Practical application of Wave Equation Based AVO Inversion

John Coffin
Delft Inversion
coffin@delft-inversion.com

Panos Doulgeris
Delft Inversion
doulgeris@delft-inversion.com

SUMMARY

This talk demonstrates a wave-equation based method to extract unique reservoir properties from seismic data. Genuine seismic data will always have some degree of non-primary energy such as interbed multiples. Using **Wave Equation Based AVO Inversion (WEB-AVO)** we consider primary reflections, together with interbed multiples, mode conversions and transmission effects. Notably different to conventional AVO inversion methods that assume primary reflections, an elusive seismic reality. A significant differentiator for **WEB-AVO** is the ability to work with a wider range of seismic gathers. possibly coming out of processing immediately after migration, without special conditioning. The **WEB-AVO** results differ from conventional methods being layer properties of compressibility and shear compliance, rather than interface properties such as P and S impedance. Compressibility; the inverse of bulk modulus and shear compliance; the inverse of shear modulus, provide a natural separation between fluid and lithological effects, that is required for robust reservoir properties prediction. This separation is key when deriving porosity, saturation, and lithology products.

The scope will include the fundamentals of the **WEB-AVO** method, important steps in a **WEB-AVO** project and a number of examples. The examples are drawn from onshore and offshore Australia considering common challenges such as coal and marl in a classic sand-shale sequence. In each situation the primary wavefield at the target reservoir is being contaminated by scattered energy arriving from the overburden. This normally first presents as an unsatisfactory well-to-seismic tie and is traditionally tackled through seismic data conditioning or well log editing. However, in our examples we build alternative elastic synthetics that consider the overburden and unravel how the wavefield at the reservoir is actually formed.

INTRODUCTION

The **WEB-AVO** inversion method provides a viable way to extract unique information from “noisy” seismic data. Unlike traditional methods that condition the seismic data to match the limitation of the algorithm. In our talk we explain the fundamentals of **WEB-AVO** theory and go through the key steps for any inversion project. This is followed by three (3) case studies taken from projects conducted in Australia over the past 2 years.

FUNDAMENTALS OF WEB-AVO THEORY

WEB-AVO inversion belongs to the class of elastic Full Waveform Inversion (eFWI) methods, simplified to 1.5D, meaning 1D earth model and 2D seismic input, i.e., gathers, see Gisolf (2016) and Gisolf et al. (2017). This simplification allows a very non-linear inverse problem to be solved efficiently with modest modern computational resources. The elastic wave-equation is solved iteratively with each iteration adding an order of scattering, until convergence between the synthetic model and the input seismic has been reached, hence, multiple scattering, mode conversions and transmission effects over the target interval are properly accounted for with this type of seismic inversion. One of the unique features of the method is that it solves directly for the reciprocals of bulk and shear moduli, compressibility (κ) and shear compliance, (M), instead of conventional parameter sets, like acoustic and shear impedance. κ is the compressional product of **WEB-AVO** inversion and it is very well constrained by the travel times of PP events.

KEY STEPS IN A WEB-AVO INVERSION PROJECT

1) A rock physics study at well and seismic resolution is a fundamental building block to any inversion study and this is equally true for a **WEB-AVO** project. We must investigate if the elastic attributes that the inversion can generate are going to help us identify the desired reservoir properties. Typically, we are using the inversion to understand if properties such as porosity, saturation, Vshale and lithology can be reliably predicted away from well locations. In figure 1 we show an example set of κ and M cross-plots of porosity and facies at well resolution (0.1524m) and at seismic resolution (0-0-50-80Hz). The link between porosity and seismic-resolution κ and M can be easily established as shown in the bottom left cross-plot.

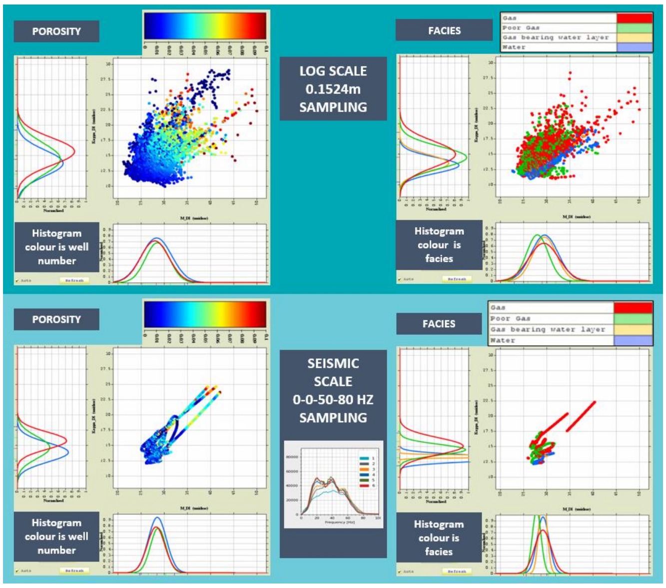

Figure 1. κ/M Cross-plots of porosity and facies at log and seismic scale

2) The value of well-ties in any inversion project cannot be understated, however before we can make a well-tie, we need to understand how a conventional primary only synthetic and an elastic wave synthetic may differ, and this poses an interesting question. For a 1.5D primary only synthetics we use the Zoeppritz equation, see Zoeppritz (1919) or an approximation, such as Aki-Richards, see Aki and Richards (1980). However, in all situations we are relying on the fundamental concept of reflectivity and wavelet convolution. This concept is assuming that all of the seismic data presented within the modelling starts and finishes within that window and that there is no interaction between different reflectors. This is often far from reality where a seismic source at the surface sends energy deep into the earth following a very complex pathway to the reservoir that involves multiple scattering, before returning through an equally complex trajectory to the receiver. Clearly whatever this seismic pulse travels through on its journey is going to have an impact on the time positioning and amplitude of the seismic sample. For the elastic synthetic we use the well-known method by Kennett (1983). We firstly look at the primary only and elastic synthetic to see if they are significantly different in the reservoir interval. A common observation that there is a complex wavefield having an impact on the seismic data in the reservoir is that the well-tie (using a primary only synthetic) is not satisfactory.

3) To understand an elastic synthetic, we need to look at how the wavefield is constructed by undertaking a wave equation based interbed multiple investigation (WEB-IMI). We often refer to WEB-IMI as a ‘virtual-VSP’. WEB-IMI has same assumptions at the forward modelling algorithm in **WEB-AVO**, namely plane waves and a 1.5D lateral assumption. In the example shown in Figure 2 taken from an onshore project in the Sichuan Basin in China, see Coffin, et al (2022) we see significant differences between the linear (Aki-Richards) and elastic modelling and critically can study where the energy at the reservoir is coming from. This then allows us to design appropriate windows for the following elastic well-tie and subsequent inversion.

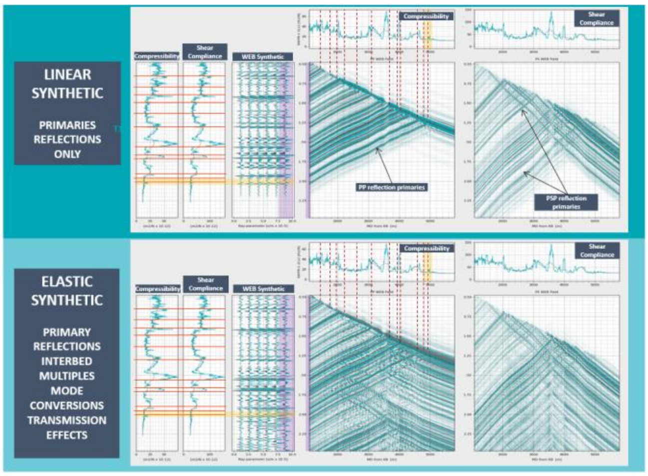

Figure 2. WEB-IMI Display of Linear & Elastic Synthetics

4) Once we have sound understanding of the interval required to model the elastic seismic response across the target interval, the time-depth relationship can be adjusted. What is different is that we may no longer be just considering tying primary reflections and can look at connecting interbed multiple and mode conversion energy present within the recorded seismic data to events present in the elastic synthetic we have available. In Figure 3 we can clearly see the curvature of mode converted energy which traditionally would have been considered residual NMO and require "flattening"

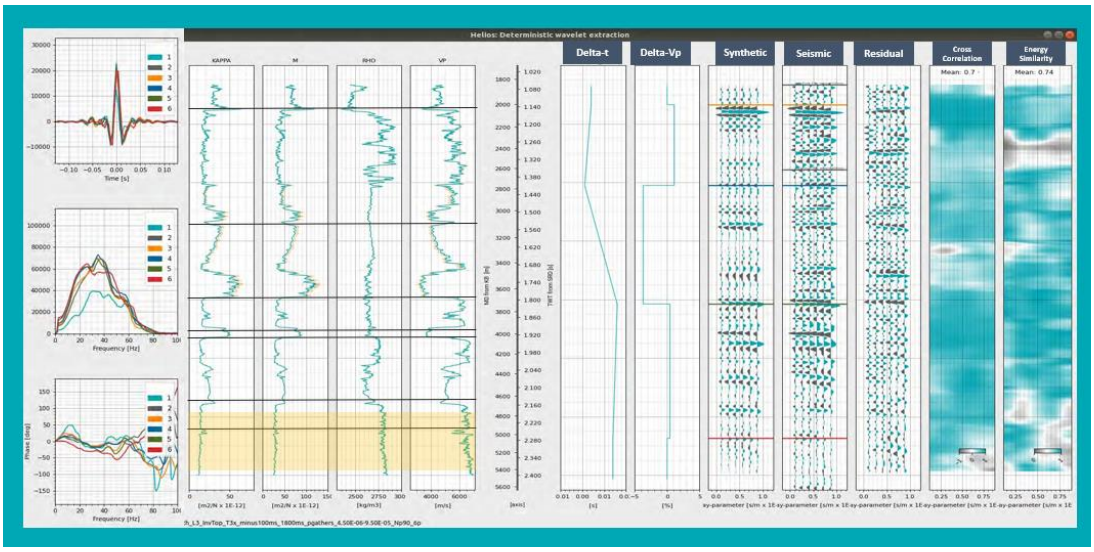

Figure 3. Elastic Well Tie

5) The low frequency model (LFM) is required to span the gap between the lowest frequency present in the recorded seismic data and DC or 0 Hz. We construct this using well log data, interval velocity from migration, depth trends and structure (interpreted horizons and fault surfaces). The purpose of the LFM is to provide a first estimate of the travel times. The travel times will then be adjusted as the algorithm converges.

6) The inversion workflow for **WEB-AVO** follows a traditional route of 1D, 2D and finally 3D inversion (we also have a 4D application which is beyond the scope of this talk). In the 1D and 2D inversion we will parameterise the inversion, using a range of statistical and deterministic wavelets which have been extracted from the seismic data. Different inversion parameters will be tested until an optimum can be found at the well location. The process continues to 2D where we undertake blind well testing using a range of LFM's constructed using the available data, once again wavelets and inversion parameters are systematically tested until an optimum set is obtained. This optimum set of wavelets, LFM and inversion parameters is applied to the 3D volume, yielding identical results on the 2D line.

ONSHORE AND OFFFSHORE AUSTRALIA CASE STUDIES

We will present three cases from recent projects conducted in Australia. In each situation we were challenged with geology that creates a complex wavefield across the reservoir intervals. The conventional approach to process or condition out what was considered "noise" obscuring the primary reflections had been unsuccessful and we applied **WEB-AVO** to unravel what the seismic data was actually telling us.

1) NW Shelf Australia Mungaroo Sands

The Triassic Mungaroo sands are a well known and prolific gas reservoir in the NW Shelf of Western Australia. In this case we studied why the Cretaceous Barrow Sands with high gas saturation presenting with a robust AVO anomaly proved to be a poor analogy for a deeper Triassic target presenting with the same characteristics. The unconformity between these two reservoir sands has small but significant marl which creates a mode conversion that arrives on top of the primary reflections in the Mungaroo.

2) Cooper Basin Coals

The dominantly Permian reservoirs in the Cooper Basin have always been a challenge to map because of the complexity of the wavefield. Multiple coals occur throughout the basin and create significant interbed multiples and transmission effects. The coals make well-ties in the area between synthetics and seismic data extremely challenging and often produced unsatisfactory results. We use elastic synthetics in **WEB-AVO** to remove a great deal of uncertainty and produce high quality well ties.

3) **Unconventional Gas Reservoir Onshore Queensland**
The Surat-Bowen basin has a number of successful gas wells in tight sands (< 10% porosity). These wells have significant production, however the presence of coals in the overburden has made it very difficult to accurately predict the location of the gas reservoir(s). In this case we will explain how **WEB-AVO** was able to remove much of this uncertainty.

CONCLUSIONS

WEB-AVO has provided a way to embrace a complex seismic wavefield for what it is, a valuable source of information about the subsurface. We have presented the key-steps in a **WEB-AVO** project showing how they differ from a conventional AVO inversion scheme. The fast elastic modelling, WEB-IMI studies and elastic well-ties prove to be significant factors in the success of the method. Finally, we provide three cases drawn from Australia where **WEB-AVO** has been successful in understanding
what the seismic data has to offer.

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