50Hz high resolution land FWI: a case study in the Carpathian foothills

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Summary

In this paper, we present a high-resolution FWI case study from the foothills of the Southern Carpathians, in Romania. The input data was acquired in 2022, mostly with dynamite source, and designed for optimal subsurface wide azimuthal illumination. The varied rough terrain and the presence of a complex thrust body represent the main imaging challenges. Firstly, we will show how the combination of Multi-Wave Inversion (MWI), and Full-Waveform Inversion (FWI) enabled us to construct a high-resolution near-surface velocity model that solved some important imaging distortions. Next, we will outline the benefit of inverting data to 50Hz to attain a high resolution FWI model which fully captures the strong lateral and vertical velocity contrasts of the upper folded structures and the underlying stratigraphy. Finally, the migrated image and derived reflectivity from this 50Hz FWI model has helped to de-risk the reservoir uncertainties in both size and positioning of the crest. These enhance the imaging to better define the spill point of the prospect.

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Introduction

In this paper, we present a high-resolution FWI case study from the foothills of the Southern Carpathians, in Romania. In this hilly area, the Spineni dataset was acquired in early 2022, composed of approximately 85% dynamite shot points and 15% vibroseis shot points. It represents a total area of 500 km^2 that fills and follows the reprocessing of the Getic Merge project for a total area of 3000 km^2 (Meffre et al., 2022). The large maximum offset x/y of 6 and 11 km, respectively, offers an optimal design for wide-azimuth subsurface illumination, which is crucial in areas with complex structural geology as described by Krezsek et al. (2011). The reservoir, located below a thick overthrust at around 5 km depth, has a number of closures with uncertainties in size and crest positioning. This thrust inclusion in the northern part of the survey, the so called Burdigalian wedge, is characterized by a very complex folded structure with steep dips and strong lateral and vertical velocity variations with high velocities. In this context, a high-resolution FWI velocity model was used to help enhance the imaging and better define the spill point of the prospect.

Near surface characterization

The challenges identified in this area include the large variation of the topography and the presence of very slow velocities (700 m/s) in the weathering zone (WZ), as shown by the up-hole information. This creates strong imaging distortions from the very shallow down to the target depth. Ground roll contamination and irregular near offset distribution make access to near surface reflectivity very challenging. That is why multi-wave inversion (MWI) was used obtain an initial high vertical resolution anisotropic velocity model for subsequent acoustic FWI updates. MWI, by minimizing the residuals of the first break (FB), ground roll dispersion curves (DC), and WZ base two-way times, allows for a reliable multi-parameter reconstruction of V_p, V_s, and ε (Bardainne, 2018; Donno et al., 2021; Prieux et al., 2020). Thanks to a dense acquisition design, we were able to clearly identify and pick the base of the WZ from the receiver-side operators of a surface consistent deconvolution (Retailleau, 2015) (Figures 1c-d). In addition, the good low-frequency content coming from the broadband signal produced by the dynamite shots coupled with long offsets of up to 10 km, enabled us to further resolve the long-to-mid wavelength velocity of the near surface model. The output QC (Figure 1) showed reliable and geologically consistent results with a flatter base of the WZ and fewer structural undulations compared to the FB tomography model.

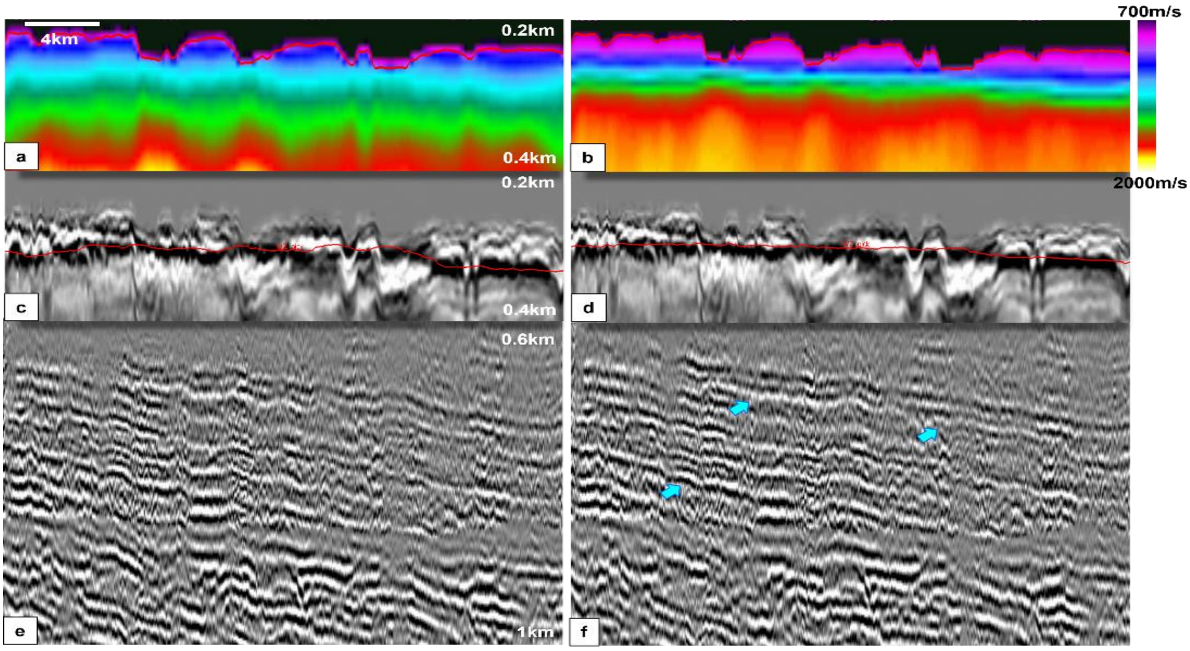

Figure 1: *(a) FB tomography model; (b) MWI + FWI 7 Hz near surface model; (c) and (d) The base of the weathering zone interpreted on the deconvolution operators using models (a) and (b), respectively; (e) and (f) Stacks after Kirchhoff pre-stack depth migration (PSDM) with models (a) and (b), respectively.*

Complex imaging underneath overthrust folded structures

The velocity shown in Figure 2a has already been through a complete near surface update as described above, plus a first pass of multilayer TTI tomography. In addition, a pass of FWI from 7 Hz up to 12Hz using diving and reflected waves for the deeper section update (Figure 2b) shows a global improvement of focusing (Figure 2e). However, some residual structural distortions and poor focusing were still visible below the thick thrust composed of heavily folded structures with strong velocity contrasts. To capture more detail in the velocity model to resolve these imaging problems, high-resolution FWI was used (Zhang et al., 2020). As the FWI frequency was increased from 12 Hz to 40 Hz, gradual imaging improvements were observed due to the additional details in the model. Beyond 40 Hz, no significant imaging improvements were observed. The 50 Hz FWI velocity model fully captured the strong variations and velocity contrasts (Figure 2c), and the structures exhibited nice details and improved focusing of the target area (Figure 2f).

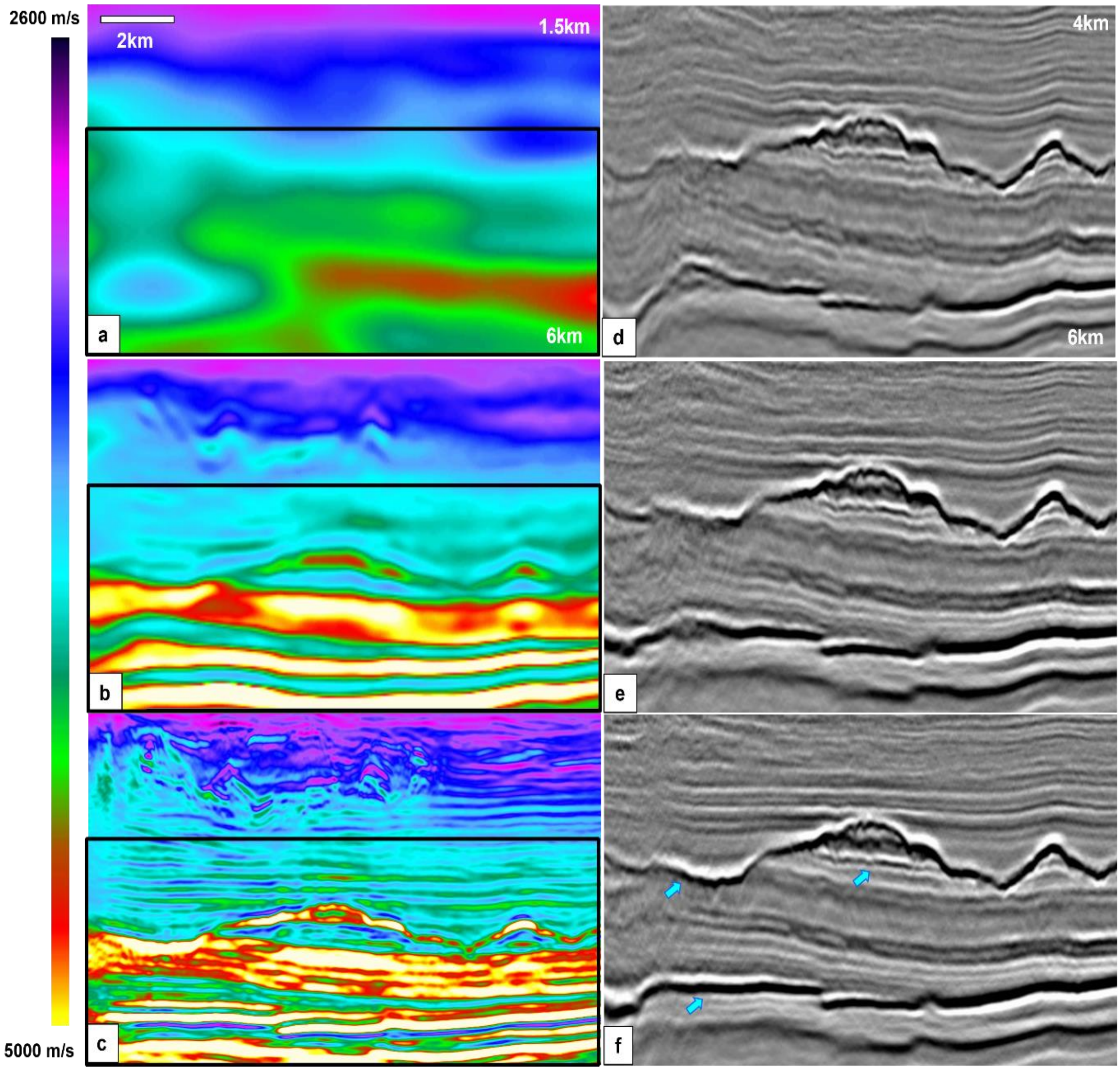

Figure 2*: (a) Section of initial model after a complete near surface update, (b) FWI at 12 Hz and (c) 50 Hz illustrating the complexity of the thrust and high-velocity contrast in the target area. Corresponding zoomed section of stacks after Kirchhoff pre-stack depth migration (PSDM) with (d) initial, (e) FWI 12 Hz and (f) 50 Hz models to illustrate the impact on the imaging in the target area.*

In addition, FWI Imaging (Zhang et al., 2020), was derived from the 50 Hz FWI velocity. FWI Imaging is seen to benefit from additional information provided by the full wavefield data and uses least-squares data fitting, which is essential to image below complex geological features (Salaun et al., 2021). Figure

3c shows clearer fault definition, better amplitude continuity, and fewer migration artifacts, as highlighted by the white arrows.

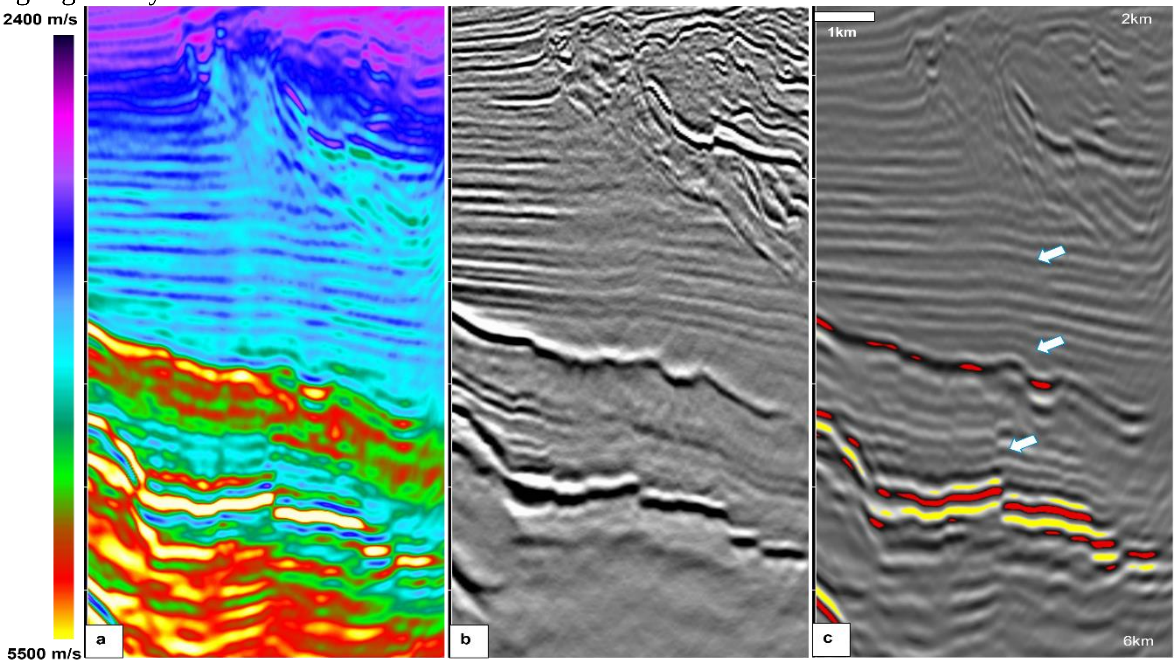

Figure 3: (a) 50 Hz FWI velocity model, (b) Kirchhoff PSDM stack and (c) FWI Imaging reflectivity derived from (a). The yellow and red extrema color palette on the reflectivity underlines stronger velocity contrasts to help delineate potential reservoir spill points.

De-risking fault closure uncertainties in the prospect area

The main prospect sitting below the overthrust, shown in the white polygon on the depth slice of Figures 4b and 4e, has multidirectional fault-dependent closures. Figure 4b shows the PSDM depth slice cutting through the prospect area, which has high uncertainties in both size and crest position in depth. The 50 Hz FWI velocity model in Figures 4d and 4f exhibits very high resolution, which captures the complex velocity contrast of the upper folded structures and the underlying stratigraphy. As a result, the fault

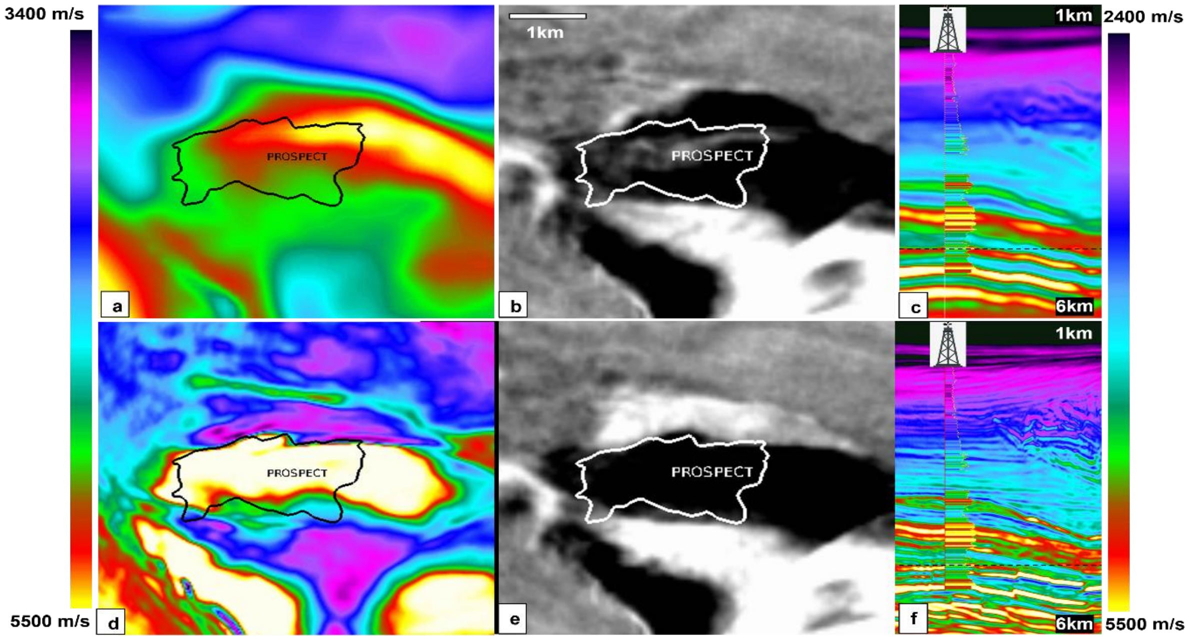

Figure 4: (a-b) 12 Hz FWI model and PSDM stack; (d-e) 50 Hz FWI model and PSDM stack; (c-f) Sonic log comparison with 12 HZ and 50 Hz FWI model, respectively.

closures around the prospect area are better imaged (Figure 4e), allowing considerable de-risking of the uncertainties in their interpretation. Moreover, the velocity contrasts are also well correlated with the well's sonic log velocities, providing further validation of the 50 Hz FWI model.

Conclusions

In this paper, we emphasized the crucial importance of adding high-resolution details to the velocity field using FWI in a complex foothills geological setting. The resulting model has greatly improved the imaging below the overthrust and helped de-risk the interpretation uncertainties of the reservoir structure and fault closure. In addition, the associated high-resolution velocity model can also be used with Kirchhoff PSDM conventional imaging to facilitate detailed reservoir interpretation work.

These results, in reaching 50 Hz, which is high frequency for land imaging, were obtained also thanks to the well-designed long offset WAZ acquisition, strong low-frequency content of the dynamite source, and the continuous effort made on computation technology over last few years. For the near future, elastic FWI could potentially offer further uplifts by deriving improved Vp and Vs models in such a high velocity contrast medium.

Acknowledgements

We are grateful to OMV PETROM and CGG for their permission to publish this study. We also thank all those who were involved in the project.

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