

The Use and Abuse of AVO: Value, Analysis, Errors and Pitfalls

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Summary

AVO might be considered the “holy grail” in the use of seismic data to remotely describe the subsurface in all its geological complexity of lithology, porosity, rock fabric, fluids, pore pressure and stress.

As with any scientific method that claims to be a “theory of everything” there are practical approximations and assumptions that must be satisfied, along with pitfalls to be avoided, in order to achieve the promise of AVO’s superior reservoir characterization ability.

This paper provides some practical considerations in the use and abuse of methods that underlie the application of AVO.

Outline of topics:

- Motivation for use of AVO methods from bright spots, AVO reflectivity to QI including rock physics and geology
- Basic theory and methods of AVO reflectivity (“Fluid Factor”) to full AVO inversion for elastic properties
- Example case study applications of both AVO reflectivity and AVO inversion to exploration
- Pitfalls and analysis of errors in general AVO methods with case study examples

Introduction

Interpreting anomalous bright amplitudes termed “bright spots” (Figure 1), on stacked seismic sections as indicative of reservoir porosity and hydrocarbon saturation, has a long history in locating exploration wells.

Motivated by this qualitative “bright spot” observation there was a need to quantifiably understand what was the underlying seismic rock physics basis that caused these anomalies. Consequently, this improved quantitative understanding of “bright spots” has evolved into various seismic methods termed Amplitude Versus Offset (AVO), AVO inversion and Quantitative Interpretation (QI).

Seismic rock physics theory also forms the basis for AVO and QI through an understanding that shear seismic waves (S-waves) contain different information about rock properties than do standard compressional seismic waves (P-waves). AVO methods to analyze pre-stack P-wave gathers for the S-wave information contained or “missing” within them is a logical and quantifiable petrophysical extension into pre-stack seismic data from the confusing and simplistic interpretation of stacked “bright spot” amplitudes.

This paper provides some basic practical considerations in the use and abuse of methods that underlie the application of AVO and QI workflows.

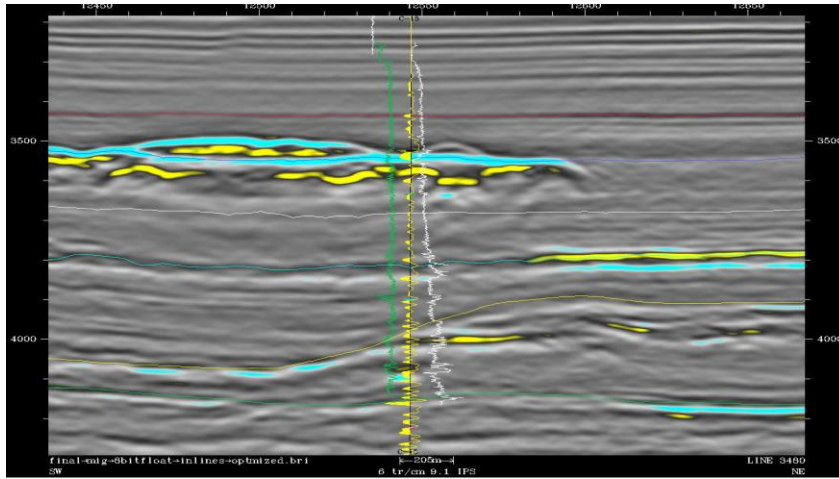


Figure 1, “bright spot” anomaly drilled offshore Nova Scotia.

AVO theory, methods and examples of seismic reservoir characterization

A common starting point for AVO analysis is the linearized 3-term approximation to the Knott-Zoeppritz equations for the partitioning of angle dependent P-wave and S-wave energy across a boundary between two elastic layers, is given by Aki and Richards (1980) shown below in equation (1). This basic linearized equation assumes small fractional velocity and density changes with 2nd order terms ignored and incident angle $\theta_p < 10$ degrees of critical.

$$R_{pp}(\theta) = \frac{1}{2} \left(\frac{\Delta V_p}{V_p} + \frac{\Delta \rho}{\rho} \right) - 2 \frac{V_s^2}{V_p^2} \sin^2 \theta_p \left(2 \frac{\Delta V_s}{V_s} + \frac{\Delta \rho}{\rho} \right) + \frac{1}{2} \tan^2 \theta_p \frac{\Delta V_p}{V_p} \quad (1)$$

where: V_p , V_s velocities, ρ density, are averaged across an interface and angle θ_p (or just θ) is the average of incident and transmitted P-wave. $\Delta V_p/V_p$, $\Delta V_s/V_s$, $\Delta \rho/\rho$ are fractional changes in V_p , V_s and ρ across an interface.

A common industry method based on equation (1) is to model fit the AVO response to extract zero angle P-impedance reflectivity (R_p) and shear impedance reflectivity (R_s) “seismic traces” through “weighted stacking” of CMP gather data using equation (2) (Fatti, Smith and Gidlow 1994) that can be derived from equation (1) with some algebraic manipulation.

$$R_{pp}(\theta) = (1 + \tan^2 \theta) \frac{\Delta I_p}{2I_p} - 8 \left(\frac{V_s}{V_p} \right)^2 \sin^2 \theta \frac{\Delta I_s}{2I_s} - \left(\frac{1}{2} \tan^2 \theta - 2 \left(\frac{V_s}{V_p} \right)^2 \sin^2 \theta \right) \frac{\Delta \rho}{\rho} \quad (2)$$

where:

$$\frac{\Delta I_p}{2I_p} = R_{pp}(0) = \frac{1}{2} \left(\frac{\Delta V_p}{V_p} + \frac{\Delta \rho}{\rho} \right) \quad \frac{\Delta I_s}{2I_s} = R_{ss}(0) = \frac{1}{2} \left(\frac{\Delta V_s}{V_s} + \frac{\Delta \rho}{\rho} \right)$$

Equation (2) forms the starting point for a 2-term approximation by dropping the small third term in fractional density reflectivity contrast $\Delta \rho/\rho$, as the number of unknowns R_p and R_s should not exceed the measurable CMP gather quantities (AVO intercept and gradient) to ensure robust unambiguous parameter estimates, especially in the presence of noise.

Figure 2 shows an example from a walkaway VSP that demonstrates and confirms the seismic AVO behavior of a gas sand that can be predicted and from equations (1) and (2) and hence used to extract R_p and R_s sections through model-based fitting as shown in figures 3 a) and b).

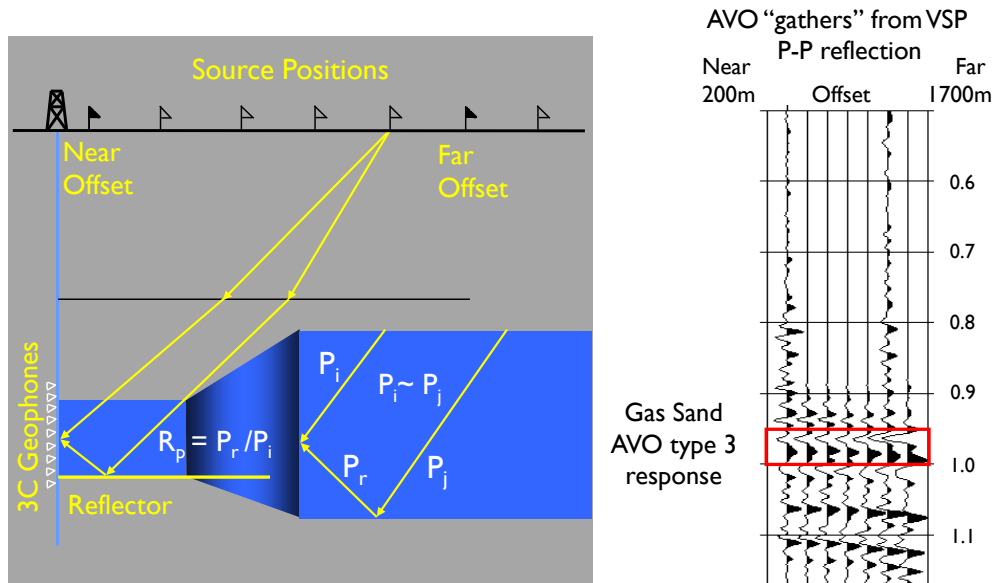


Figure 2, walkaway VSP that demonstrates and confirms the true AVO response of a gas sand to P-wave seismic reflections.

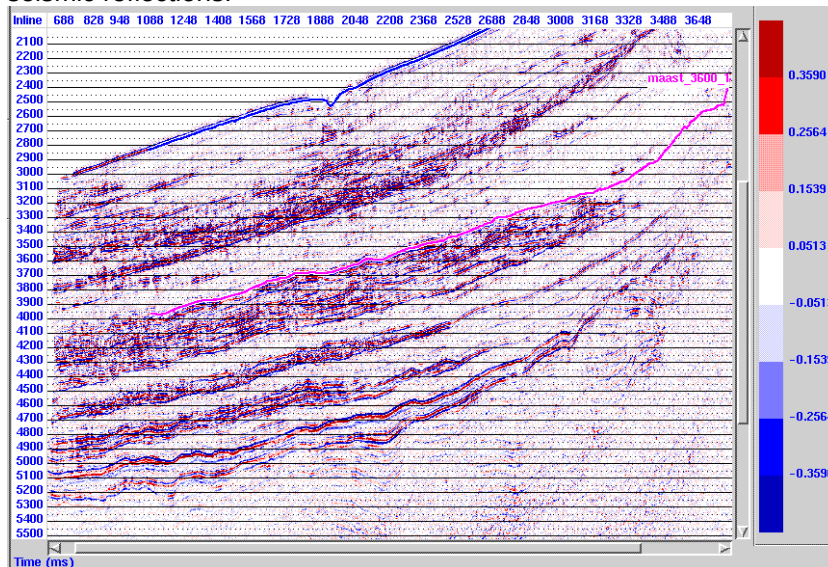


Figure 3a, R_p section from offshore West Africa.

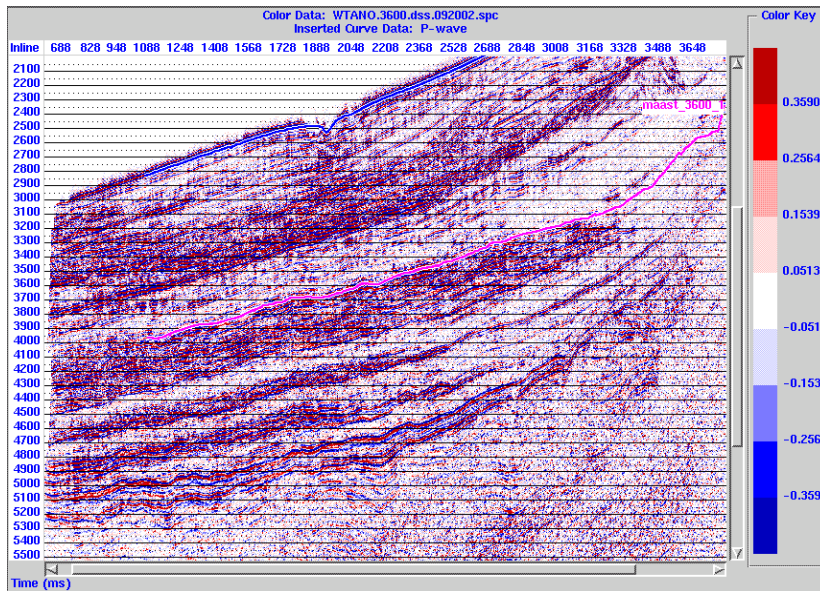


Figure 3b, Rs section from offshore West Africa.

From this extraction of Rp and Rs sections, a “Fluid Factor” or “Geogain” section can be produced from equation (3) following the 2-term version of AVO equation (2), that attempts to remove the background encasing lithology to reveal just the porous hydrocarbon charged reservoir (figure 4) that is ironically similar in appearance to the simplistic stacked “bright spot” section in figure 1.

Fatti, Smith & Gidlow Geogain (Geophysics Sept 94'): From Impedance background "mudrock" relationship $I_p = A + B I_s$

$$\Rightarrow \text{Fluid Factor FF(Geogain)} = R_p - \frac{B I_s}{B I_s + A} R_s \quad (3)$$

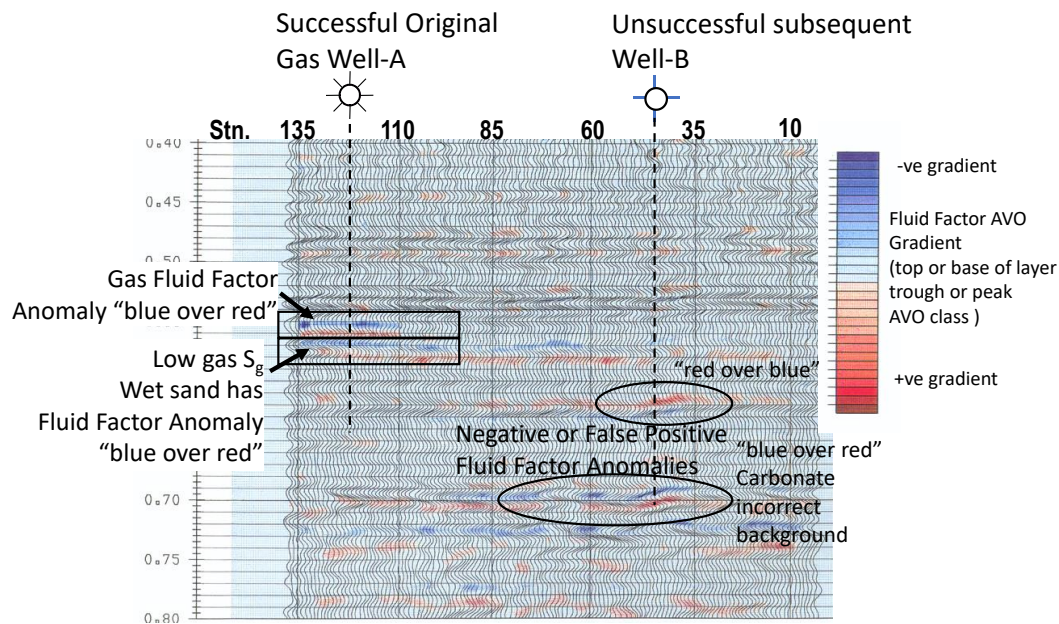


Figure 4, “Fluid Factor” section with drilling results and interpretation.

Pitfalls and analysis of errors

The “Fluid Factor” section in figure 4, shows several negative or false positive anomalies. These are a result of various errors or assumptions in the AVO method that the pre-processed seismic data has a “true” AVO response i.e., seen in the walkaway VSP in figure 2, that has preserved the AVO signal and is uncontaminated by noise and multiple interference or numerous other factors, that cause a failure of the method to correctly predict hydrocarbon charged reservoirs.

A list of the factors contributing to lack of robustness of AVO inversion/QI that need to be considered include:

Tuning and interference, poor S/N, inadequate offset, inadequate bandwidth, inadequate fold, unbalanced channels, coherent noise, complex structure and stratigraphy, geometric spreading, focusing, scattering, dip, Fresnel zone effects, fault shadows, near surface effects including source and receiver coupling and directivity, array effects, overburden attenuation, attenuation and dispersion, anisotropy, lateral velocity variations, improper processing (PSTM vs PSDM) and amplitude scaling, weak petrophysical signal, inappropriate indicators, inversion non-uniqueness, incorrect NMO correction etc.

An example of one such factor that is rarely considered is the impact of pre-stack migration scaling in preserving the AVO spatial response. Figure 5 a, and b, shows the difference between Pre-stack Time Migration (PSTM) compared to Pre-stack Depth Migration (PSDM) where the 40-degree incident angle PSTM section shows an isolated AVO amplitude that is reminiscent of the “bright spot” in figure 1, whereas the PSDM section in figure 5b, does not show an isolated AVO anomaly.

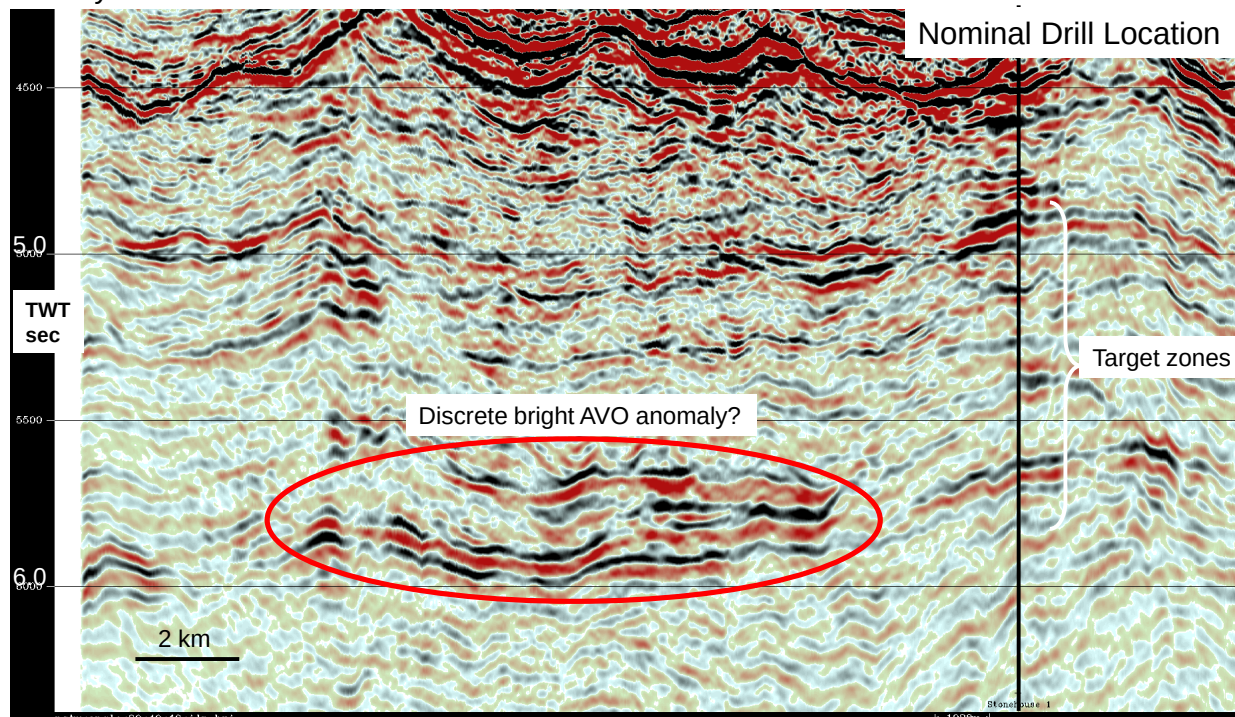


Figure 5a, 40-degree incident angle PSTM section showing isolated AVO amplitude anomaly.

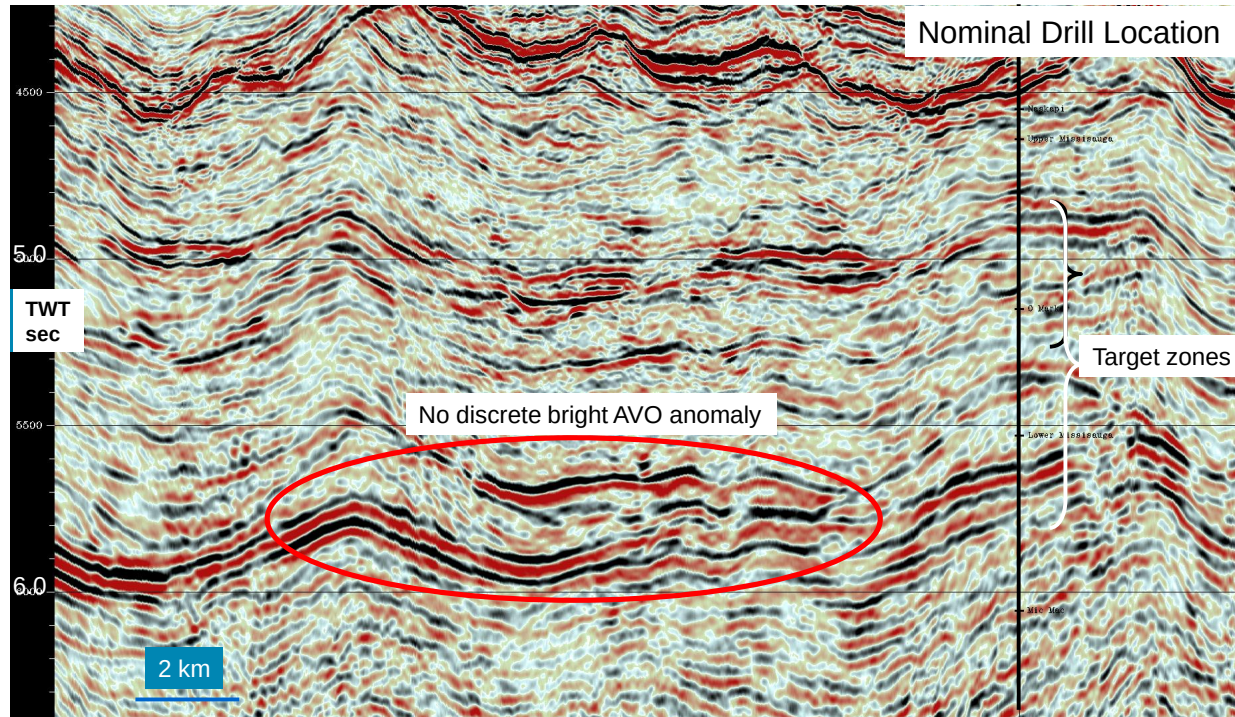


Figure 5b, 40-degree incident angle PSDM section showing no isolated AVO amplitude anomaly.

References

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