



Success and opportunities of advanced full-waveform inversion on ocean bottom seismic data

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ABSTRACT

The latest full-waveform inversion (FWI) developments and their application on ocean bottom seismic (OBS) field data sets are discussed in this paper. Geological complexity including shallow gas absorption, strong azimuthal anisotropy and substantial velocity heterogeneity can result in severe subsurface imaging degradation which hinders hydrocarbon exploration. OBS is a preferred acquisition solution to improve sub-surface imaging and provide new insight for exploration in complex environments. FWI is the natural choice for velocity updates using OBS data. To maximize the value of OBS data, new developments of advanced FWI algorithms have been implemented to tackle different geological challenges. Visco-acoustic time-lag FWI (Q-FWI) has been developed to address gas absorption issues. Orthorhombic time-lag FWI (ORT-FWI) has also been implemented to tackle strong azimuthal anisotropy. We demonstrate how the OBS acquisition and advanced FWI algorithms together produce a high-resolution velocity model that effectively solves the imaging challenges and enhances the exploration potential in several real data examples.

KEYWORDS

Ocean-bottom seismic, time-lag FWI, Orthorhombic time-lag FWI, visco-acoustic time-lag FWI

INTRODUCTION

OBS has emerged as an acquisition solution to improve sub-surface imaging and provide new insight for exploration in complex environments. For velocity model building, OBS data sets provide rich low frequency signals, full-azimuth coverage, and long-offset illumination, making them ideal for building a reliable velocity model using FWI. The long offsets allow for deeper penetration of diving waves, which mainly drive FWI updates. The full azimuth coverage better constrains the inversion and improves its reliability, and the rich low frequency content alleviates some of the cycle-skipping issues caused by an inaccurate starting velocity model. Further, with the advance of processing technology and computing capacity, the multi-

component recordings in OBS data sets enable both pressure-wave imaging (PP imaging) and converted-wave imaging (PS imaging).

THEORY/METHOD

FWI is an elegant and natural way to handle full-wavefield data which can generate all wave modes, including diving waves, primaries, ghosts, and both surface and internal multiples. The time-lag FWI cost function (TLFWI, Zhang et al., 2018) has proven to be a robust FWI algorithm to tackle the challenges of velocity model building for complex structures. Its advanced algorithm can better tackle problems such as cycle skipping and amplitude mismatch which has greatly widened FWI applications on different data types and in different geological settings (Shen et al., 2017; Zhang et al., 2018; Wang et al., 2019). Its application on OBS data is particularly successful given its full-azimuth and long-offset coverage.

The presence of azimuthal anisotropy can pose severe challenges to imaging with wide-azimuth (WAZ) OBS data, in particular when imaging fault planes, which are very sensitive to velocity errors. The fault images can be smeared and fault shadows observed within complex strike-slip fault systems if the azimuthal dependency of wave propagation is not properly modeled and velocity variations across faults are not properly resolved. To address these kinds of imaging challenges, we have developed a practical orthorhombic FWI approach to reconstruct high-resolution models in the presence of azimuthal anisotropy (Xie et al., 2017). Orthorhombic full wavefield modeling was incorporated into TLFWI, such that it can lead to a more accurate velocity update.

Gas pockets and channels in the near surface are commonly present in many geological settings. They can introduce strong kinematic distortions, as well as amplitude loss due to spatial velocity variation and absorption (Q) effects. To compensate for the kinematic

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distortion and amplitude loss from this shallow overburden, both the velocity and Q models need to be accurately estimated (Wang et al., 2018). Visco-acoustic wave propagation was incorporated into TLFWI to honor the visco-acoustic effects. This allows us to jointly update the velocity and Q models, reducing crosstalk between velocity and Q in the inversion process.

RESULTS

The first data example is located at Bohai Bay, offshore China. This is a challenging area for seismic imaging due to the presence of substantial velocity heterogeneity and strong azimuthal anisotropy in both the overburden and reservoir layers. Driven by the need for high quality seismic imaging for exploration and field development, a WAZ, long-offset, OBS survey was acquired in 2019.

The WAZ illumination and higher signal-to-noise ratio (S/N) provided by the OBS data not only improved the stacking power but also provided the chance for detailed orthorhombic anisotropy modeling, a key to successful FWI application in this area. To build an accurate anisotropic model for the overburden, we separated the WAZ OBS data into 6 azimuthal sectors, performing VTI TLFWI and reflection tomography to update the velocity separately for each azimuthal sector. After this, the 6 VTI models were used to derive the orthorhombic model through elliptical fitting. ORT-FWI using the TLFWI cost function was then performed using the full-azimuth data (maximum frequency of 9Hz). The velocity update revealed geological anomalies such as shallow gas pockets, sharp velocity contrast across fault planes, and volcanic features (Figure 1). Compared with the legacy streamer pre-stack depth migrated (PSDM) images, Figure 2 shows the final OBS PSDM images using the final ORT-FWI model improved the S/N of the fault and volcanic systems in the overburden (red circles in Figures 2a-2b) and revealed important fractures inside the basement reservoir (red arrows in Figures 2a-2b), which were completely missing in the streamer results. The reservoir distribution is highly correlated to the fracture behavior near the top basement (Figure 2c). Very dense fractures were observed at two successful wells, while the dry well was located in a poorly developed fracture area. The improved images may shed light on drilling results and will offer new insights into future well planning.

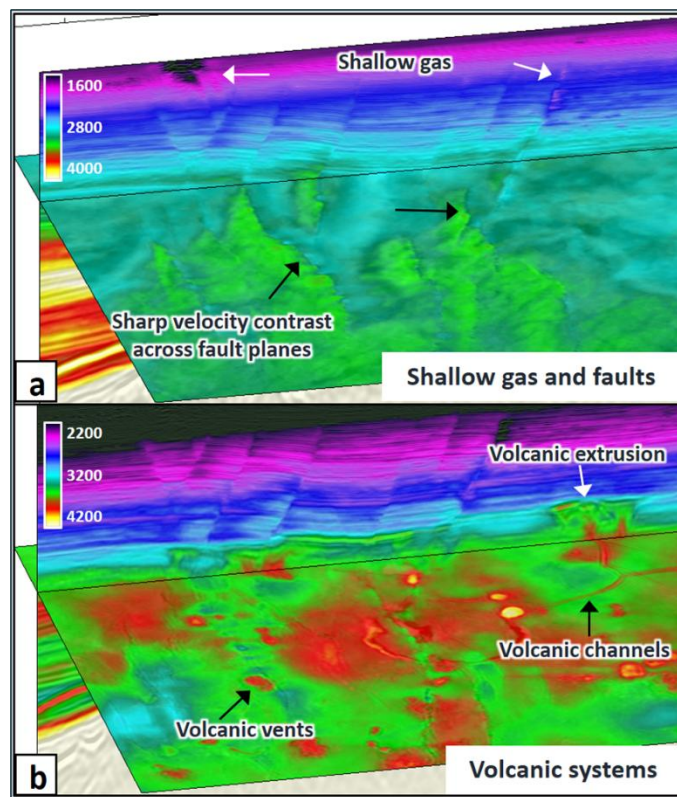


Figure 1: ORT-FWI captures velocity details of (a) the shallow gas and faults, and (b) the deeper complex volcanic system.

The second data example is located at Yinggehai basin of South China Sea. Vintage seismic data has suffered severely from complex structures, particularly the strong absorption from shallow gas and a diapir formed by thermal fluids. Shallow gas can introduce strong kinematic distortion and amplitude loss. A modern OBS acquisition was carried out in 2021 with maximum offsets of 16 km. Q-FWI (maximum frequency of 12Hz) using the TLFWI cost function was applied to this dataset. It allowed us to jointly update the velocity and Q models. Figure 3a shows the PSDM stack using OBS data and the vintage streamer smooth velocity (this model is the starting point for the FWI update). Structural sagging and amplitude dimming combined with lower resolution is observed when compared to the neighboring area less affected by the shallow gas channels. With the updated high-resolution velocity (Figure 3b) and inverse Q model (Figure 3c) inverted by Q-FWI, the kinematic distortions and amplitude loss at the core of the diapir zone are well corrected in the Q-compensated PSDM stack (Figure 3b and 3c). The frequency content is now more consistent with the adjacent area that suffers less from attenuation effects.

Figures 3d and 3e show the depth slices of the inverted velocity and inverse Q models at 240 m, demonstrating

that the inverse Q model is high resolution and consistent with the geological features of the area.

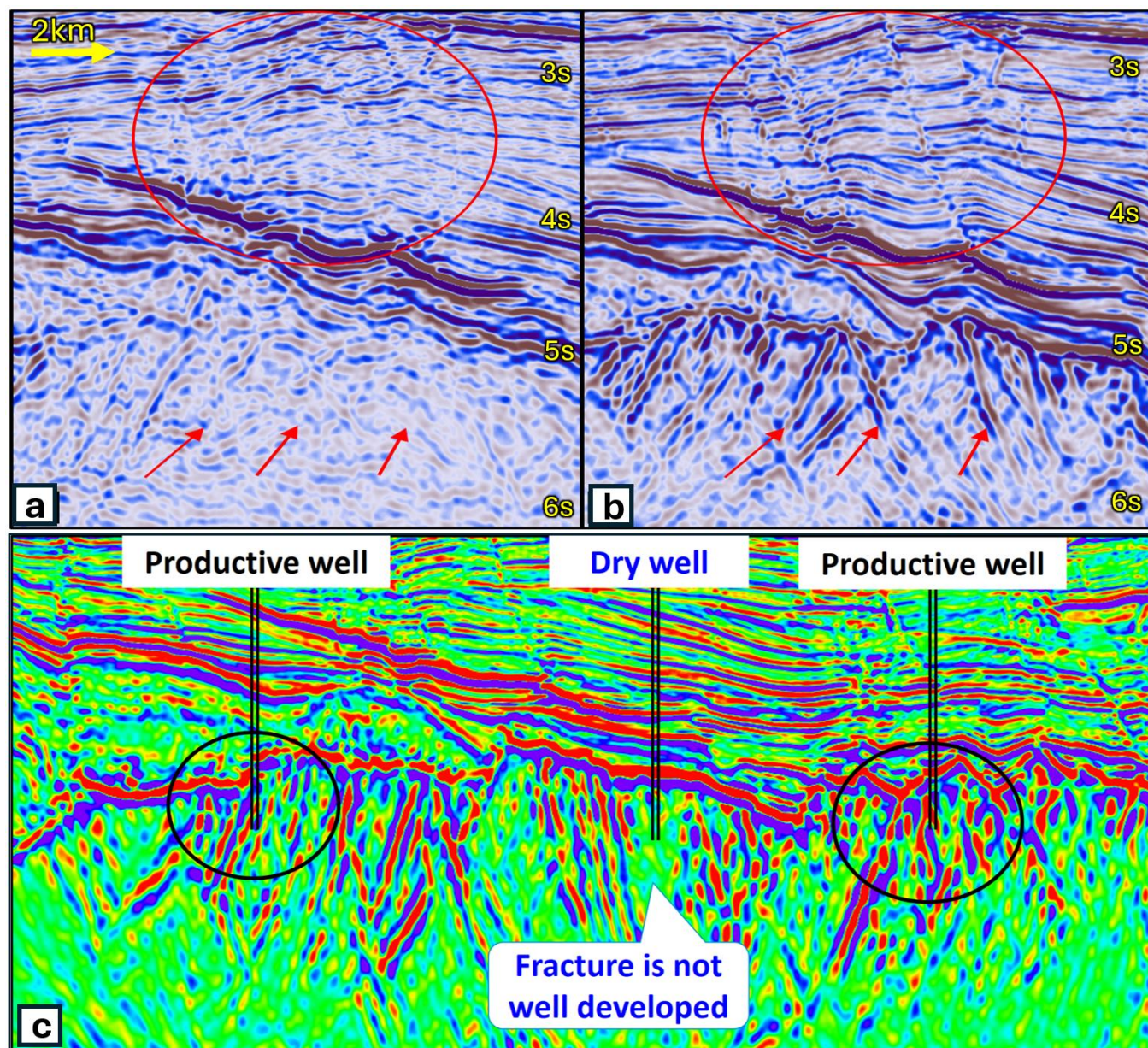


Figure 2: Section display of (a) the legacy streamer PSDM image, and (b) the OBS PSDM image. (c) The improved images provide good consistency with the drilling results.

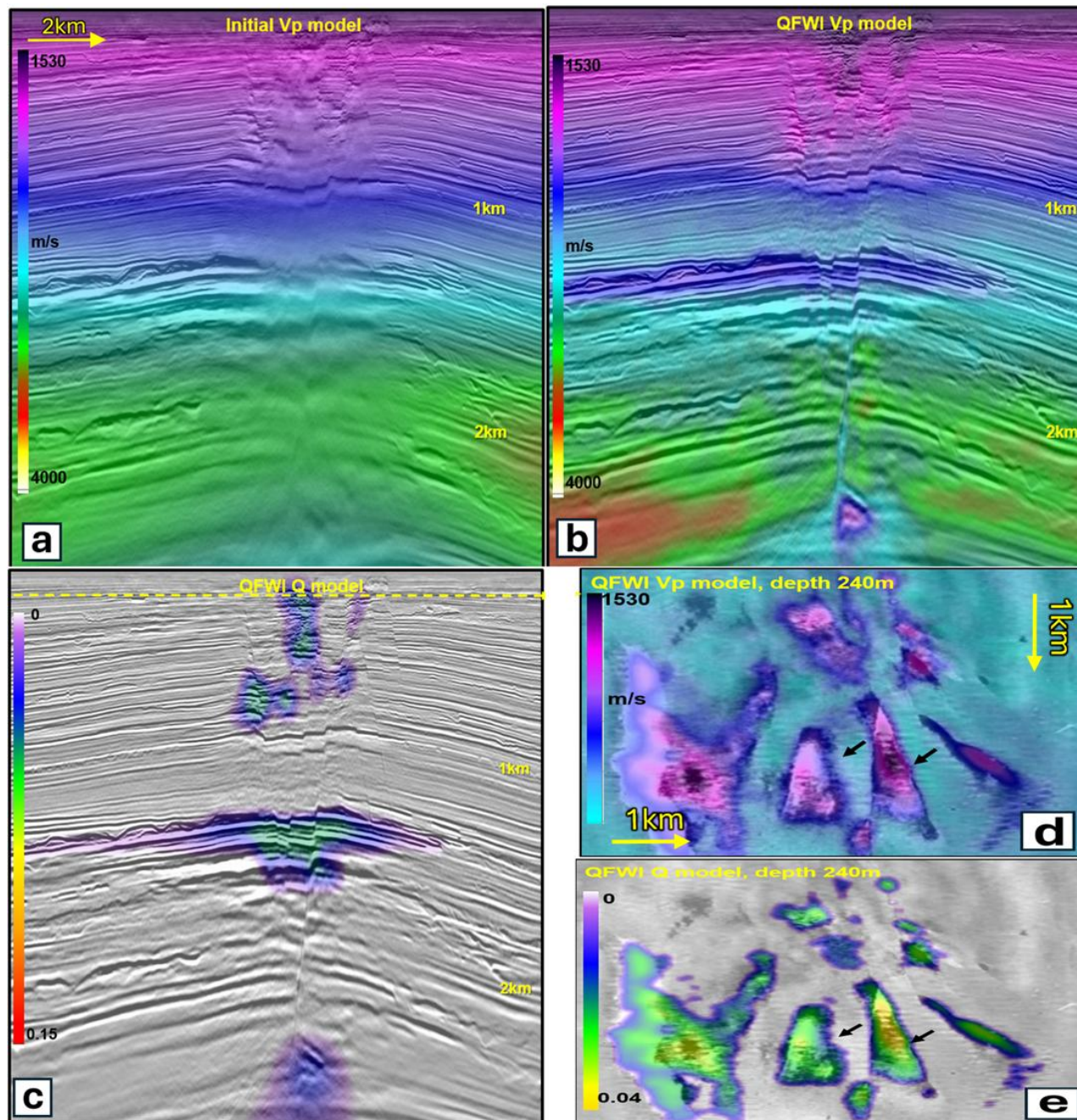
DISCUSSION

Both PP and PS imaging are important to realize the full potential of OBS data. In the above work we have concentrated on the PP image with P-wave velocity updates. S-wave velocity model building is a critical and

difficult step in PS imaging. Conventional model building technology like PP-PS joint interpretation-based image registration, and PP-PS joint tomography, can suffer from practical challenges such as an ambiguity of PP and PS event correspondence and poor-quality PS common-image gathers from uneven

PS angle illumination. PS reflection-FWI (PS-RFWI) (Wang et al., 2021) for S-wave velocity updates has been developed to address some of these concerns. PS-RFWI updates the S-wave velocity by minimizing the kinematic difference between the modeled and

recorded PS reflections, while keeping the P-wave parameters unchanged. Compared with conventional methods, PS-RFWI can deliver a superior PS image to further take advantage of the data OBS surveys provide.



(a) PSDM stack using the vintage streamer velocity with the vintage streamer velocity model overlaid. (b) Q-compensated PSDM stack with Q-FWI velocity model overlaid. (c) Q-compensated PSDM stack with Q-FWI 1/Q model overlaid. (d) Depth slices at 240 m of Q-FWI velocity overlaid. (e) Depth slices at 240 m of Q-FWI 1/Q overlaid.

CONCLUSIONS

Rich azimuth illumination provided by OBS data can help better evaluate azimuthal anisotropy effects and ORT-FWI can subsequently greatly improve velocity model resolution. Visco-acoustic effects in the Earth can be captured by Q-FWI, which can invert for a high-resolution Q anomaly model which can subsequently be used in a Q-compensating migration. WAZ and long-offset OBS acquisition combined with advanced FWI algorithms can effectively resolve the geological complexity and provide a step-change improvement for subsurface imaging in different geologic settings. Finally, FWI with full elastic modeling for joint Vp and Vs updates would be the ultimate solution and present even more opportunities ahead. 

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BIOGRAPHIES



Xiaodong Wu received his Ph.D. in electrical engineering from the National University of Singapore in 2008. He began his career as a geophysicist with Viridien (previously CGG) and is currently serving as Imaging Supervisor at Viridien Singapore. Xiaodong has extensive experience in high-end 3D marine imaging projects across the Asia-Pacific region, working with both streamer and ocean-bottom seismic (OBS) data. He has been actively involved in technological development and has contributed to advancements of FWI and least-squares migration.



Yitao Chen received his M.Sc. degree in solid mechanics from Peking University in 2014. He commenced his professional career as a geophysicist at Viridien (previously CGG) and now serves as an Imaging Supervisor at Viridien Singapore. With wide experience across the Asia-Pacific and Middle East regions, he has worked on marine, land, and ocean-bottom seismic (OBS) PP/PS imaging projects. His professional activities involve technological enhancements, particularly in advancing full-waveform inversion (FWI) and multi-component processing techniques.



Jian Cai received his Ph.D. in geophysics from the University of Science and Technology of China (USTC) in 2015. He began his career as a geophysicist with Viridien (previously CGG) and is currently serving as Team Leader at Viridien Singapore. He has extensive expertise in deblending and advanced 3D seismic imaging across the Asia-Pacific region, with hands-on experience in both towed-streamer and ocean-bottom seismic (OBS) acquisitions. His work has been integral to the development and refinement of cutting-edge algorithms, particularly in Full Waveform Inversion (FWI) and deblending methodologies.



Min Wang received her M.Sc. and Ph.D. degrees in engineering mechanics from Tsinghua University, China. She is currently a Senior Research Advisor at Viridien (CGG), Singapore. She began her career as an imaging geophysicist and has been part of the R&D team since 2009, working on a wide range of topics including interbed multiple modeling and attenuation, deblending, and velocity model building. Her recent research focuses on full-waveform inversion (FWI), covering areas such as multi-parameter joint inversion, enhancing the contribution of reflections for deep targets, visco-acoustic FWI to account for absorption effects, and shear-wave velocity inversion using PS-converted waves—challenges that are particularly relevant in the APAC region. She is an active member of EAGE.



Dun Deng received his master's degree in geophysical prospecting and information technology from China University of Petroleum (East China), specializing in research and management of geophysical exploration technologies and methodologies.



Peipei Deng received her Ph.D. in industrial and systems engineering from National University of Singapore in 2013. She began her career as an imaging geophysicist since then and she is currently the Imaging Manager of Singapore center at Viridien Singapore. Peipei has extensive experience in various imaging projects across the Asia-Pacific region, including marine streamer acquisition, ocean-bottom seismic, land and transition zone surveys. She has been actively involved in the new technology deployment in production projects, especially in full-waveform inversion.



Yi Xie received his B.E. degree from University of Science and Technology of China and a Ph.D. from Tsinghua University, China, both in precision measurement. He began his career as a research geophysicist with Veritas DGC, where he is currently serving as Research Manager for Viridien (CGG), Singapore. His recent research focuses on seismic imaging and inversion, FWI and model building. He is an active member of SEG.

Answers to Geo-Quiz on page 160.

