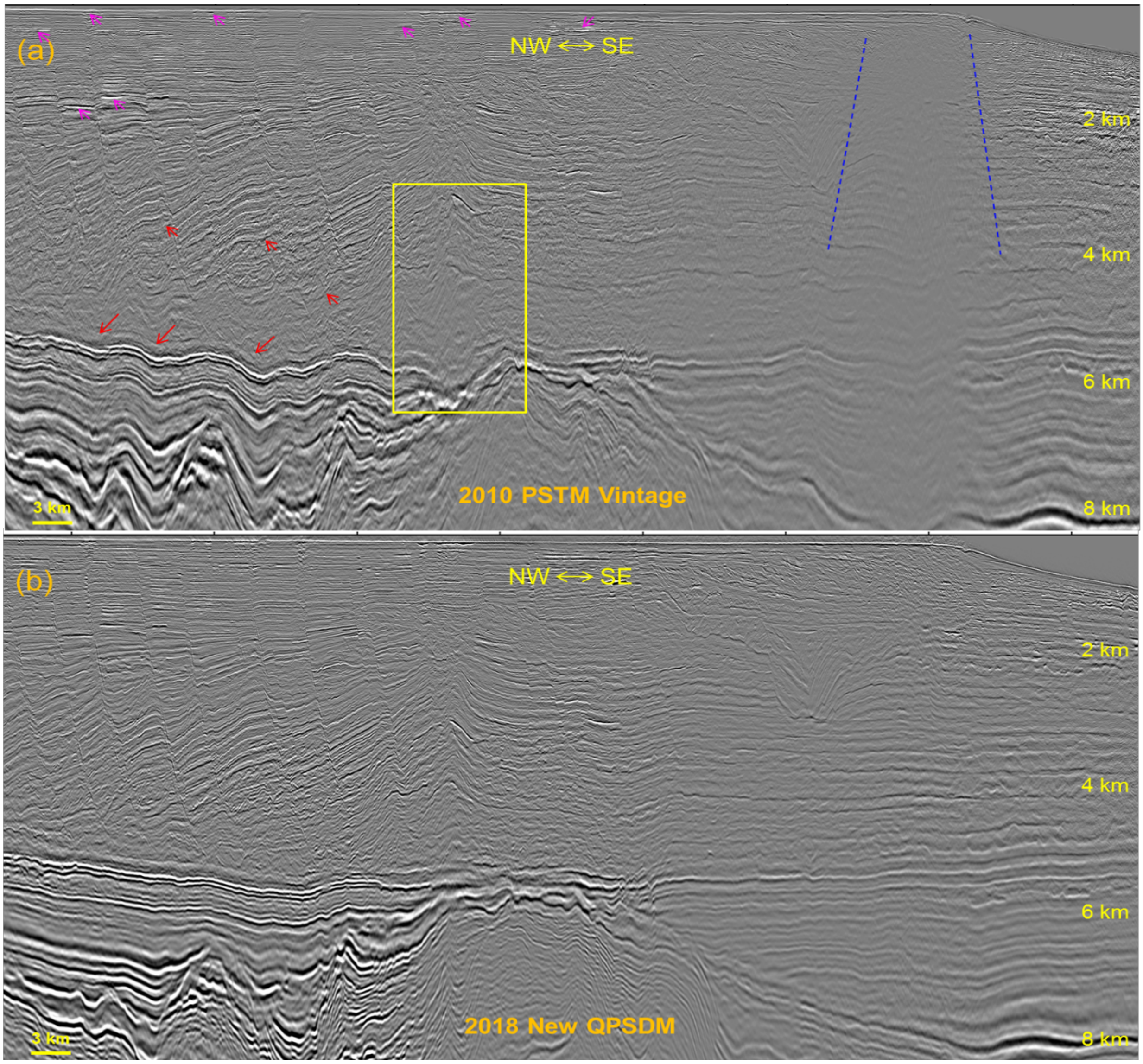

Figure 2. Final result comparison. (a) 2010 vintage PSTM (converted to depth); b) 2018 new QPSDM (Data courtesy of PGS).

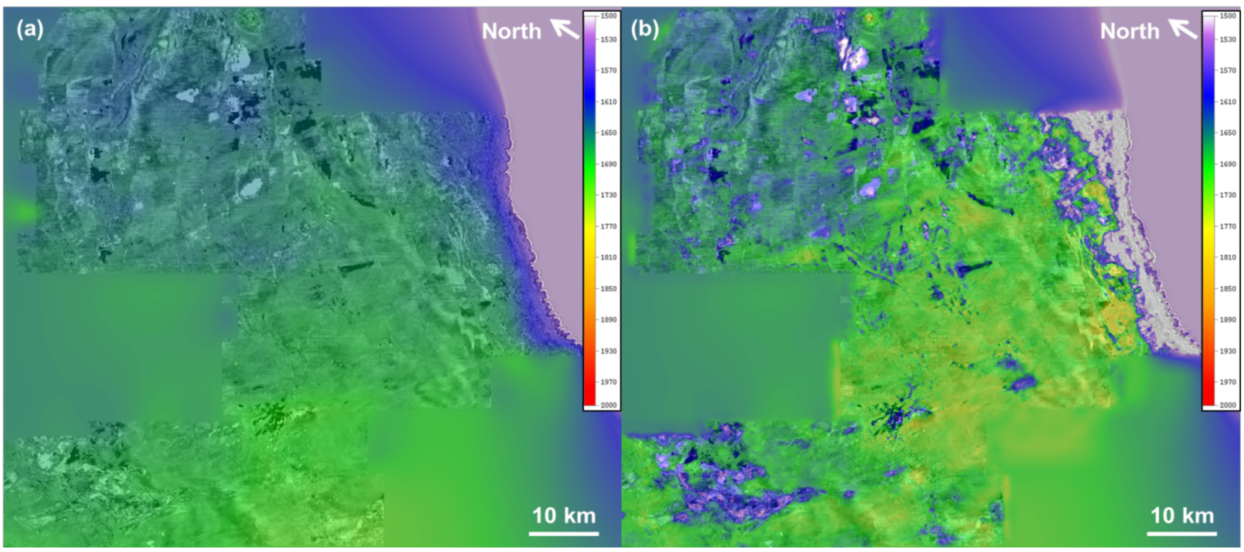

Figure 3. Comparison of velocities at 300 m depth slice before (a) and after (b) FWI inversion (Data courtesy of PGS).

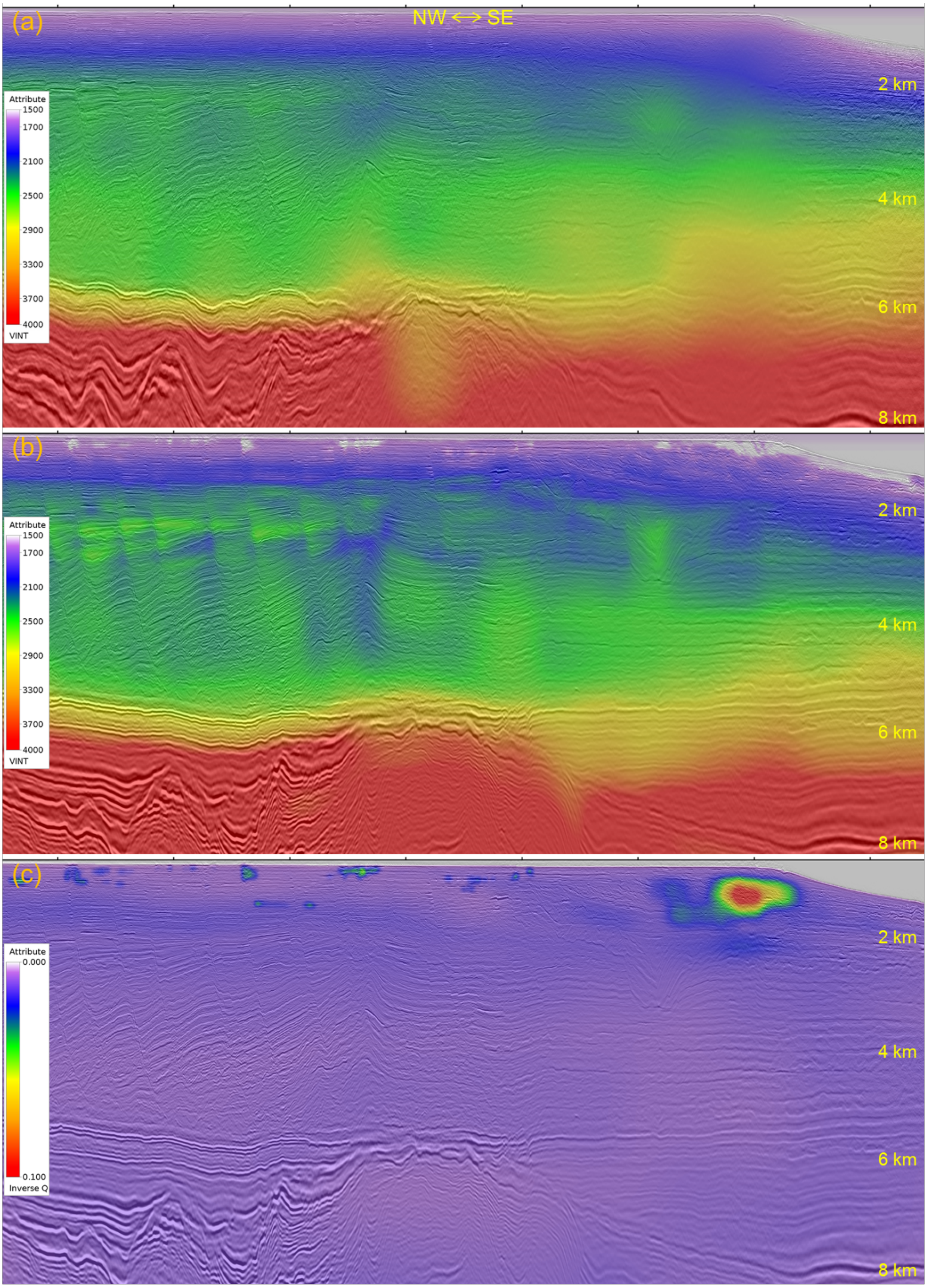

Figure 4. Velocity and Q model comparison. (a) Initial velocity from 2010 vintage PSTM; (b) 2018 final velocity overlaid on final stack; (c) 2018 final inverse Q model overlaid on final stack (Data courtesy of PGS).