# Potential of full waveform inversion of vertical seismic profile data in hard rock environment

**Anton Egorov***
*Curtin University*
*GPO Box U1987*
*Perth WA 6845*
*anton.egorov@postgrad.curtin.edu.au*

**Andrej Bóna**
*Curtin University*
*GPO Box U1987*
*Perth WA 6845*
*A.Bona@curtin.edu.au*

**Roman Pevzner**
*Curtin University*
*GPO Box U1987*
*Perth WA 6845*
*R.Pevzner@curtin.edu.au*

**Konstantin Tertyshnikov**
*Curtin University*
*GPO Box U1987*
*Perth WA 6845*
*Konstantin.Tertyshnikov@curtin.edu.au*

## SUMMARY

Complex structure of the subsurface in hard rock environment often complicates traditional processing and interpretation of seismic datasets based on the analysis of reflected waves. Full-waveform inversion (FWI), in turn, utilizes the whole wavefield, including the transmitted waves and reflections, to build the models of physical properties (such as P wave velocity and density), which is one of its main advantages over traditional methods of seismic imaging. We conduct a feasibility study of 2D full-waveform inversion (FWI) applied to vertical seismic profile (VSP) synthetic data computed in a model that is based on a real hard-rock survey site for the purpose of identification of heterogeneities.

Using this complex model of the subsurface that contains steep interfaces, high seismic wave velocities and densities, we generate a synthetic VSP dataset with a finite-difference code. Multi-offset VSP geometry is considered due to the abundance of transmitted waves. We then apply FWI to this dataset. We use finite-difference modelling for the forward problem in FWI, optimization is conducted using the limited-memory BFGS method. FWI is applied in a multiscale manner, from 10 Hz to 190 Hz. Inversion results suggest that FWI of VSP data is a suitable tool for building the models of physical properties of the subsurface that are crucial for mineral exploration and mine planning.

**Key words:** full waveform inversion, FWI, vertical seismic profile, VSP.

## INTRODUCTION

Full Waveform Inversion (FWI) is a method for solving the inverse problem in seismic exploration that was introduced by Lailly (1983) and Tarantola (1984). FWI uses a forward problem engine and solves the inverse problem by minimizing the misfit between the observed and synthetic wavefields. L2 norm of the misfit is most commonly applied.

Nowadays, FWI is widely used for the estimation of physical properties of the medium in seismic exploration (Virieux and Operto 2009). It is generally applied to marine seismic data, though there are examples of successful application of FWI to land vibroseis datasets (Kamei, et al. 2015), which requires careful noise attenuation and complex data preconditioning (Adamczyk, et al. 2015).

Our goal is to evaluate the applicability of FWI to seismic data acquired in hard rock environment. As FWI workflow does not require any assumptions on the structure of the subsurface, it should be capable of imaging the complex medium structures that are commonly found on hard rock mining sites. Instead of using surface seismic geometry, we use Vertical Seismic Profile (VSP) with the receivers located in the well. Direct arrivals that are recorded in VSP geometry facilitate the requirements for low frequencies (Neklyudov, et al. 2013), which allows us to start the inversion from frequencies that are realistic for conventional land acquisition (~12 Hz). Placing receivers in the well also reduces ambient noise. These properties of VSP geometry explain a large number of successful applications of FWI to field VSP data (Charara, et al. 1996, Owusu, et al. 2016).

For our study, we invert a 2D finite-difference synthetic dataset computed in an acoustic approximation using a model that contains steep interfaces, high seismic wave velocities and densities. The results show that the inversion is capable of building high-resolution models of physical properties. However, due to high P-wave velocities, high frequencies (up to ~190 Hz) are needed for accurate reconstruction. The results also suggest that careful survey design should be performed in order to illuminate the survey targets by both transmitted and reflected waves.

## METHOD AND RESULTS

We use a time-domain acoustic FWI technique based on a finite-difference forward problem code (Köhn 2011, Köhn, et al. 2012). LBFGS optimization method is used for the minimization of the misfit functional (Nocedal and Wright 2006). Multiscale inversion algorithm is applied using high-order high-cut Butterworth filters (Bunks, et al. 1995). At the first iteration, the filter slope frequency is 12 Hz. At the end of the inversion, the high-cut filter slope reaches 190 Hz.

Figures 1 and 2 compare true, initial and inverted models of P-wave velocity $V_P$ and density $\rho$. The acquisition geometry is outlined on the Figures. Source interval is 50 m, receiver interval is 2.5 m. True models of the medium (Figures 1a and 2a) are used to generate a synthetic dataset. FWI of that dataset is then performed. Initial models displayed in Figures 1b and 2b are used for the inversion. The inverted models of $V_P$ and ρ are displayed in Figures 1c and 2c.

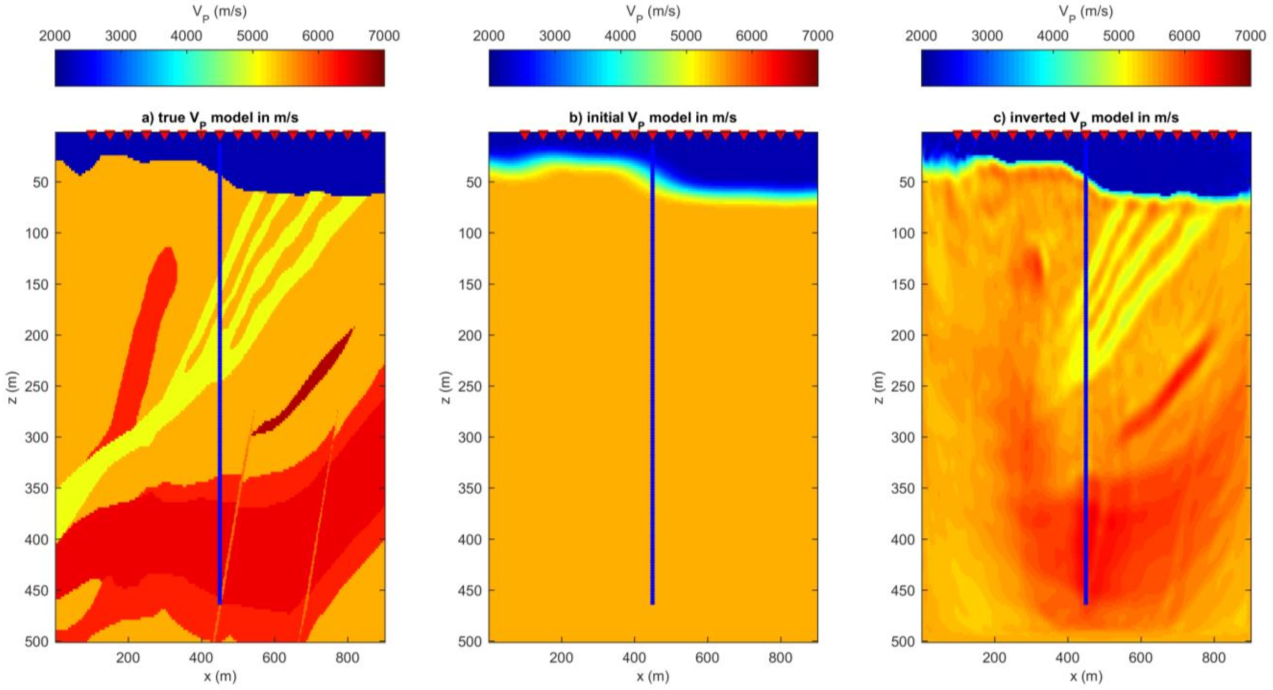


**Figure 1: P-wave velocity models of the medium: true model (a), initial model (b) and inverted model (c).**

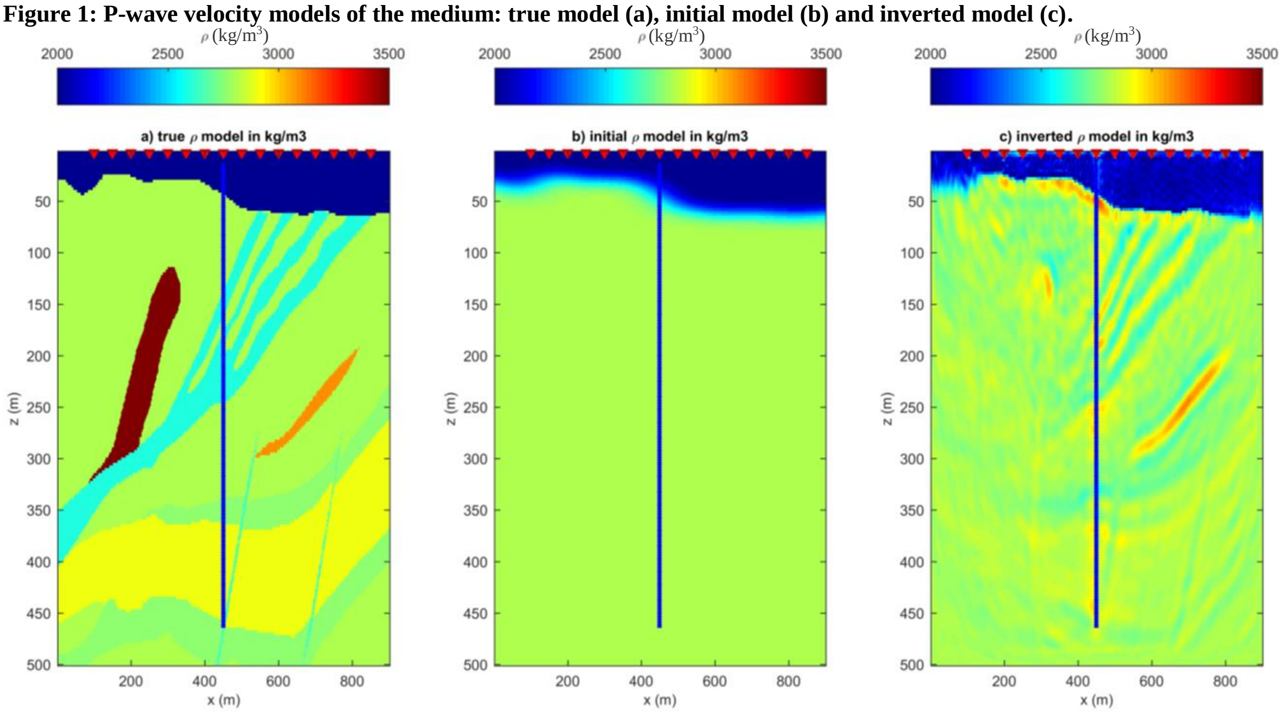


**Figure 2: Density models of the medium: true model (a), initial model (b) and inverted model (c).**

Both $V_P$ and ρ models in Figures 1c and 2c contain the small-scale features of the mineral bodies that are present in the original model. It is important that only the parts of the bodies that dip towards the well are imaged. The reflections from the surfaces of those bodies are recorded by the receivers in the well. These reflections contribute to the result of the inversion. The body with high density to the left of the well is not present in the inversion result due to the fact that the reflected waves from its surfaces are not recorded in the used acquisition geometry, as its top and bottom surfaces dip away from the well. This may be fixed by using multiple wells around the targets in the inversion.

## CONCLUSIONS

The results of this study show that FWI of VSP data is capable of building high-resolution models of physical properties in complex hard rock environments. In our example, very high frequencies (~ 190 Hz) are needed for the reconstruction of $V_P$ and density models, due to high velocities and (as a consequence) long wavelengths of seismic waves. Our example also shows that, in case of steep interfaces, careful illumination analysis of VSP survey geometry needs to be performed in order to ensure that the inversion is successful.

The study shows that FWI of VSP data has high potential of assisting hard rock seismic investigations. However, more testing on synthetic and field datasets needs to be conducted. We used acoustic wave equation for the analysis presented here. Taking elastic effects into account is a next step needed to make FWI a tool in the hard rock geophysicist's arsenal.

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## REFERENCES

Adamczyk, A., Malinowski, M., and Górszczyk, A., 2015, Full-Waveform Inversion of Conventional Vibroseis Data Recorded Along a Regional Profile from Southeast Poland. *Geophysical Journal International* **203**, 351-365.

Bunks, C., Saleck, F.M., Zaleski, S., and Chavent, G., 1995, Multiscale Seismic Waveform Inversion. *Geophysics* **60**, 1457-1473.

Charara, M., Barnes, C., and Tarantola, A., 1996, The State of Affairs in Inversion of Seismic Data: An Ovsp Example. *SEG Technical Program, Expanded Abstracts*, Society of Exploration Geophysicists, 1999-2002.

Kamei, R., Miyoshi, T., Pratt, R.G., Takanashi, M., and Masaya, S., 2015, Application of Waveform Tomography to a Crooked-Line 2d Land Seismic Data Set. *Geophysics* **80**, B115-B129.

Köhn, D., 2011, *Time Domain 2d Elastic Full Waveform Tomography*. PhD Dissertation, Christian-Albrechts-Universität zu Kiel.

Köhn, D., De Nil, D., Kurzmann, A., Przebindowska, A., and Bohlen, T., 2012, On the Influence of Model Parametrization in Elastic Full Waveform Tomography. *Geophysical Journal International* **191**, 325-345.

Lailly, P., 1983, The Seismic Inverse Problem as a Sequence of before Stack Migrations. *Conference on Inverse Scattering, Theory and Application*, Society of Industrial and Applied Mathematics, 206-220.

Neklyudov, D., Silvestrov, I., and Tcheverda, V., 2013, How Important Are Low Time Frequencies for Offset Vsp Full Waveform Inversion? *75th EAGE Conference & Exhibition incorporating SPE EUROPEC*, European Association of Geoscientists and Engineers, We P10 12.

Nocedal, J. and Wright, S., 2006, *Numerical Optimization*. Springer New York.

Owusu, J.C., Podgornova, O., Charara, M., Leaney, S., Campbell, A., Ali, S., Borodin, I., Nutt, L., and Menkiti, H., 2016, Anisotropic Elastic Full-Waveform Inversion of Walkaway Vertical Seismic Profiling Data from the Arabian Gulf. *Geophysical Prospecting* **64**, 38-53.

Tarantola, A., 1984, Inversion of Seismic Reflection Data in the Acoustic Approximation. *Geophysics* **49**, 1259-1266.

Virieux, J. and Operto, S., 2009, An Overview of Full-Waveform Inversion in Exploration Geophysics. *Geophysics* **74**, WCC1-WCC26.