Submission code: MNLW87D5Y5

See this and other abstracts on our website: https://home.sbgf.org.br/Pages/resumos.php

From Seismic Data to Reservoir Properties: A Paradigm Shift with Wave Equation-Based Inversion

Panos Doulgeris (Delft Inversion), Peter Haffinger (Delft Inversion), Dries Gisolf (Delft Inversion)

From Seismic Data to Reservoir Properties: A Paradigm Shift with Wave Equation-Based Inversion

Panos Doulgeris, Peter Haffinger, and Dries Gisolf, Delft Inversion

Abstract Summary

We present a 1.5D wave-equation-based inversion method (WEB-AVO) for quantitative reservoir characterisation. By solving the elastic wave equation in integral form, the method accounts for interbed multiples, mode conversions, and transmission effects, enabling inversion on raw migrated gathers. It directly estimates compressibility and shear compliance—elastic parameters closely linked to pore fill and lithology. A field example demonstrates good agreement with well data despite seismic noise. The approach is particularly relevant to Brazilian settings, including pre-salt carbonates and clastic reservoirs, where complex overburden and multiple scattering challenge conventional AVO inversion techniques.

Introduction

As exploration moves into more geologically complex and economically sensitive environments, the need for accurate, quantitative seismic reservoir characterisation in exploration, development, and time-lapse production monitoring becomes increasingly important. While Full-Waveform Inversion (FWI) offers a powerful framework for extracting high-resolution subsurface models by solving the full 3D elastic wave equation, see Tarantola (1984), its application remains computationally very demanding and is therefore often limited to background velocity estimation. To address this, we introduce a 1.5D wave equation-based (WEB-AVO) inversion method tailored to reservoir characterisation. It focuses on the estimation of compressibility, shear compliance, and density in a locally horizontally layered medium, offering a tractable and efficient alternative, grounded in full physics, see Gisolf (2017) for more details.

This approach is the next step in the historical evolution of forward modelling in seismic inversion. From Zoeppritz's exact solution for a single interface (1919) to Kennett's extension to layered media (1983), and the widespread use of linearized approximations such as Aki-Richards (1980), the field has continually sought better trade-offs between realism and practicality. By solving the integral representation of the nonlinear wave equation, our method overcomes the limitations of linearizations and provides a robust framework for quantitative interpretation. In this abstract, we outline the key elements of this technology and explore how it can address important subsurface challenges in Brazil and abroad.

WEB-AVO inversion theory

WEB-AVO inversion is a non-linear solver to the 1D elastic wave equation. It retains the efficiency of conventional AVO by operating in a localized, horizontally layered framework using migrated seismic data, but solves the full elastic wave equation in integral form to iteratively account for interbed multiples, mode conversions, and transmission effects. The inversion targets fundamental rock physics parameters and proceeds through successive updates of the wavefield and subsurface model, converging toward a physically consistent solution. Unlike traditional methods that rely on primary reflections and linearizations of the wave equation, WEB-AVO captures the full complexity of the seismic response with modest computational overhead, offering a practical and scalable alternative for reservoir-scale quantitative interpretation.

Figure 1 illustrates the core workflow of the WEB-AVO inversion. It begins with migrated seismic data and a low-frequency background model. An initial inversion of the data equation is performed assuming primary reflections only, yielding a first estimate of the elastic properties. This is

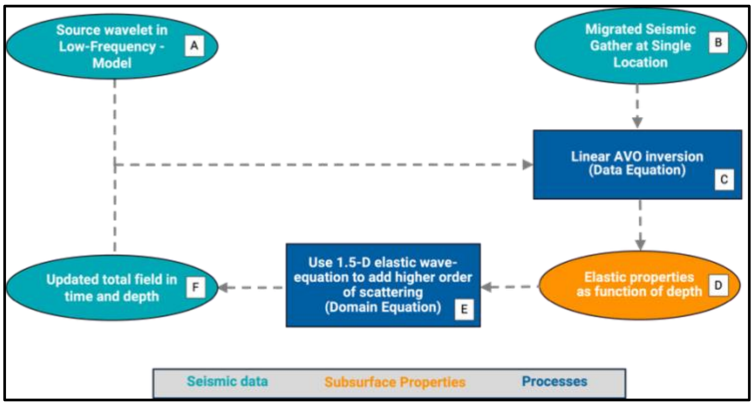

Figure 1: Block diagram of the WEB-AVO inversion: Iterative linear inversions (C) for properties followed by feed-forward operations (E) to model additional orders of scattering.

followed by forward modeling of the domain equation to compute a total wavefield that now includes one order of scattering more than before. This updated wavefield is then used in a new inversion step, forming an iterative loop where elastic properties and wavefields are refined until convergence. The output of WEB-AVO inversion consists of a set of elastic properties of the subsurface and the wavefields calculated in the medium. The latter can be used for quality control purposes by the interpreter. The key innovation of WEB-AVO inversion lies in progressively incorporating complex wave phenomena - such as interbed multiples and multiple mode conversions - into the inversion without abandoning the linear inversion core, ensuring physical realism and computational efficiency.

The role of rock physics

Rock physics provides the fundamental link between seismic-derived elastic properties and reservoir characteristics such as lithology, porosity, and fluid content. In WEB-AVO, the use of compressibility (κ), inverse of bulk modulus (K), and shear compliance (M), inverse of shear modulus (μ) - rather than impedances - enhances the interpretability and sensitivity of inversion results. Compressibility is responsive to changes in pore fill, around three times more sensitive than acoustic impedance, see Figure 2, making it valuable for identifying saturation variations in clastic settings, such as the turbidite reservoirs of the Campos Basin. In contrast, shear compliance is largely fluid-insensitive and offers a stable, lithology-driven view of the subsurface.

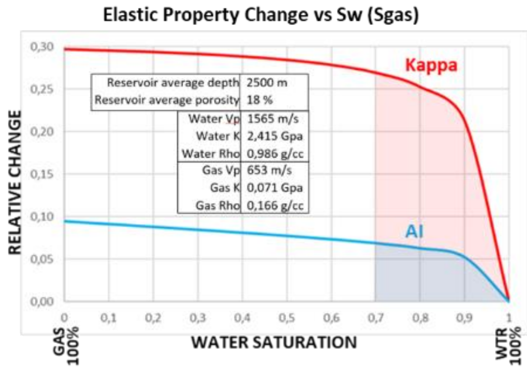

Figure 2: Fluid sensitivity comparison between AI and κ in a gas-filled sandstone reservoir.

In Brazilian pre-salt carbonate plays, notably in the Santos and Campos Basins, these parameters have the potential to enable better discrimination of intra-carbonate facies and improved porosity mapping. Compliances are particularly effective in these carbonates due to their greater dynamic range in rocks with moderate to high porosity, allowing subtle textural and diagenetic variations to be resolved seismically. These characteristics often extract added value from the available seismic and well data. By directly inverting for κ and M, the method provides interpreters with elastic attributes that are both physically meaningful and operationally discriminative for reservoir evaluation, de-risking, and development planning, features that can prove to be critical in complex and high-stakes exploration environments such as those offshore Brazil.

Understanding multiple scattering

Multiple scattering is an inherent component of seismic data, particularly in stratified overburdens where interbed multiples and transmission effects can distort the amplitude behavior of reflections at reservoir level. In conventional workflows, these effects are often treated as noise and removed through extensive pre-conditioning of migrated gathers - an effort that is both time-consuming and imperfect. In contrast, the WEB-AVO method explicitly models multiple scattering through the full elastic wave equation, incorporating these interactions directly into the inversion. As a result, their influence is not only understood but systematically accounted for, reducing the need for aggressive data conditioning. This provides a significant timing advantage in project workflows, while also preserving critical wavefield information that contribute to the accuracy of the predicted properties. Figure 3 illustrates the progressive build-up of multiple scattering using a synthetic VSP display generated via the integral formulation of the elastic wave equation. By gradually expanding the analysis window originally defined for primary reflections, we observe how multiples originating in the overburden begin to contaminate the primaries' time interval. While this analysis is performed at a well location, WEB-AVO models the complete elastic wavefield across the domain, enabling similar interpretations away from wells. The primary goal of this exercise is to define an optimal temporal window that captures relevant scattering while avoiding contamination from unrelated wavefield components. Additionally, this type of wavefield analysis can offer valuable insights for seismic processing workflows, particularly in determining the impact of overburden-related energy on reservoir amplitudes.

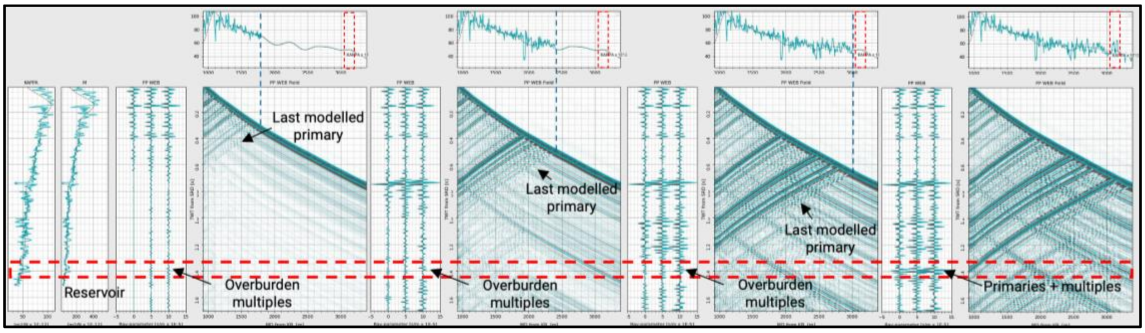

Figure 3: Synthetic VSP displays highlight the generation of multiple scattering above the reservoir that directly distorts the amplitudes at reservoir level. This study can be performed based on well logs or with the wave fields produced by WEB-AVO.

Field example: Application to the Penobscot Dataset

The WEB-AVO method was applied to the Penobscot 3D seismic dataset, a publicly available open file volume from the Scotian Shelf, offshore Nova Scotia. The inversion was performed directly on raw migrated seismic gathers without additional preconditioning applied, demonstrating the method's robustness in the presence of moderate noise and limited data fidelity. The dataset includes two wells (L-30 and B-41) that penetrate a well-imaged clastic reservoir within the Early Cretaceous Missisauga Formation. Figure 4 shows the inverted κ and M at the location of a well (orange line), overlaid with the well log response (gray line). Despite the presence of noise in the seismic gather, the match between the inverted and logged κ is remarkably good, validating the method's ability to extract quantitative elastic properties under realistic conditions. To assess lateral consistency, Figure 5 presents a section of inverted κ and M along a seismic line that crosses both wells. The inversion clearly delineates the target formation and reveals its lateral continuity, offering insight into

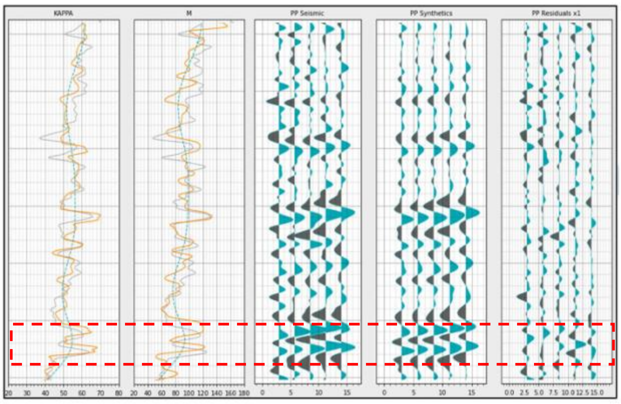

Figure 4: Inverted κ and M at a well location along with the seismic gather, the predicted gather and the residual. The input gather has not been conditioned, however, a lot of the noise present is rejected by the wave equation

reservoir extent and compartmentalization. This example underscores the potential of WEB-AVO to deliver high-resolution elastic attributes in challenging datasets; similar uplift is anticipated in Brazil's clastic reservoirs - such as those in the Campos and Ceará Basins - where multiple scattering and complex overburden often hinder conventional interpretation.

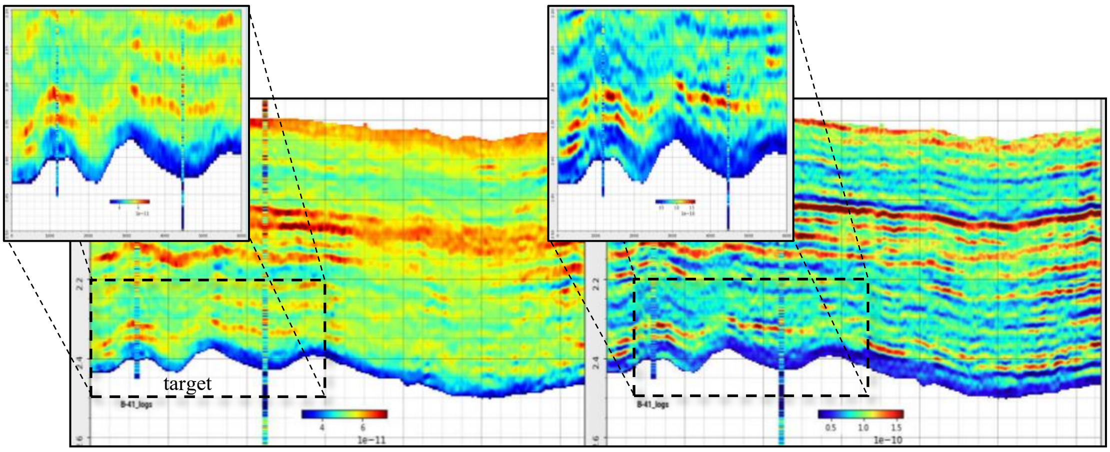

Figure 5: Cross section along a line that connects the two available wells in the field. Both κ and M help delineate the extent of the reservoir and lateral variations.

Conclusions

The WEB-AVO methodology provides a wave-equation-based inversion framework that can iteratively model multiple scattering, mode conversions, and transmission effects. This enables the use of raw migrated gathers, reducing the need for extensive pre-conditioning while preserving critical amplitude information. Results presented here demonstrate that the method can recover compressibility (κ) and shear compliance (M) with good agreement to (blind) well data, even in the presence of moderate seismic noise. These parameters are directly linked to pore fill and lithology, making them particularly useful for characterising both clastic and carbonate reservoirs. This is especially relevant in the Brazilian context: clastic targets in the Campos and Ceará Basins, as well as pre-salt carbonate reservoirs in the Santos Basin, are known to be affected by strong interbed multiples and complex overburden effects.

Acknowledgments (Optional)

The authors kindly thank Effie Amanatidou for producing the field case figures and dGB Earth Sciences for making the data available as an OpendTect project via their TerraNubis portal terranubis.com.

References

Aki, K., & Richards, P. G. (1980). Quantitative Seismology: Theory and Methods. W. H. Freeman and Co., San Francisco.

Gisolf, D., Haffinger, P., and Doulgeris, P. (2017). Reservoir-oriented wave-equation-based seismic amplitude variation with offset inversion. Interpretation, 5(3), SL43-SL56.

Kennett, B. L. N. (1983). Seismic Wave Propagation in Stratified Media. Cambridge University Press.

Tarantola, A. (1984). Inverse problem theory and methods for parameter estimation. Geophysics, 49(8), 1259–1266.

Zoeppritz, K. (1919). Erdbebenwellen VII. Über Reflexion und Durchgang seismischer Wellen durch Unstetigkeitsflächen. Nachr. Ges. Wiss. Göttingen, Math.-Phys. Klasse, 66–84.