Improved depth conversion with FWI – a case study

A.J. O'Neill[1*] and T.A. Thompson[1] present a case study showing the application of FWI to help solve the problem of heterogeneous shallow carbonates in field development.

In the study region, notoriously heterogeneous shallow carbonates, here between depths of approximately 1.5-2.5 km, give rise to short-wavelength velocity variations in the overburden, which can cause severe depth undulations at the reservoir level (~3 km depth subsea). As the reservoirs are relatively thin (~30 m), stacked, fluvial-deltaic channel sands with sharp meanders and lateral truncations, even a localised 1% velocity error can produce a 30 m depth error at 3 km, which is not acceptable for development well planning.

The resolution of traveltime-tomography is limited and may not resolve overburden variability in a manner suitable for depth conversion in a development setting. Geostatistical scaling using the available well control is one option to further improve depth conversion reliability. This workflow utilizes time-depth data at well locations along with geophysically constrained statistics to derive a stable, geologically plausible background trend that accounts for the majority of depth error. The result is a regionally consistent model that ties the available well control and provides more reliable depth conversion away from wells.

The background trend provided by the well-based velocity calibration is however a long-wavelength solution and is unlikely to be able to correct for the short-wavelength depth errors which can arise at depth. FWI on the other hand provides a resolution of less than half a seismic wavelength to capture thin and localized subsurface features. With short-wavelength features accurately resolved, well control can then be used to correct for any residual long-wavelength errors and ensure more reliable depth conversion away from the wells.

In this study, reflection tomography and 3D TTI (tilted transverse isotropy) FWI velocity models were geostatistically calibrated to wells and compared for depth conversion accuracy. Using the calibrated reflection tomography model, early appraisal wells were still more than 50 m off prognosis at the top reservoir level. These appraisal wells were just a few hundred metres away from the exploration wells used for control. 3D TTI FWI was then run using the reflection tomography model as input. The same geostatistical calibration to wells was applied to the FWI output and ultimately provided a model with depth conversion accuracy to within 15 m at the reservoir level.

FWI overview and input data

FWI is a methodology for estimating a high-resolution, high-fidelity subsurface velocity model using the entire seismic wavefield (Warner et al., 2013). Velocity is almost always the target parameter, but any property to which seismic is noticeably sensitive to may be recovered. The entire wavetrain of transmitted and reflected arrivals is used to tomographically update the model. The method works best for shallow targets using long-offset, broadband and (preferably) multi-azimuth data.

At a high level, what FWI tries to do is actually quite simple. It iteratively updates an initial model by forward modelling synthetics and comparing them to field data. Advances in supercomputing make wave equation-based inversions like reverse time migration and full waveform inversion much more practical in modern times. Just as the physics of wave propagation is non-linear, FWI is a highly non-linear parameter estimation problem. In order to generate synthetics, the seismic experiment that was carried out in the field must be reproduced. This requires knowledge of the source wavelet, the acquisition geometry, and the physics of 3D wave propagation. The

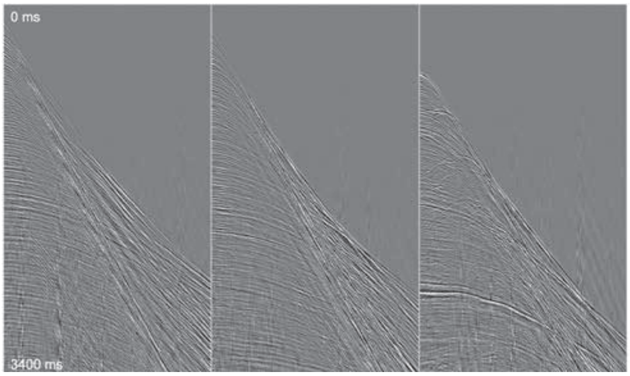

***Figure 1** A selection of shot records from a central cable in shallow (left), medium (centre) and deeper (right) water. With 6 km long cables, sufficient transmitted wave arrivals (refracted and diving waves) have been recorded.*

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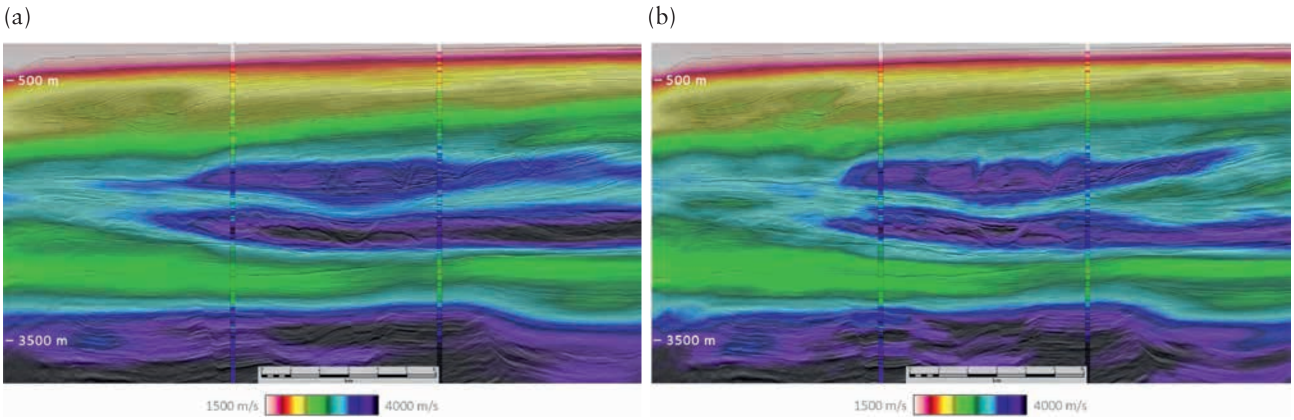


Figure 2 *Arbitrary cross section (in depth) through the: (a) Reflection tomography model, and; (b) FWI velocity model, co-rendered with the seismic data. Note the additional stratigraphic detail in the FWI model including pinch-outs, channels, better conformability and better match to the well data.*

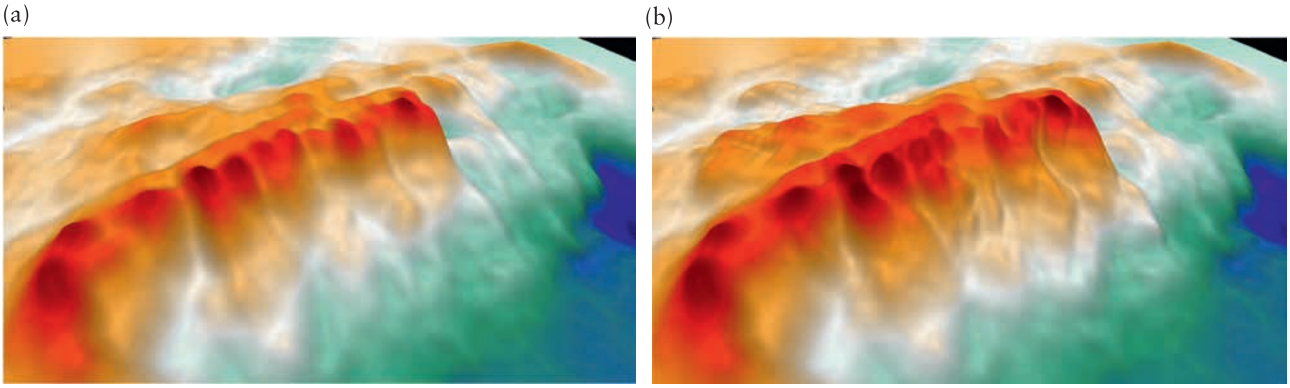


Figure 3 *Time slice (1500 m TVDSS) through the: (a) Reflection tomography model, and; (b) FWI velocity model. The velocity values have been displayed as a 3D surface to help highlight the stratigraphic and structural complexities that have been resolved post-FWI.*

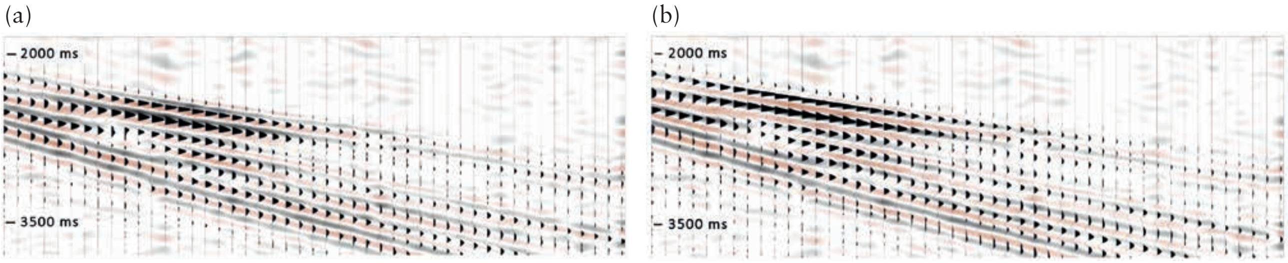


Figure 4 *Synthetic shots (wiggles) compared to seismic shots (colour), using: (a) Reflection tomography model, and; (b) FWI velocity model. Note how the reflection tomography model gives synthetic refracted (transmitted wave) arrivals half a loop out of phase with the observed seismic data, while the FWI model has a much better match.*

objective function is then straightforward: optimize the Earth model parameters, such as the P-wave velocity, to minimize the difference between the synthetics and the field data.

In this case, the seismic data was from a conventionally acquired 3D marine survey with 6 km cables. The survey was acquired in 2005 and while FWI was not a consideration in the survey design the example shot records in Figure 1 show there are sufficiently recorded transmitted wave arrivals (refracted and diving waves). It was hoped these would provide velocity model updates to approximately 3 km TVDSS, which is close to the top of the reservoir section. The shallow water (<200 m) and invariably hard seafloor gives rise to strong guided wavetrains in the water column, which in this case were muted prior to running the FWI.

For the FWI, the initial velocity, delta and epsilon models were obtained from a previous pre-stack, anisotropic depth imaging effort which included ten reflection tomography model building iterations. Thus the starting model was already very good. A model grid size of 40 m and time step of 3 ms allowed FWI updates up to 10 Hz. For each shot, a propagation time of four seconds was used to capture the entire transmitted wavetrain.

FWI output models and analysis

Figures 2 and 3 compare cross-sections and time-slices respectively through the initial and FWI models. The FWI model reveals the detailed rugose structure of the carbonates, with sharper bed terminations, improved stratigraphic conformance and a better match to the well VSPs. As will be shown, this additional detail in the shallow carbonates is critical for improving the depth conversion accuracy at the reservoir level.

Comparing the synthetic match to field data, Figure 4a shows how the reflection tomography model gives synthetic refracted (transmitted wave) arrivals half a loop out of phase with the observed seismic data. The FWI model is driven by these shallow diving waves, and as such, match the field data much better at far offsets, as can be seen in Figure 4b. Additionally, a Kirchhoff pre-SDM test shows that there is an uplift in the image gather flatness and focus when using the FWI model (Figure 5a), compared to the initial model (Figure 5b). While the goal of the study was solely to obtain a suitable velocity model for depth conversion of the existing data, improving the imaging with the refined model is an obvious extension. This, however, was not pursued in this case.

Geostatistical velocity model scaling

The primary objective of the velocity scaling workflow is to produce a model that will enable more accurate, unbiased depth conversion and ties to the available well data. The

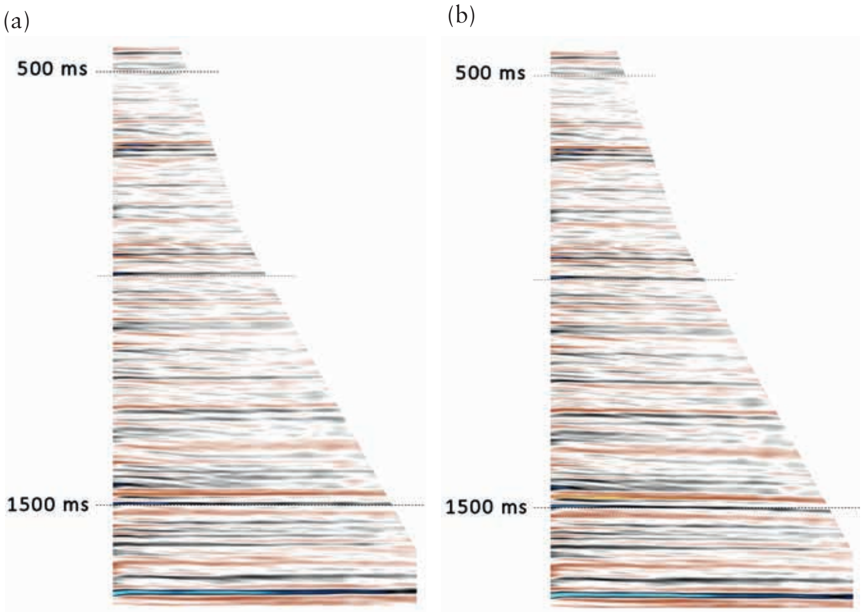


Figure 5 *Image gathers from the two velocity models: (a) Reflection tomography model, and; (b) FWI velocity model, both with 40 degree outer mute. Migrated events using the the FWI model are flatter and with improved focus compared to the reflection tomography (initial) model.*

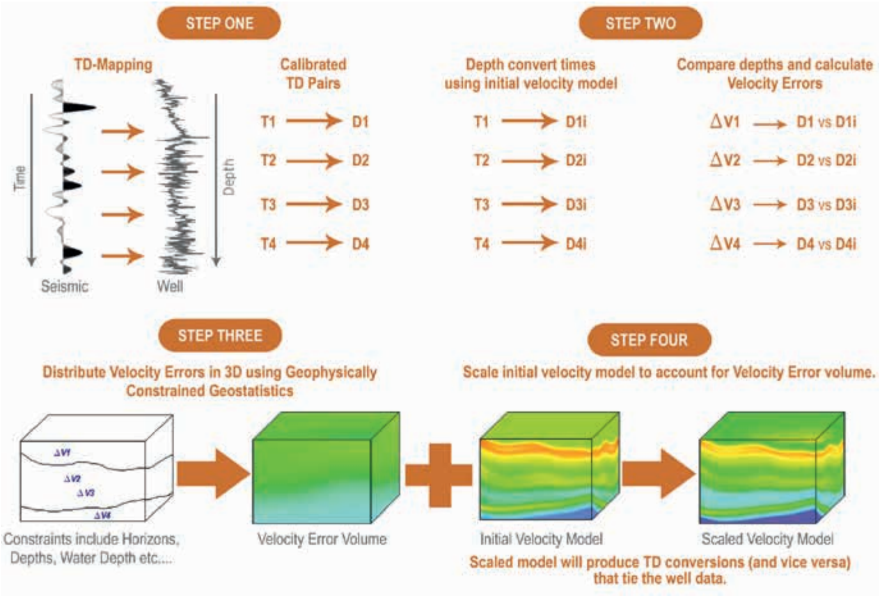


Figure 6 *Geostatistical velocity scaling workflow schematic.*

input velocity model is corrected using a stable, geologically plausible background trend that accounts for the majority of depth error (such that the mean of all residual well marker depth errors are zero). This is accomplished by enforcing geophysically constrained statistics that utilize all available and relevant information to produce a data-consistent update.

The background trend is a stable, long wavelength solution in the form of a polynomial function of geophysically meaningful and measurable quantities (Equation 1).

$$\text{Trend} = C_1T_1 + C_2T_2 + C_3T_3 + \ldots + C_nT_n \qquad (1)$$

C_n = coefficient for trend term T_n

The trend terms are variables that can be defined in three dimensions, such as velocity, depth, water depth, geobodies constrained by seismic horizons or any other available data deemed likely to influence (for geologically sound reasons) the observed variations in velocity. The background trend is obtained using the geostatistical machinery of universal kriging. An optional residual kriging can be applied to the background trend-corrected model to obtain a perfect match at well locations. Only the background trend was applied in this study. The velocity scaling workflow is schematically shown in Figure 6.

Typically, the trend terms do not contain short wavelength variability and well control is also normally sparse with respect to its spatial sampling. As a result, the trend is a long wavelength correction, so accurate short wavelength features must already be resolved in the input model. The key point of this study is to illustrate how the FWI model provided that shorter-wavelength resolution required to further improve the depth conversion accuracy.

Calibrated model results

The reflection tomography model and FWI model were calibrated to 25 wells, utilizing time-depth control from well ties. The pre-SDM seismic derived from the reflection tomography model was used for the well tie workflow. The scaling equation used the following trend terms: the input velocity itself, depth below water bottom, a constant and the overburden thickness geobody.

Depth conversion results of the pre-SDM seismic stack with the two velocity models are compared in Figure 7 where we have zoomed in around a key reservoir. Visually the difference is subtle, but on close inspection, the reflection tomography model (Figure 7a) shows misties at top reservoir of clearly more than the bed thickness. It is clear how, even if the model ties existing exploration wells, new development wells can be hard to assess, even just a few-hundred metres away. This is the effect of short-wavelength velocity variability in the overburden. The FWI model (Figure 7b) improves these ties, and moreover, reduces a number of structural undulations compared to the reflection tomography model.

Since the wells were not hard-tied by the calibration process in this case (as a residual kriging was not performed), a quantitative measure of the model accuracy can be made from the distribution of the residual depth errors along the wellbores. Each well is left out in turn as a ‘blind’ well and the remaining wells are used to calculate and correct for the background trend. The ability of that trend to correctly predict the blind well can be recorded and statistics can be calculated using the results from all wells.

The results of such an analysis are shown in Figure 8 where we compare the blind well depth error results from the unscaled reflection tomography model with the scaled FWI model. Distributions have been calculated over three different (but contiguous) stratigraphic intervals. The deepest interval is the reservoir level. The initial reflection tomography model (Figure 8a) shows broader distributions, with a non-zero mean and many outliers of 50 m or more, which was similar to the misprognoses observed in many wells during development drilling. These are the short wavelength ‘busts’ in the reflection tomography model, which the FWI model has adequately corrected and provides an unbiased depth conversion with much reduced uncertainty, approximately 15 m, or less than 1% of depth at reservoir level (Figure 8b).

A further validation of the FWI model was observed after drilling a development well into the lower

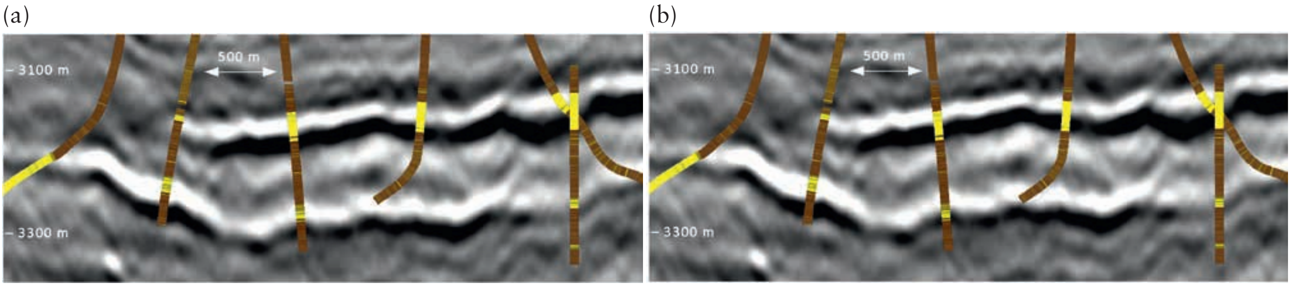


Figure 7 Zoom in around a channel sand reservoir, comparing depth conversion of pre-SDM stacks after geostatistical velocity model scaling of: (a) Reflection tomography model, and; (b) FWI velocity model. The gamma ray log is show along each well bore with the yellow colours representing sand. The central wells show an improved tie at the top sand using the FWI model.

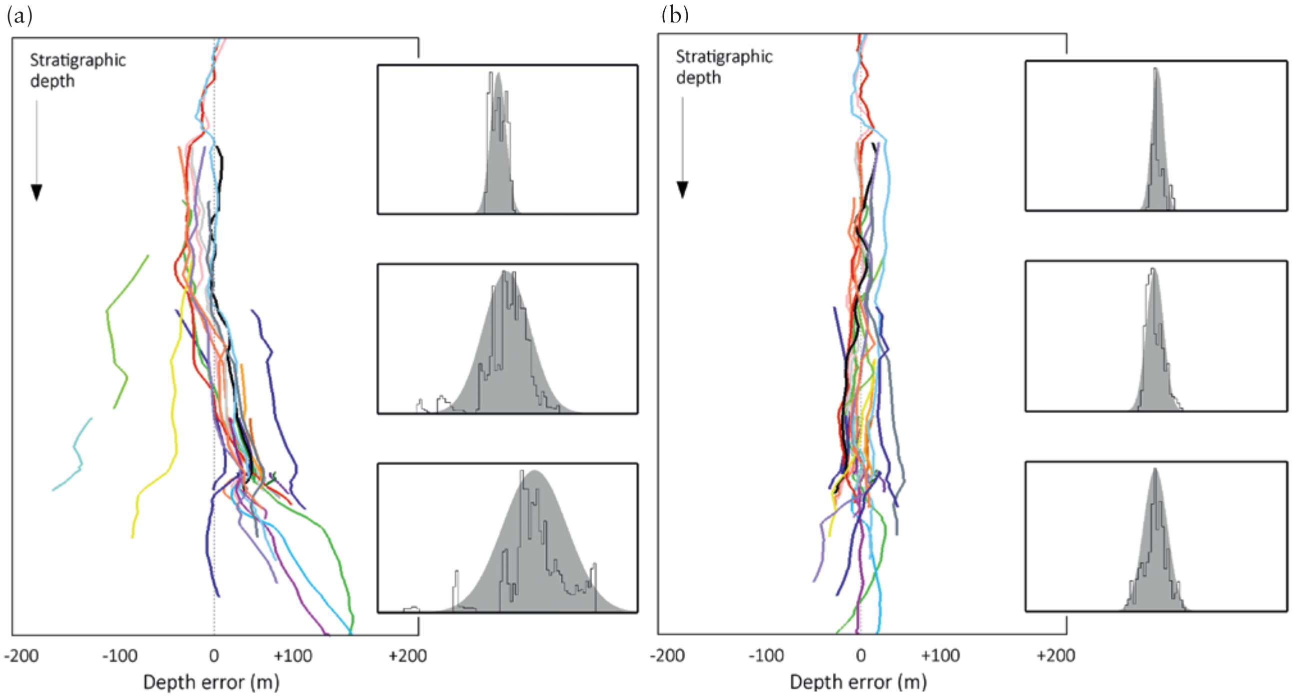
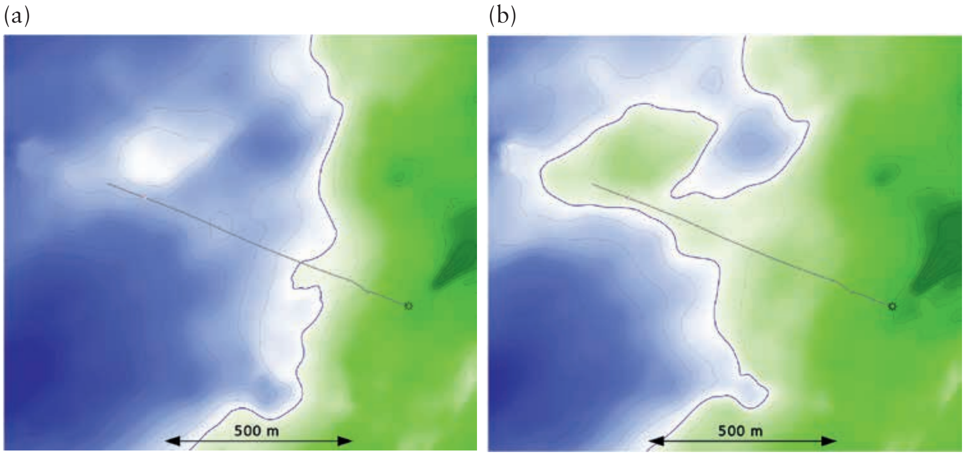


***Figure 8** Distributions of depth errors for all wells from: (a) Reflection tomography model (uncalibrated), and; (b) FWI velocity model (calibrated). Distributions are shown for three different stratigraphic levels. Note the tighter distribution and the removal of the bias in the calibrated FWI model. The standard deviation of the depth errors at the reservoir level has been reduced from ~50 m to less than 15 m.*

***Figure 9** Top reservoir depth map created using calibrated velocity models from: (a) Reflection tomography, and; (b) FWI. The well intersected hydrocarbons at the highlighted point (small white circle) on the well path (grey line). The depth map from the FWI model correctly positions this intersection above the fluid contact (shown by the dark blue contour).*



(hydrocarbon bearing) reservoir of Figure 7. Top reservoir depth maps created using the scaled reflection tomography and FWI models respectively are shown in Figure 9. The reflection tomography model (Figure 9a) incorrectly positions the top reservoir deeper than the well marker, but the FWI model (Figure 9b) correctly places the well intersection above the fluid contact.

Conclusions

Full-waveform inversion combined with geostatistical calibration to wells has provided a reliable velocity model for accurate depth conversion at a development field, with notoriously heterogeneous carbonates in the overburden and relatively thin (~30 m) stacked channel-sand reservoirs at depth. Previous depth misties at development wells of several tens of metres are reduced to less than the bed thickness (<15 m), equivalent to less than 1% of depth (at ~3200 m TVDSS). The improved accuracy and resolution of the FWI model deems it more suitable than the reflection tomography model for well planning and reservoir characterization.

References

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