What do Acoustic FWI derived amplitudes mean in terms of elastic properties?

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Summary

Full waveform inversion (FWI) derived reflectivity (FDR) is a derivative product of FWI velocity models. FDR provides improved images below complex overburden compared to conventional seismic imaging. The next objective is to leverage FDR volumes to extract attributes for reservoir characterization. However, one should first understand the meaning of FDR amplitude in terms of elastic properties. In theory, FDR, which is derived from the FWI velocity, should be a derivative response of velocity, and a P-wave sonic log should be used to calibrate FDR before interpretation. While elastic FWI is a cutting-edge approach, current processing practices commonly use acoustic FWI with constant density. In analyzing acoustic FWI models at multiple wells from offshore Trinidad, we observe that the FWI velocity model correlates more strongly with acoustic or elastic impedance than with P-wave velocity. Therefore, we suggest using acoustic or elastic impedance well logs for the seismic well-tie and calibration of FDR volumes derived from an acoustic FWI model. This ensures a more accurate interpretation of FDR data in context of reservoir characterization.

Introduction

FWI is a transformative technology for building high-resolution accurate velocity models for better imaging of the subsurface (Tarantola, 1986; Shen et al., 2017; Huang, et al., 2021; Vigh et al., 2023). FDR is a derivative product of the FWI model, and it has consistently shown enhanced subsurface imaging under complex overburden compared to traditional seismic imaging (Liu et al., 2023; Buist et al., 2023). Soon we will have FDR gather for amplitude variation with offset (AVO) analysis (Jin et al., 2024). FWI processing can be done up to the maximum frequency in the data to provide FWI velocity models to be used in reservoir characterization. Preference is for an elastic FWI inversion (Wang et al., 2021) to derive P-wave velocity (Vp), S-wave velocity (Vs) and density (ρ). However, the more common practice to save cost and run acoustic FWI with a constant density model. In this study, the focus is on the lower frequencies (up to 20Hz) for acoustic FWI models and corresponding FDR volumes. The objective is to understand the meaning of FDR amplitudes by correlating FWI models with well logs. Once the meaning of the FDR amplitude is established, the integration of FDR data into seismic interpretation becomes viable (Kumar and Ali, 2024).

Seismic reflectivity amplitude is proportional to the derivative of impedance (Figure 1). Figure 2 shows an example of impedance (layer property, e.g., FWI model) and its corresponding reflectivity (interface response, e.g., FDR). Vertical incident seismic is a derivative of Acoustic Impedance (AI), and 20^0 mid angle stack is a derivative of Elastic Impedance (EI) (Connolly, 1999) at 20^0 (EI20). Similarly, FDR amplitude should be proportional to derivative of velocity. This can be evaluated at well locations, by correlating FWI values with well logs or by correlating FDR with well-log reflectivity. In this study, data from offshore Trinidad is utilized to correlate acoustic FWI models with well logs, establishing relationships between the two and enhancing our understanding of the meaning of FDR amplitude.

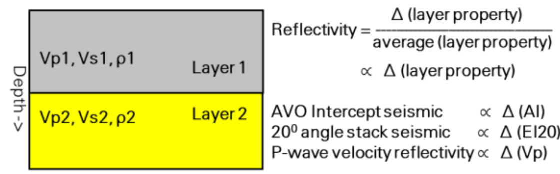

Figure 1: Schematic 2-layer earth model and how reflectivity (interface response) is related to layer property. For example, seismic amplitude is proportional to changes in impedance. The Δ symbol represents change in layer property across interface, which is layer 2 property minus layer 1 property. The ∝ sumbol shows proportional relationship.

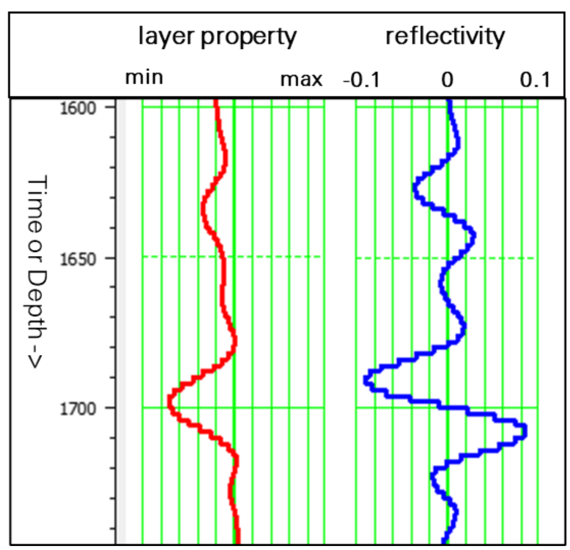

Figure 2: Example of how layer property (FWI model, well logs) and its reflectivity (FDR, seismic) response are related. Absolute amplitude is shown as layer property within seismic bandwidth (0-0-30-50 Hz filtered well log in this example). Reflectivity trace was generated from layer property as its derivative.

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Study area and data

Figure 3 depicts our study area, the Columbus Basin, offshore Trinidad, known for its prolific clastic reservoirs with unconsolidated sands (Wood, 2000). We utilized high quality OBC data acquired during 2011-2012 (Paramo et al., 2013). Recently, the seismic data has been reprocessed including the acoustic FWI based velocity model building for Kirchhoff pre-stack depth migration. Figure 4 shows 10Hz acoustic FWI velocity, its FDR response, and full-stack seismic along a well. Note that 10Hz FDR volume is showing better "sand 2" anomaly than seismic volume. The FDR response resembles seismic data but exhibits lower frequency content than the stacked seismic data, as illustrated in Figure 5. Our dataset includes acoustic FWI velocity models, employing a constant density model, at five frequencies (6Hz, 10Hz, 12Hz, 16Hz, 20Hz). These FWI velocity models are used to establish frequency dependent relationships between elastic properties (well logs) and FWI models. Figure 6 shows data available at a well location.

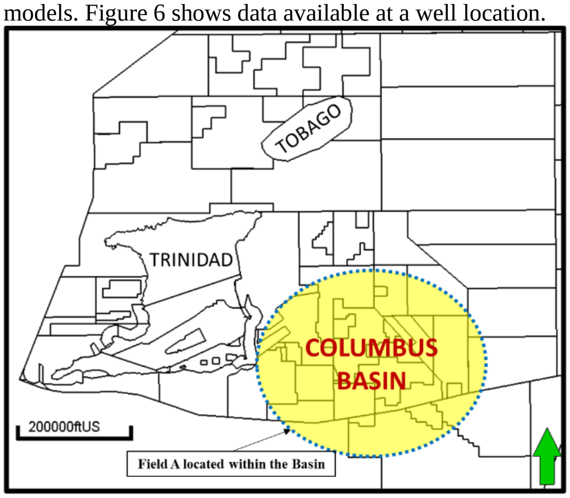

Figure 3: Location of our study area, Field A, offshore Trinidad.

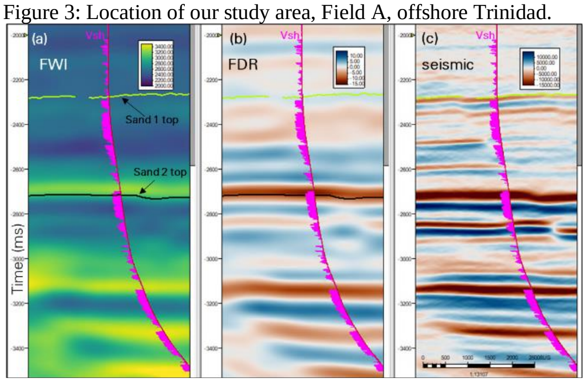

Figure 4: Comparing 10Hz acoustic FWI velocity (a), the 10 Hz FDR response (b), and Kirchhoff migrated full-stack seismic (c) along well A. FDR looks like low frequency seismic data. Shale volume (VSH) curve in pink is displayed along well.

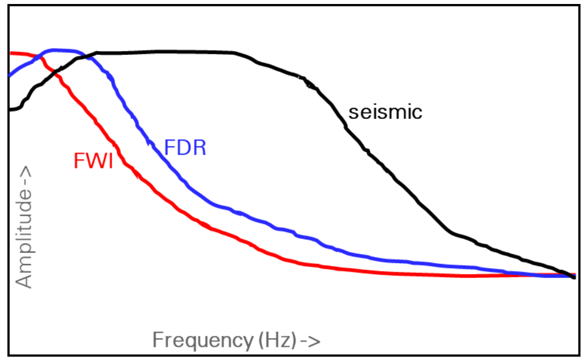

Figure 5: Schematic frequency spectrum of 10Hz acoustic FWI model (red), its FDR response (blue), and full-stack seismic (black).

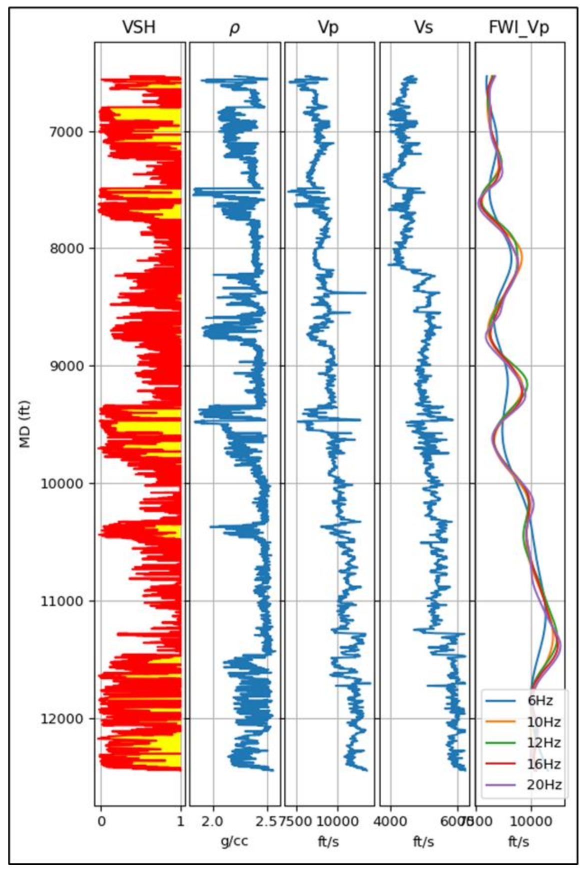

Figure 6: Example of data available at a well location (well B) for analyzing relationships between well logs and FWI models. First 4 tracks are insitu well logs (VSH, ρ, Vp, Vs) and the last track shows 5 curves extracted from 5 FWI volumes at 6Hz, 10Hz, 12 Hz, 16Hz, and 20Hz. Note that the 6Hz FWI model chacracter is distinct compared to the rest of the FWI models.

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Workflow

To understand the significance of the FDR amplitude, we extracted traces from FWI volumes along the trajectories of 8 selected wells. Subsequently, a spectrum analysis was applied to both available FWI and FDR volumes. After FWI volumes spectral analysis, the well log data from all wells underwent a uniform filtering process to align with the resolution of the FWI volumes. Following this, we derived AI, GI, and EI (ranging from 10 to 50 degrees) logs. To identify potential correlations and patterns, we conducted a Kendall cross-correlation analysis (Abdi, 2007). The data was visualized in various forms, facilitating the discernment of meaningful relationships. Figure 7 illustrates our workflow providing an overview of our approach. An alternative method involves generating the reflectivity of each well log and comparing it with FDR. However, the workflow described in Figure 7 was more straightforward requiring fewer steps.

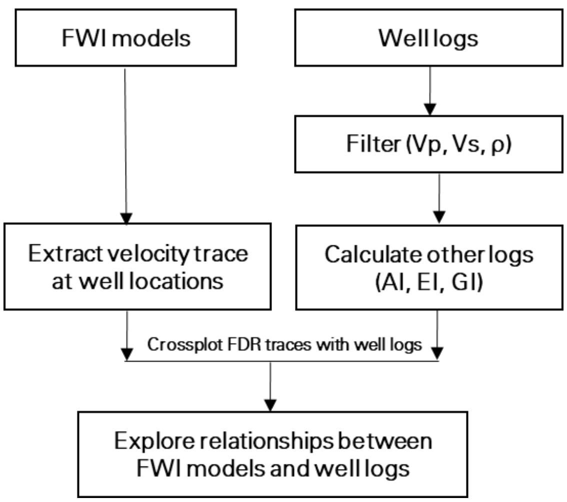

Figure 7: Workflow used to correlate FWI models with elastic properties from well logs. Traces from FWI volumes were extracted along well's trajectory. For well logs, first high-cut filter (0-0-6-12 Hz) Vp, Vs, and ρ logs to compare with FWI models (Figure 8), then calculated additional elastic response: AI, EI at 10, 20, 30, 40 and 50 degrees, and GI (Gradient Impedance). Note that EI and GI include Vs response along with Vp and ρ (Connolly, 1999).

Figure 8 shows an example of datasets at a well location used in correlating well logs with FWI response. Each FWI model is correlated with each elastic response from the well log. Figure 9 shows an example of qualitative correlation of FWI velocity at 6Hz to Vp, Vs, density, and AI well logs. Clearly, AI is better correlated to FWI velocity than Vp.

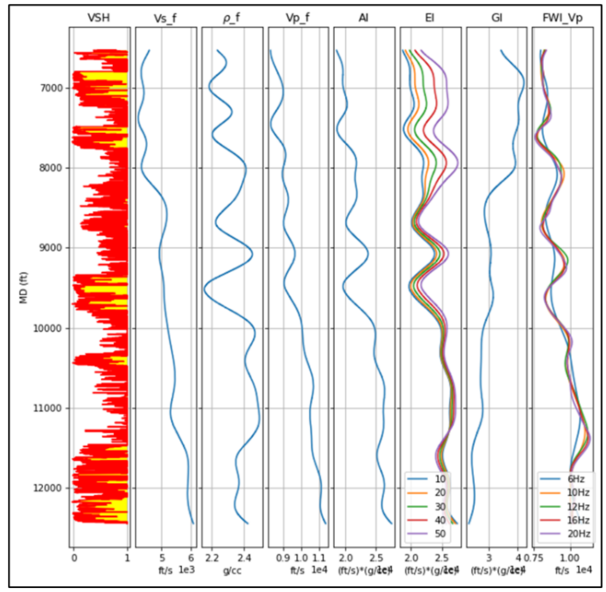

Figure 8: Example of filtered well-logs and FWI models at well B. First track is VSH to observe the lithology response and it is not used in actual correlations between well logs and FWI models. Next 6 tracks are filtered well logs used to correlate with FWI velocity models (last track).

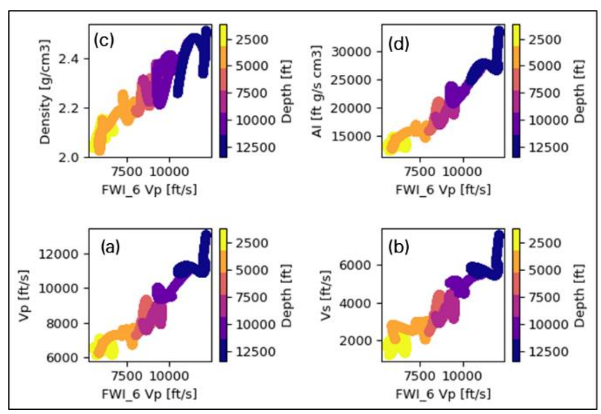

Figure 9: An example of a cross-plot of FWI model at 6Hz (x-axis) and filtered well logs (y-axis), colored by measured depth. Entire 12000 ft long well (well C) is used in this crossplot. FWI velocity at 6Hz is compared with Vp (a), Vs (b), density (c), and AI (d). Clearly AI is best correlated with FWI velocity.

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Results

Qualitative comparisons of cross-plots (Figure 9) are challenging when dealing with multiple combinations between FWI models and well logs across various wells. Figure 10 presents correlation coefficients between FWI models and wells logs for the entire well at two well locations. The blue color signifies higher correlation coefficients and therefore stronger linear relationships.

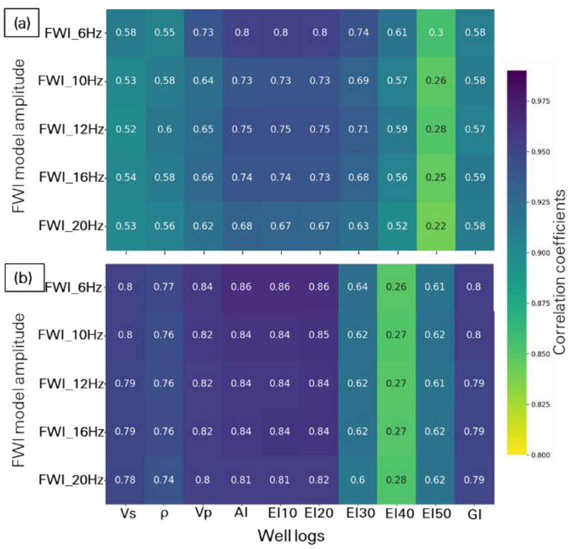

Figure 10: Table summarizing correlation coefficient between FWI models at multiple frequency (y-axis) and well logs (x-axis) at two wells: well B (a) and well C (b). Correlation values are listed for each combination and each grid is colored by the same correlation coefficient. Higher correlation (blue) means stronger linear relationship between FWI velocity and well logs.

Several key observations emerge from the analysis of the correlation between FWI models and elastic properties (Figure 10). This was not only observed in these two wells but in 6 of the 8 wells studied.:

1) AI (column 4) is better corelated with FWI velocity models than Vp (column 3)
2) EI10 (column 5) and EI20 (column 6) are equally or better correlated with FWI models than AI (column 4)
3) There is a small but notable decrease in correlation with an increase in the frequency of FWI models.

Discussion

It is evident that AI is better correlated with acoustic FWI velocity models than Vp, indicating a density leakage in the acoustic FWI models. For 2 out of 8 wells, EI10 and EI20 demonstrated stronger correlations with FWI models than AI. This is possible because we are not accounting for the elastic (Vs) effect in acoustic FWI processing. This suggests that density leakage in acoustic FWI model is most noticeable effect and Vs leakage in acoustic FWI model is less obvious. Above observations can also be explained by that in general Vs is more linearly related to Vp than ρ is related to Vp (Mavko et al., 1998). A higher correlation between Vs and Vp can result in more difficulty to differentiate the effect of Vs from Vp in FWI models.

Surprisingly, there is a diminishing correlation between FWI and elastic response as the frequency of FWI model increases. Knowing that P-to-P wave reflection energy is a function of Vp, Vs and ρ, but P-to-P-wave transmitted energy (diving waves) is a function of only Vp and ρ (equation 5.46, Aki and Richards, 2002); we anticipated more elastic effect (EI) leakage at higher frequencies, given that higher frequency FWI utilizes more reflected energy and lower frequency (say, < 8Hz) utilizes more diving energy. A potential explanation lies within the frequency dependent behavior of subsurface materials and the potential impact of attenuation effects. Spectrum analysis of FWI volumes revealed consistent spectra at 10 Hz, 12 Hz, 16 Hz, and 20 Hz, while the 6 Hz FWI volume showed significant differences (last track in Figures 6 and 8). This disparity can be attributed to the dominance of diving waves in the 6 Hz volume. This suggests that the nature of seismic waves, whether dominated by diving or reflection waves, plays a crucial role in the correlation with elastic properties. Further field studies are necessary to gain a comprehensive understanding of the connections between acoustic FWI models and elastic properties. Moreover, we employed a single set of filtering to well logs when correlating them with multiple frequency FWI models.

Conclusions

We present a workflow with data examples to understand the meaning of acoustic FDR amplitude in terms of elastic response. Correlating acoustic FWI velocity models with well logs across multiple wells from offshore Trinidad, we found that the FWI velocity model is more closely related to AI than Vp. Additionally, elastic impedances (EI10 and EI20) demonstrate equal or better correlations with FWI velocity compared to AI. This implies the presence of density and Vs leakage into the acoustic FWI velocity model. If one must pick one elastic property to use for well-tie and calibration of FDR volume, we should use AI. This leakage of ρ and Vs in the acoustic FWI velocity model is a function of geology. Therefore, we should perform a similar analysis for every project before making use of FDR amplitude in attribute extractions.

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