REVEALING COMPLEX SUB-BASALT STRUCTURES OFFSHORE INDIA THROUGH ADVANCED SEISMIC PROCESSING

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Summary

Sub-basalt seismic imaging is very challenging due to large impedance contrasts at sediment-basalt interfaces. The impedance of basalt usually gives a strong reflection coefficient at the top of basalt, and thus generates strong multiples. Offshore western India, this issue is compounded by short-period seabed multiples generated by the shallow sea floor. Moreover, the presence of the basalt layer limits the angle of reflections from sub-basalt structures, making velocity modeling difficult. The combination of strong, complex multiples and the challenges of obtaining a reliable velocity model gives rise to poor imaging beneath and within the basalt. In this study, a comprehensive pre-migration demultiple flow was devised to tackle the strong surface and interbed multiples. For velocity model building, full-waveform inversion (FWI) was applied for the shallow velocity update and non-linear scanning tomography was then utilized to update the velocity within and beneath the basalt layer. Due to the poor initial velocity model, an enhanced dynamic-warping FWI approach was used to mitigate the cycle-skipping issue, and the maximum FWI frequency was extended to 20 Hz. With the benefits from the comprehensive demultiple process and advanced velocity model building, imaging of the complex sub-basalt structures in this area was improved.

Introduction

Sub-basalt Mesozoic sediments in offshore western India are very important hydrocarbon reservoirs (Fainstein et al., 2019). However, the heterogeneous, high-velocity nature of the basalt layer poses a challenge to seismic imaging. Besides being the cause of scattering and absorption of seismic energy and mode conversion (Kumar et al., 2012), the basalt layer generates sub-basalt multiples that hinder interpretation of the reservoirs (Kumar et al., 2004) and make it difficult to obtain a reliable velocity model within and beneath the basalt (Talukdar and Behera, 2018).

Due to the high impedance contrast between the sediment and the basalt, the top and base of basalt are strong generators for both surface-related and interbed multiples. Moreover, in this case study, the shallow seafloor, which varies from 70 m to 120 m, generates strong short-period, multi-order peg-leg multiples. These multiples severely mask the sub-basalt structures. Imaging is made even more challenging when the data is not suitable for the application of advanced velocity model building (VMB) tools. Ideally, long-offset, full-azimuth data with rich low-frequency content would be used for modelling the velocity within the basalt. However, the available data for this study was acquired using a narrow-azimuth variable-depth streamer configuration (12 – 30 m), with maximum offsets of 8100 m. These data limitations present a difficult task for updating the velocity model.

To handle the above-mentioned issues for better imaging of the sub-basalt structures, we present a comprehensive demultiple workflow that involves a curvelet-domain joint subtraction of short-period shallow water multiples, long-period surface-related multiples and interbed multiples, and an advanced VMB flow that includes enhanced dynamic-warping full-waveform inversion (FWI) and non-linear scanning tomography. Significant imaging improvements were observed, which allows for better delineation of the sub-basalt structure for interpretation and reservoir characterisation.

Comprehensive pre-migration multiple attenuation workflow

A comprehensive demultiple workflow was devised for this study, including hybrid shallow water demultiple (HSWD) (Yang and Hung, 2013), 3D surface-related multiple elimination (SRME) (Lin et al., 2005), and inverse scattering series (ISS) demultiple (Wang and Hung, 2014). HSWD was first used to predict the short-period multiples related to the water bottom and other shallow reflectors. By combining the estimated Green's function of sea floor reflections, HSWD was able to overcome the near offset data gaps due to the survey's wide tow (10 cables with 100 m cable separation) and very shallow sea floor (70 m ~ 120 m), and therefore predict a reliable short-period multiple model. With a priori removal of short-period multiples, 3D SRME was then able to predict a more reliable long-period multiple model with less cross-talk. Adaptive subtraction was done in the 3D curvelet domain, where primaries can be better separated from multiples than in the spatial-time domain (Wu and Hung, 2013). Additionally, ISS and high-resolution radon demultiple were also applied to further attenuate interbed and other residual multiples prior to migration.

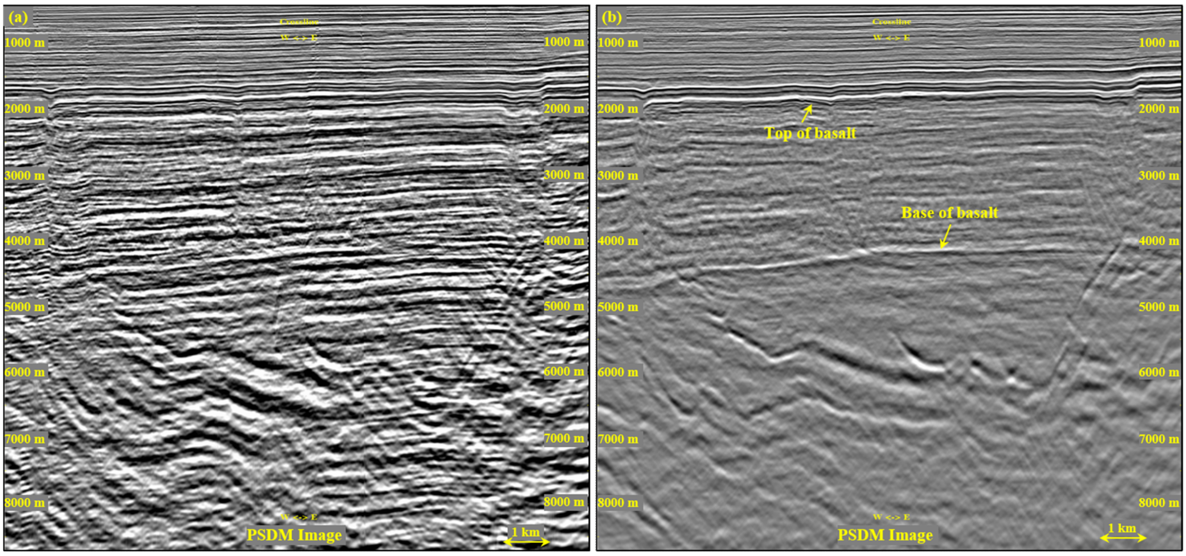

Figure 1 *Comparison of: (a) PSDM image before multiple attenuation; and (b) PSDM image after the comprehensive pre-migration demultiple process.*

Figure 1 shows the comparison of pre-stack depth migration (PSDM) images before and after the proposed demultiple flow. For illustration purposes, both PSDM images were migrated using the final velocity model. As shown in Figure 1a, seismic reflections from sub-basalt structures were masked by strong multiples due to the specific geological features in this area. By applying the comprehensive demultiple workflow, the multiples were effectively attenuated, and thus the PSDM image was significantly improved from shallow to deep (Figure 1b).

High-resolution velocity model building

I. Shallow velocity update using enhanced dynamic-warping FWI

FWI was applied to update the shallow velocity model using an enhanced dynamic-warping approach to handle the cycle-skipping issue (Wang et al., 2019). Figure 2 shows the comparison of the initial velocity model and different FWI models, all of which were run from 3 Hz to 8 Hz. The initial velocity model for FWI was from the legacy model after correcting water velocity (Figure 2a). The comparison shows that conventional FWI suffered from significant cycle-skipping, resulting in an unrealistic model (Figure 2b) even though the inversion started from 3 Hz. Enhanced dynamic-warping FWI (DFWI) was able to overcome this issue, and therefore produced a more reliable velocity model that correlated well with geological structures (Figure 2c). Enhanced DFWI also successfully recovered the fast velocity layer in the shallow part due to the presence of limestone, while the velocity for this section is too slow in the initial model.

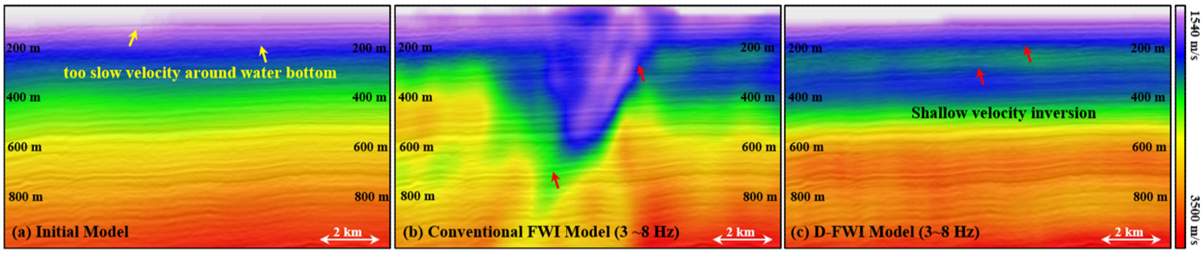

Figure 2 *Comparison of velocity models overlaid on final PSDM image: (a) Initial velocity model; (b) conventional FWI velocity model (3~8 Hz); (c) enhanced DFWI velocity model (3~8 Hz).*

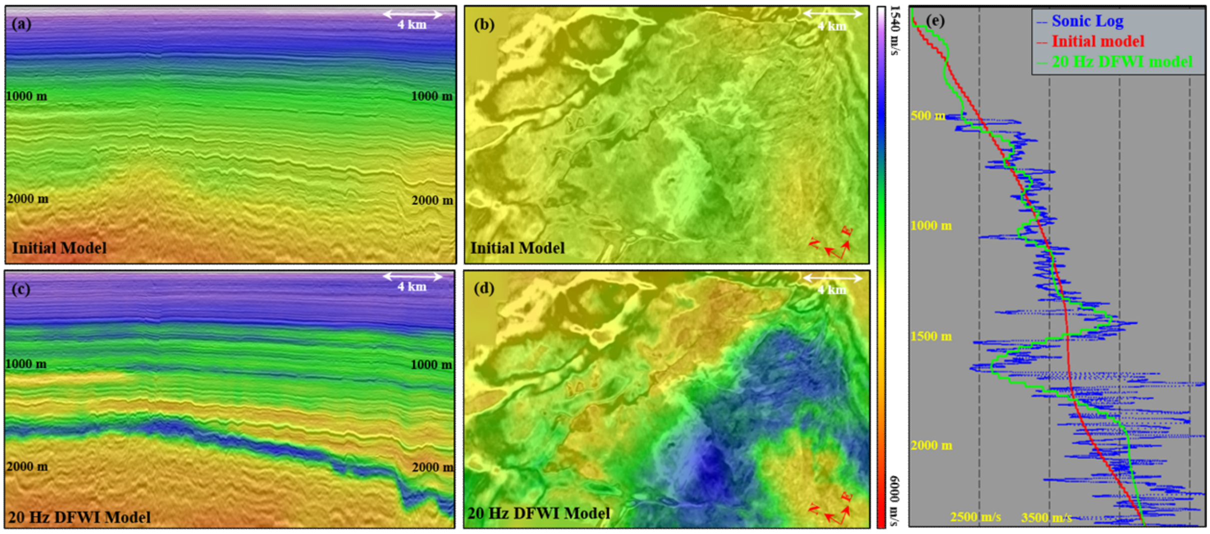

Figure 3 *Comparison of velocity models overlaid on final PSDM image: (a) Vertical section and (b) depth slice at 1700 m of initial velocity model; (c) Vertical section and (d) depth slice at 1700 m of 3~20 Hz enhanced DFWI velocity model; and (e) comparison between velocity models and sonic log.*

The maximum frequency of FWI was extended to 20 Hz to obtain a high-resolution velocity model (Figures 3c and 3d). The shallow structures here are dominated by gentle dipping layers (as shown in Figures 3a and 3b), and there are multiple velocity inversions (as indicated by the sonic log in Figure 3e). With the help of the enhanced dynamic-warping approach, FWI was able to capture the velocity inversions and produce a more geological velocity model (Figures 3c and 3d). Compared with the legacy velocity model, the inverted velocity model from 20 Hz FWI better matched the shallow layers (Figure 3c), spatial structural variation (Figure 3d), and sonic log (Figure 3e).

II. Non-linear scanning tomography to update velocity inside and beneath basalt

The velocity updates for deep targets (below 4 km) need to rely on reflections because they are beyond diving wave penetration due to the thick basalt layer (about 2 km) and limited maximum offset of the data (8100 m). However, the deep reflections were clouded by scattering noise, converted waves, and residual multiples associated with the heterogeneous and large velocity contrast of the basalt layer. This introduces strong uncertainties into the model from reflection FWI (Gomes and Chazalnoel, 2017). It also causes conventional tomography to suffer from poor quality residual moveout (RMO) picks from common image gathers (CIGs), resulting in an unreliable velocity update. To avoid these issues, non-linear scanning tomography (Gong et al., 2018) was applied to further update the velocity within and beneath the basalt layer.

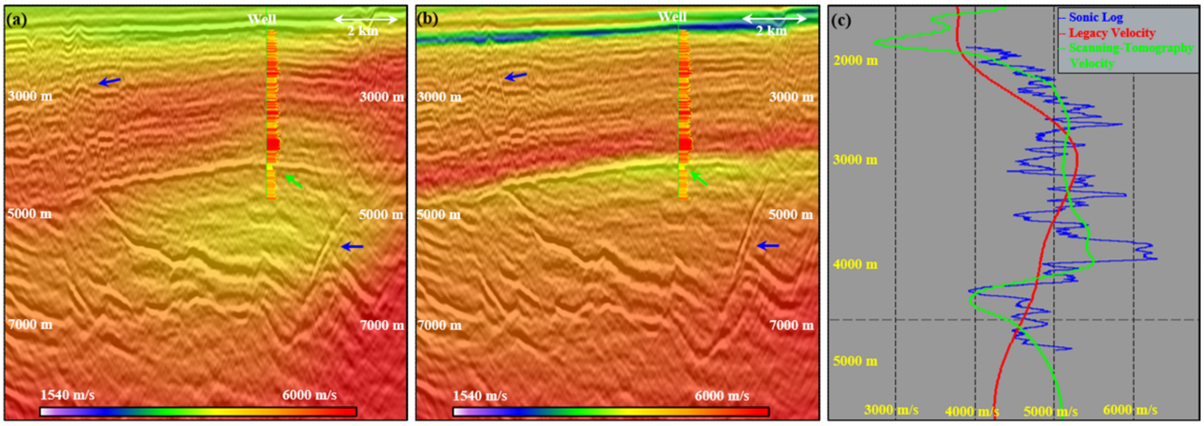

Figure 4 *Comparison between: (a) Legacy velocity model and (b) velocity model after scanning-tomography update, both overlaid on well log and their corresponding Kirchhoff PSDM images migrated with the data after demultiple. (c) Comparison between the velocity models and sonic log.*

One pass of global tomography was first applied to obtain a more reliable starting model (denoted as 100%). The velocity was then scanned between 90% and 110% with a 2% velocity increment as the scanning interval. Seismic events were picked on the stack and used to constrain the CIG picking to increase the reliability of the CIG picks. All the picks were then de-migrated and combined as input for a joint non-linear tomography velocity update. By using the above approach, a geological velocity model was inverted for the deep section. The new velocity (Figure 4b) provided better correlation with the well log (Figure 4c) inside and beneath the basalt layer compared with the legacy model (Figure 4a). As for the target layers, the new inverted model captured the high contrast velocity inversion just beneath the basalt layer (as indicated by green arrows in Figure 4b and green curve in Figure 4c). The dipping structures, including the fault inside the basalt layer, were better imaged with the new model (as indicated by blue arrows in Figure 4b).

Final sub-basalt image

The final PSDM was performed after the demultiple processing and velocity model building discussed above. Figure 5 shows the comparison between the legacy beam migration and new final Kirchhoff migration. The base of basalt, one of the key events, was well imaged across the whole survey in the final image while it was broken in the legacy image, as indicated by the yellow arrows. The sub-basalt image was clearer, while the legacy image contained strong residual multiples that cut through the real events and caused them to look broken. The faults beneath the basalt were clearly imaged and pushed to the right position by using the new velocity model. The PSDM image comparisons of both vertical sections and depth slices show that the complex sub-basalt structures were well delineated.

Conclusions

The devised demultiple workflow effectively attenuated the strong multiples generated by high impedence contrast layers like basalt and the shallow sea floor. DFWI and non-linear scanning-tomography handled the velocity update difficulties in this area well, and therefore inverted a velocity model that strongly correlated with both the seismic images and sonic log. The advanced processing outlined in this study led to significant uplifts in the final PSDM image, which indicates that the comprehensive demultiple workflow and high-resolution velocity model building approach can be effective solutions for revealing complex sub-basalt structures.

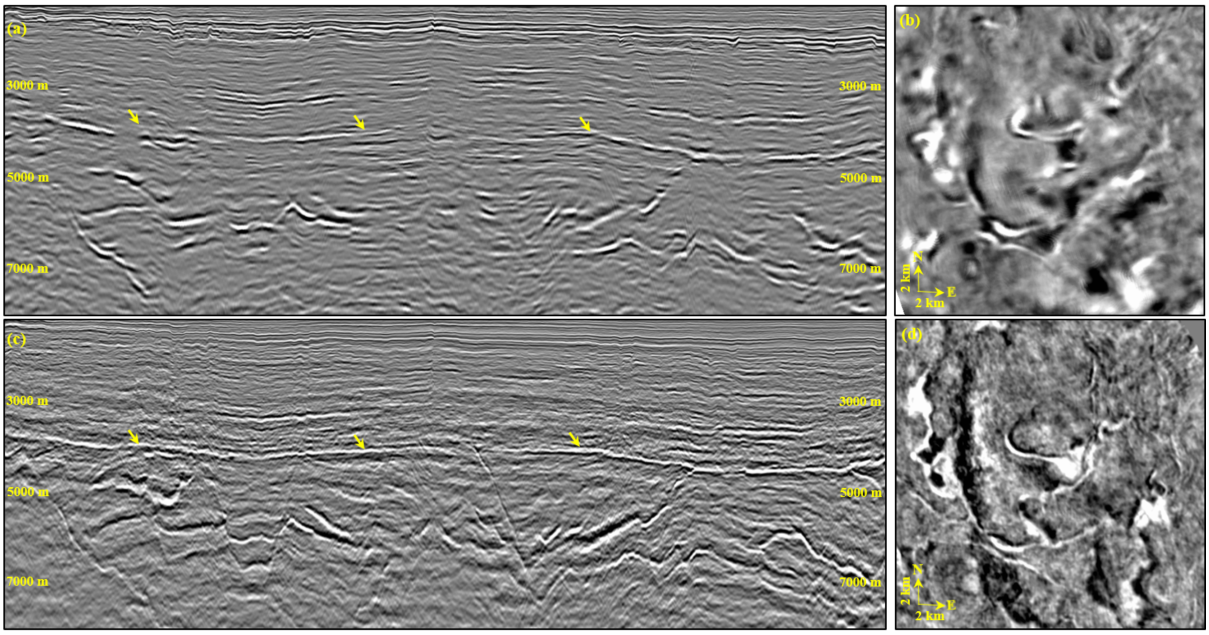

Figure 5 *Comparison of: (a) Arbitrary line and (b) Depth slice at 5700 m of legacy beam PSDM image; (c) Arbitrary line and (d) Depth slice at 5700 m of final Kirchhoff PSDM image.*

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References

Fainstein, R., Richards, M. and Kalra, R. [2019] Seismic imaging of Deccan-related lava flows at the K-T boundary, deepwater west India. *The Leading Edge*, **38**(4), 286-290.

Gomes, A. and Chazalnoel, N. [2017] Extending the reach of FWI with reflection data: Potential and challenges. *87th SEG Annual International Meeting,* Expanded Abstracts, 1454–1459.

Gong, Z., Wu, X., Lin, Y. N., Benfield, N. and Alperin, J. P. [2018] Non-linear scanning tomography for velocity model building in seismic-obscured area. *88th SEG Annual International Meeting,* Expanded Abstracts, 5128–5132.

Kumar, A., Akula, K.G. and Hari, K.K. [2012] Integrated studies for sub basalt imaging. *9th Biennial International Conference & Exposition on Petroleum Geophysics, SPG*, Expanded Abstracts, P-129.

Kumar, D., Bastia, R. and Guha, D. [2004] Prospect hunting below Deccan basalt: imaging challenges and solutions. *First Break*, **22**(7), 35-39.

Lin, D., Young, J., Griffiths, M. and Hartmann, M. [2005] 3D SRME prediction and subtraction practice for better imaging. *75th SEG Annual International Meeting,* Expanded Abstracts, 2088-2092.

Talukdar, K. and Behera, L. [2018] Sub-basalt imaging of hydrocarbon-bearing Mesozoic sediments using ray-trace inversion of first-arrival seismic data and elastic finite-difference full-wave modeling along Sinor–Valod profile of Deccan Syneclise, India. *Pure and Applied Geophysics,* **175**(8), 2931-2954.

Wang, T., Xie Y., Wang, M., Guo, Y., Wu, S., Ding, X., Wolfarth, S., Supriatna, Y. and Santoso, P. [2019] Enhance dynamic-warping for FWI to mitigate cycle-skipping. *81th EAGE Conference & Exhibition*, Extended Abstracts, We R08 02.

Wang, M., and Hung, B. [2014] 3D inverse scattering series method for internal multiple attenuation. *76th EAGE Conference & Exhibition*, Extended Abstracts, We E102 06.

Wu, X. and Hung, B. [2013] High-fidelity adaptive curvelet domain primary-multiple separation. *75th EAGE Conference & Exhibition incorporating SPE EUROPEC*, Extended Abstracts, Tu 14 06.

Yang, K.L. and Hung, B. [2013] Shallow water demultiple using hybrid multichannel prediction. *75th EAGE Conference & Exhibition incorporating SPE EUROPEC*, Extended Abstracts, Tu 14 03.