# ADVANCED DEPTH IMAGING TECHNOLOGIES: A CASE STUDY IN THE CARPATHIANS FOOTHILLS

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## Summary

In this paper, we present a depth imaging case study from the foothills of the Southern Carpathians in Romania. The input data consist of a merge of 12 land surveys, mostly acquired with dynamite source. The varied rough terrain and the presence of a complex thrust body represent the main imaging challenges. At first, we will show how the combination of Multi-Wave Inversion (MWI), joint first break (FB) and slope tomography, and Optimal Transport Full-Waveform Inversion (OT-FWI) enabled us to construct a high-resolution near-surface velocity model that solved some important imaging distortions. Next, we will detail an advanced Multi-Layer Tomography workflow complemented by Time-lag FWI (TLFWI), that enabled us to capture the strong lateral and vertical velocity contrasts of a large thrust and, consequently, restore the focusing and the faulted structure of the Jurassic reservoir units underneath.

# Advanced depth imaging technologies: A case study in the Carpathians Foothills

**Introduction**

This case study involves the Getic Depression, which is located in southern Romania, and explores the foothills of the Southern Carpathians. The input data consists of 12 land seismic surveys with a small overlap. They were acquired between 2006 and 2014 and cover an area of 2447km$^2$. All surveys have a sparse orthogonal design with a mix of dynamite (80% of shots), vibroseis and airgun sources. On average, the bin size of the common midpoint (CMP) is 25m by 25m with a nominal fold of 60 and a maximum offset of 3500m.

The recent full reprocessing of all these surveys as a merged single volume included the application of advanced surface-wave attenuation techniques, surface-consistent processing and 5D regularization techniques. It produced a homogeneous set of mid-point gathers with broadband for imaging (Meffre et al., 2022).

In this paper, we will focus on the imaging challenges in this area. At first, we will show how the combination of Multi-Wave Inversion (MWI), joint first break (FB) and slope tomography, and Optimal Transport Full-Waveform Inversion (OT-FWI) enabled us to construct a high-resolution near-surface velocity model that solved some important imaging distortions. Next, we will give insight into an advanced Multi-Layer Tomography workflow, which was complemented by Time-lag FWI (TLFWI). This workflow enabled us to capture the strong lateral and vertical velocity contrasts of a large thrust and, consequently, restore the focusing and the faulted structure of the Jurassic reservoir units underneath.

**A complete high-resolution near-surface solution**

The main objective was to compute a reliable near surface velocity model accounting for the highly variable topography and the presence of a variable thickness layer of very low velocities (700m/s) in the weathering zone (Figures 1 and 2).

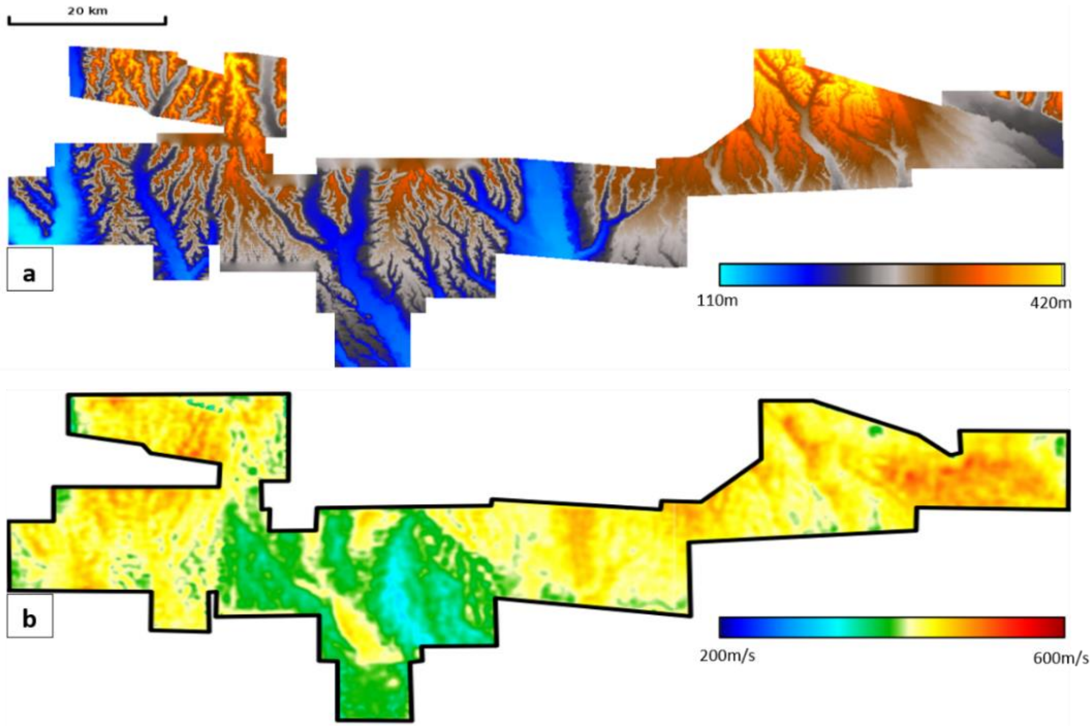


*__Figure 1__: a) Topographical map of the Getic area in the southern part of Romania exhibiting abrupt elevation changes. b) Result of surface-wave tomography for 7Hz frequency. These maps reveal the heterogeneity of the near surface over the whole survey without obvious artefacts at the survey inner boundaries.*

We used MWI to jointly update the P and S wave velocities from the surface waves Dispersion Curve (DC) and the FB picks (Bardainne, 2018).
The DC picking was the main challenge due to irregular and sparse acquisition geometries. An iterative sequence, which was made up of successive dispersion curves picking and ground-roll regularization, was used to improve the consistency and reliability of the fundamental mode picks (Figure 1b) (Donno et al., 2021). These picks were input into surface wave tomography from which we derived an initial vertically varying Vp/Vs model for MWI (Socco et al., 2017), which honored the velocity variations in the quaternary sedimentary shallow layers.
The MWI result was integrated into the initial depth velocity model for a joint reflection/refraction tomography. In the inversion, we used the residual move-out (RMO) picks from reflected waves and the FB picks from diving waves to reconcile both vertical and horizontal velocity and, therefore, update the P-wave velocity and anisotropic epsilon parameter (Allemand et al., 2020).
The OT-FWI, which is less affected by data mismatch, was used to finalize the near-surface velocity model. To handle rough topography, a curvilinear, topography-conforming, finite-difference grid was used for the wavefield propagation with accurate implementation of a free-surface boundary condition (Royle et al., 2021). The OT-FWI was run over the whole area, inverting for both the diving waves and the reflections from 4Hz up to 10Hz. The benefit of the complete near-surface workflow is shown in Figure 2. The distortions due to the strong near-surface velocity variations were well corrected from the surface down to the deeper targets (green arrows) as a result of the improved lateral and vertical resolution of the near-surface velocity model.

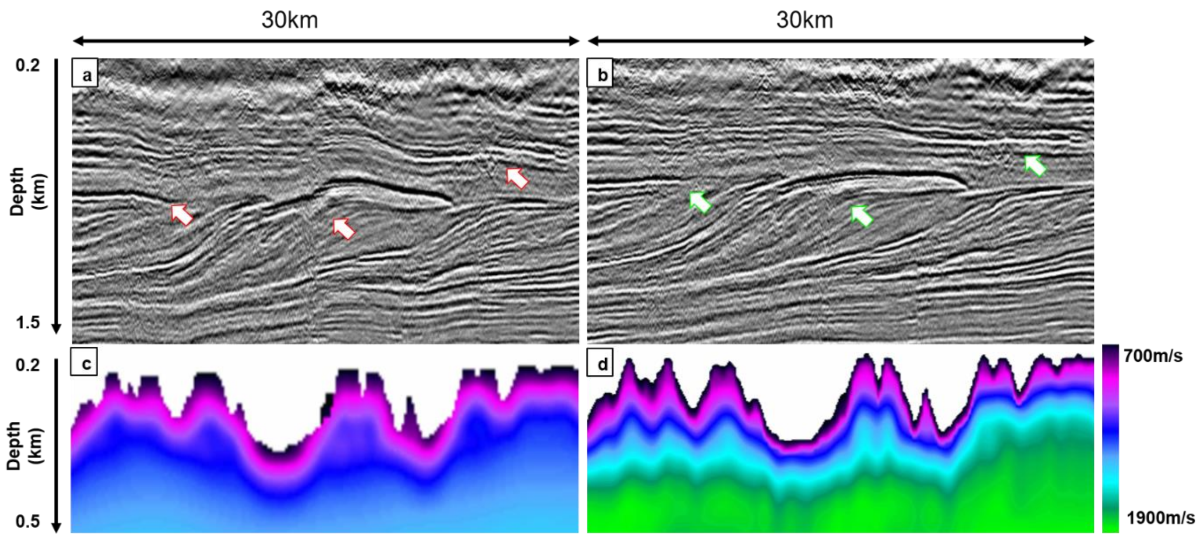


***Figure 2**: (a-b) Stacks after Kirchhoff pre-stack depth migration (PSDM) with initial near-surface velocity models (c) and a complete high-resolution near-surface model (d) respectively. The green arrows in (b) show the significant reduction in the distortions at the Meotian and Clinoform targets.*

**Jurassic reservoir Imaging underneath a complex geology setting using High-Definition (HD) Multi-Layer Tomography**

The south of the Carpathian Mountains is characterized by an important thrust inclusion located in the north of the merged surveys. This inclusion is inserted inside the younger sediments of the Getic basin, as described by Krezsek et al. (2011). The thrust body has a variable thickness up to 5 km, it is characterized by a very complex structure with steep dips and strong lateral and vertical velocity variations with some high velocities, leading to important imaging issues down to the Jurassic reservoir. The “sinusoidal” events on the Wide Azimuth (WAZ) gathers shown in Figure 3c indicates velocity errors from the initial model.
After the near-surface velocity model was completed, the deeper velocity model was updated by using a HD multi-layer tomography from the WAZ RMO picks proposed by Guillaume et al. (2012). With a poor starting model derived from PSTM RMS velocity, a complex environment, and limited maximum offset of 3.5km, it was very challenging for multi-layer tomography to recover the medium spatial wavelength of the velocity in the deep section. Therefore, we implemented the ‘stack and gather

scanning tomography' approach described by Gong et al. (2018). To begin, the PSDM stack scans were used to pick the different percentage models by examining the reflector focusing and the simplification of the geological structure. The conversion of these percentage picks into a velocity model allowed us to update the long spatial wavelength of the velocity. Next, the WAZ RMO picks and invariants from this model and from the different percentage models were generated and merged to feed the so-called 'joint gather scanning multi-layer tomography'. This step enabled us to update the medium spatial wavelength of the velocity and to further improve the stack focusing. Finally, a global pass of HD multi-layer tomography was run with finer perturbation grid using denser WAZ RMO picks to bring high frequency details and was followed by a well-tie tomography to calibrate the model to the well markers and to update the anisotropic parameters. A machine learning analysis of the azimuthal RMO QCs was conducted to confirm the global reduction of the move-out in the final PSDM gathers (Figure 3g). The results in Figure 3 show a clearer definition of the thin reflectors, less distortions, and a better definition of the faults in the final velocity model below the thrust.

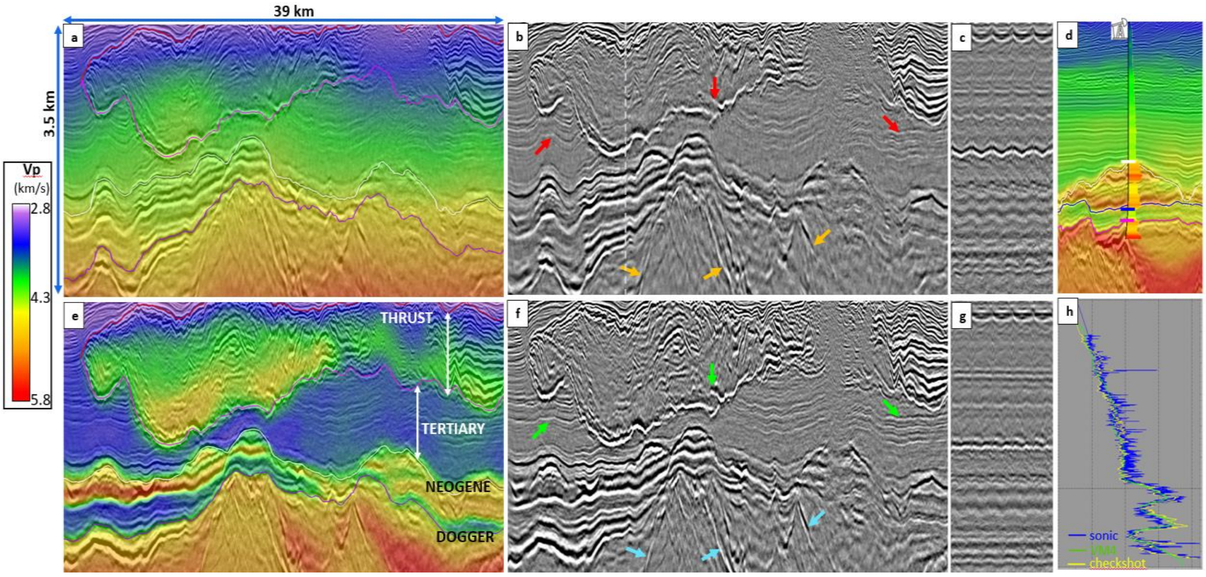


***Figure 3**: Velocity models superimposed on the corresponding Kirchhoff PSDM stacks (a, b) after the first tomographic update and (e, f) with the final velocity model. (c, g) Corresponding WAZ gathers extracted at the blue dashed line position in (b). (d, h) Comparison between the sonic and the final velocity profile; a good match of the seismic is seen with the depth of well markers.*

**High-resolution velocity model through Time-Lag Full-Waveform Inversion (TL-FWI)**

Some small velocity anomalies and sharp contrasts inside the thrust were very challenging to resolve, even with HD multi-layer tomography. As a result, residual distortions were still visible below the thrust (red arrows in Figures 4b, d). Thus, TLFWI (Zhang et al., 2018) was performed in addition to the multi-layer tomography in order to better use the full reflection data and, therefore, improve the accuracy and resolution of the velocity model despite the limited offset range. The inclusion of these high-frequency vertical and horizontal velocity variations in the TLFWI model was able to resolve most of the residual distortions and reflector discontinuities visible on seismic events underneath the thrust (green arrows in Figures 4f, h).

**Conclusions**

In this case study, we have demonstrated that the application of new high-end imaging technologies on sparse legacy land surveys provided new insight into the complex geological structure of the area. We built the velocity model from top to bottom, starting with an update of the near-surface velocity model, which jointly used surface, diving and reflected waves. The final high resolution velocity model in this geologically complex setting was obtained with a dedicated tomography and full-waveform inversion workflow.

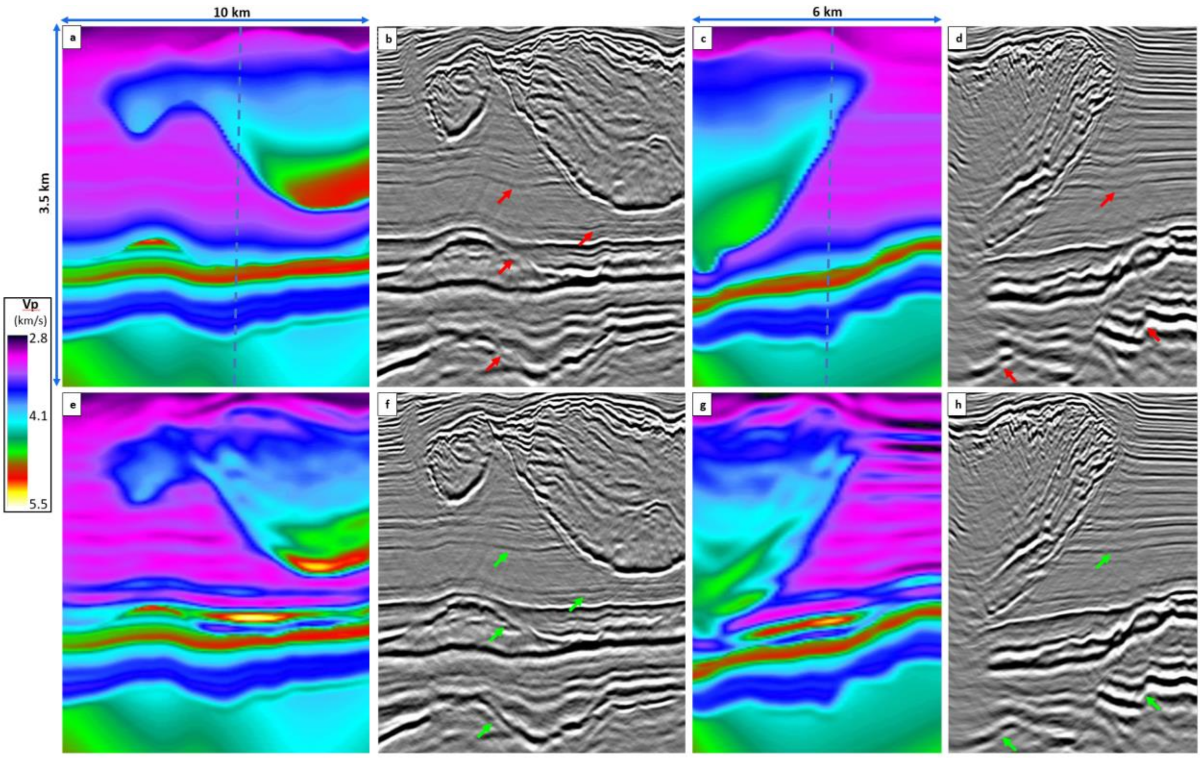


***Figure 4**: Crossline (left) and subline sections (right) positioned at the blue dashed line in (a,c). Velocity models and their corresponding stacks are displayed for the output of multi-layer tomography (top row) and the output from TLFWI (bottom row).*

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