AVO Crossplotting II: Examining Vp/Vs Behavior

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Introduction

The development of AVO crossplot analysis has been the subject of much discussion over the past decade and has provided interpreters with new tools for meeting exploration objectives. Papers by Ross (2000) and Simm et al. (2000) provide blueprints for performing AVO crossplot interpretation. These articles refer to the Castagna and Swan (1997) paper which laid the foundation for AVO crossplotting. The AVO classification scheme presented by Castagna and Swan, which was expanded from the work of Rutherford and Williams (1989), has become the industry standard. Castagna and Swan also investigated the behavior of constant Vp/Vs trends, concluding that for significant variations in Vp/Vs many different trends may be superimposed within AVO crossplot space, making it difficult to differentiate a single background trend. A misapplication of this concept has been to infer a direct correlation between these changing background Vp/Vs trends with rotating intercept/gradient crossplot slopes (what Gidlow and Smith (2003) call the fluid factor angle, and Foster et al. (1997) the fluid line) observed in seismic data. The central question of this paper is: when is this background trend (or fluid line) rotation a representation of real geology and when is it a processing-related phenomenon? This paper is a shortened version of a recent CSEG Recorder article (December 2008).

AVO Crossplot Rotations

The key value of AVO crossplot interpretation is the ability to differentiate population outliers relative to background trend points within crossplot space. Incorporating *direct hydrocarbon indicators* (*DHI*s) via crossplotting can play a significant role in minimizing the risk associated with an exploration play. The stability of the background trend (fluid angle) can have an impact on what is being interpreted as anomalous, be it fluid or lithology induced outliers. Castagna and Swan's (1997) *Interpreter's Corner* article concluded that many background trends can be erroneously superimposed in AVO crossplot space, particularly if too large a depth range is brought into the interpretation window. This presents difficulties when performing crossplotting analysis, particularly as it pertains to non-uniqueness. For a given anomaly (population outliers) an interpretation of an *increase* in Vp/Vs (due to a superimposed background trend) can be just as feasible as a *decrease* in Vp/Vs (due to a fluid response or coal) dependent upon the choice of background trend. The Castagna and Swan crossplot template, seen in figure 1a, is often used in the literature to explain crossplot behavior observed in seismic data. However, the constant Vp/Vs lines used in the design of this crossplot template do not reflect most worldwide compaction trends and established empirical mudrock line relationships. Figure 1b highlights how constant Vp/Vs lines cut across a given mudrock line only within a limited range. Outside these overlap zones the constant Vp/Vs lines would be considered physically unrealistic. A follow-up *Interpreter's Corner* article by Sams (1998) also questions the appropriateness of using these constant Vp/Vs trends in crossplot templates. Sams demonstrates that constant Vp/Vs lines approach a mudrock line relationship only at very high P-wave velocities.

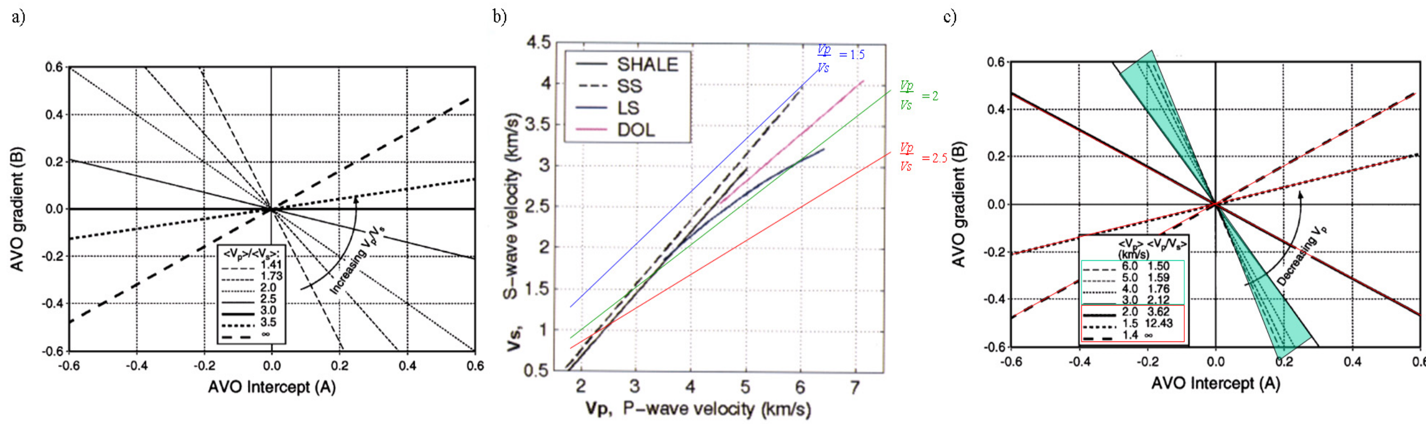


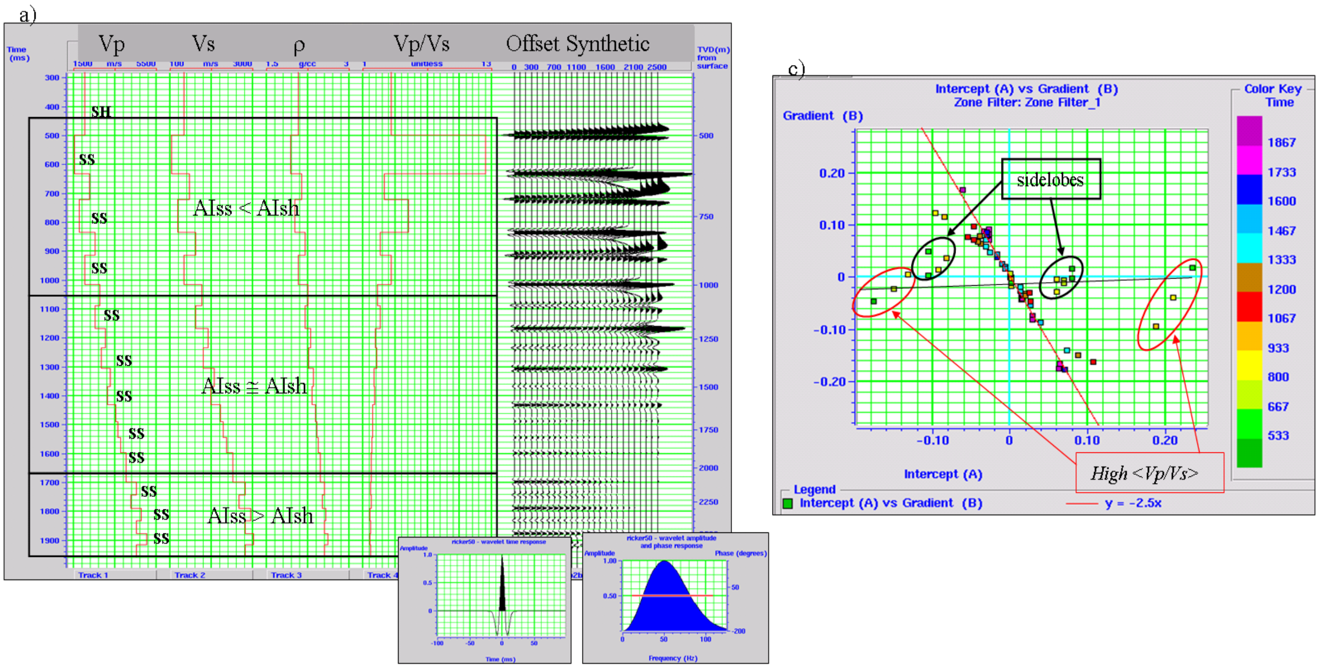
Figure 1. AVO behavior in crossplot space. (a) Castagna and Swan's (1997) background trend illustrates AVO crossplot rotation as Vp/Vs varies. (b) The empirical relationship that exists between Vp and Vs cuts across constant Vp/Vs lines. Image modified from Scott Pickford poster (2000). (c) Castagna et al.'s (1998) revised background trend rotations incorporating a linear Vp versus Vs trend. The amount of rotation present in the crossplot that incorporates a mudrock relationship is significantly less than for the constant Vp/Vs scenario (for all but extremely low velocity ranges), suggesting that large rotations in crossplot space should not be considered normal in most seismic datasets. This also presents a case for utilizing larger windows in crossplot analysis than previously considered.

Castagna et al. (1998) address this very concern in their expanded follow-up article. Figure 1c shows the rotation of the intercept/gradient slope when a linear *Vp versus Vs* trend is taken into account in the creation of the crossplot template. The result is a less dramatic rotation of background trend rocks within moderate ranges of Vp/Vs ratios. The AVO crossplot rotation effect can be problematic for interpretation only when low velocity unconsolidated materials (and their associated high Vp/Vs ratios) are encountered. An example from the Western Canadian Sedimentary Basin (WCSB) illustrates the significance of this result. Most reservoirs in the WCSB have velocities on the low end of 2500m/s (clastics) and at the high end of 6000m/s (carbonates). Within this velocity range Vp/Vs ratios of 1.6-2.5 encompass most background trend rocks and this places their AVO responses within the green background trend highlighted in figure 1c. Another factor to consider during the interpretation of crossplots is the signal-to-noise ratio (S/N) issues which tend to broaden the intercept and gradient (I/G) reflectivity points within crossplot space into oval distributions (Simm et al., 2000). This seismic noise acts to further blend the background trend lines together into a singular cloudy trend. Therefore, since depth dependent fluid angle variations are typically small and often embedded within seismic noise, larger temporal windows can be brought into AVO crossplot space when searching for AVO anomalies in the WCSB.

The term rotation is used frequently in this article to describe observations made in AVO crossplot space. A more appropriate term to use is *apparent rotation*, as points in crossplot space are not actually going through a true rotation (denoted by $I' = I\cos\theta + G\sin\theta$, $G' = -I\sin\theta + G\cos\theta$) but instead are being subjected to scaling and/or skewing operations (denoted by $I' = k1 \times I$, $G' = k2 \times G$ and $I' = k1 \times I$, $G' = k2 \times G + k3 \times I$, respectively).

AVO Modeling

Modeling was performed using a Castagna mudrock line relationship (Castagna et al., 1985) to verify the assertion that AVO crossplot slopes should be comparable when the Vp/Vs trend is depth dependent (i.e. following a compaction trend). In this model (figure 2a) the shallow section contains sands with lower impedance than surrounding shales, the intermediate section contains sands and shales of similar impedance, while the deeper section contains sands with higher impedance. An offset synthetic was created using a zero-phase seismic wavelet of reasonable bandwidth (Figure 2b), and AVO extraction was performed using the Shuey equation (1985).



b) Wavelet with associated bandwidth

Figure 2. AVO Model Example. (a) An AVO model was built using: *Vp* honoring a compaction trend; *Density* estimated using the Gardner et al. (1974) equation; *Vs* estimated using the Castagna et al. (1985) equation. These logs and a seismic wavelet (b) were used to create an offset synthetic. (c) AVO crossplot of the modeled data highlighting: the background trend line; data points associated with wavelet side lobe effects; and rotated data points stemming from the lower velocity reflections. This model is a confirmation of figure 1c where background trends lines (fluid lines) are closely spaced in compacted sediments (low Vp/Vs).

Several things stand out in the AVO crossplot model (Figure 2c). First, there is a relatively tight background trend (red line). Next, there are data points (circled in black) representing wavelet side lobes, not geology. Finally, there is an offset population (circled in red) with a near horizontal slope (i.e. with zero gradient). This model was constructed using background trend rocks (wet/brine) and no hydrocarbon induced responses are included. As with the Castagna et al. (1998) template (Figure 1c) the lower velocities present in this model (i.e. the shallowest sands) represent the transition in the Castagna mudrock line from a matrix supported formation to a fluid supported one. These observations highlight the importance of recognizing where and when potential sources of confusion can be introduced into a crossplotting template.

Since seismic data is a reflectivity attribute (measuring the contrast between impedance quantities) it is helpful to re-express the model parameters as a function of average Vp/Vs change, <Vp/Vs>. In Figure 3, each of the reflectivity interfaces used in the model is identified using the letters A (shallow) through U (deep), along with their corresponding <Vp/Vs>. The same letters identify these interfaces in crossplot space, with the previously noted side lobe effects removed to better visualize the impedance contrasts only. Figure 3a (left, upper crossplot) used the Castagna mudrock line relationship, as seen in figure 2, while figure 3b (right, lower crossplot) repeated the modeling using the Han mudrock line relationship (Han et al., 1986).

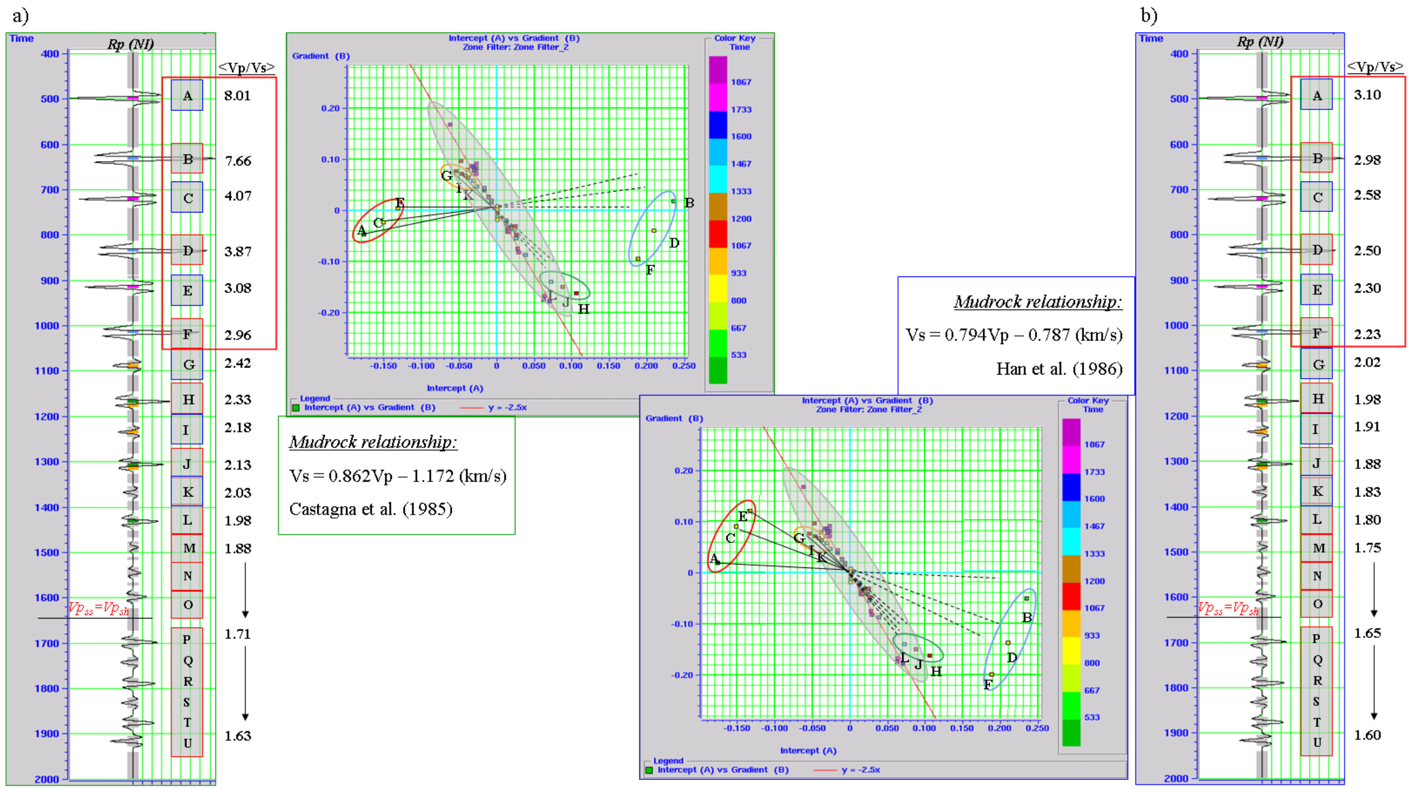


Figure 3. AVO Crossplot interpretation. (a) Using the Castagna et al. (1985) equation for estimating shear velocity produced numerically unrealistic <Vp/Vs> values in the low velocity (shallow) section. The higher <Vp/Vs> contrasts experience the most rotation in I/G crossplot space (identified by letters A-F). Compacted rocks (<Vp/Vs> values of 2.42 or lower) were concentrated on a relatively tight background/fluid trend line. (b) Using the Han et al. (1986) equation to estimate shear velocity produced similar results as the Castagna case for most of the reflectors G-U. The exception being that the <Vp/Vs> values in the shallow section reflectors A-F seemed more reasonable and the fluid angle rotation was less dramatic as a result.

This modeling reinforces the work presented by Castagna et al. (1998) where AVO trend lines are relatively tight in compacted rocks (lower Vp/Vs) and rotate more strongly for unconsolidated sediments (high Vp/Vs) only. The grey polygons in both crossplot spaces are a qualitative approximation of the data point scatter that would take place when seismic noise is introduced. The amount, and type, of noise present in the gathers will have an impact on the size and configuration of this data scatter. The model converges on a well behaved background trend for <Vp/Vs> values below 2.42 using the Castagna mudrock line and values below 2.02 when using the Han relationship. For the lower velocity wet sands in the shallow section, highlighted by red boxes in figures 3a and 3b, the rotation towards anomalous AVO space (Class III/IV response) happens at different rates depending on the magnitude of <Vp/Vs>. Great care should be taken in undercompacted basins to determine the AVO crossplot sensitivities so that population outliers associated with background trend rocks are not interpreted as *DHI*s. How large a fluid angle variation to expect should be modeled up-front so that comparisons of anomalous population rotations (due to all factors including hydrocarbon, lithology, and/or overpressure effects) are incorporated into the pre-AVO risking. As expected, since the Han relationship was designed using lower velocity sands and shales it yielded the lower and more realizable <Vp/Vs> contrasts for the shallower rocks, and experienced the smaller fluid angle rotation of the two.

Application

An important aspect of any AVO study is to understand the AVO sensitivities and/or limitations within the local environment. It has been demonstrated in the discussion above that one would expect to see noticeable rotations of the background trend within AVO crossplot space in lower velocity regimes only. An evaluation of several diverse basins around the world was performed to see how each regional AVO crossplot space behaves, and to find where crossplot rotations could be present within the AVO background trend. Figure 4 shows that for the vast majority of target depths within the studied areas the Vp/Vs ratios were sufficiently low (2.25 or lower) such that the degree of rotation present in the AVO fluid angle is subtle. Potential confusion or non-uniqueness errors that could arise during the AVO analysis process are restricted to the near surface only in these areas. In the GOM examples, at depths of ~6000 ft or shallower, the rapid sedimentation rates associated with younger basins present a risk for complicated AVO crossplot rotations, as shown in figure 4 (a) and (b). It is important to note that well logs in the shallower more unconsolidated zones can suffer from bad hole data and extra care must be taken before incorporating them into an AVO study. This is apparent in both the Alaska and Qatar Vp/Vs crossplots, in figure 4c.

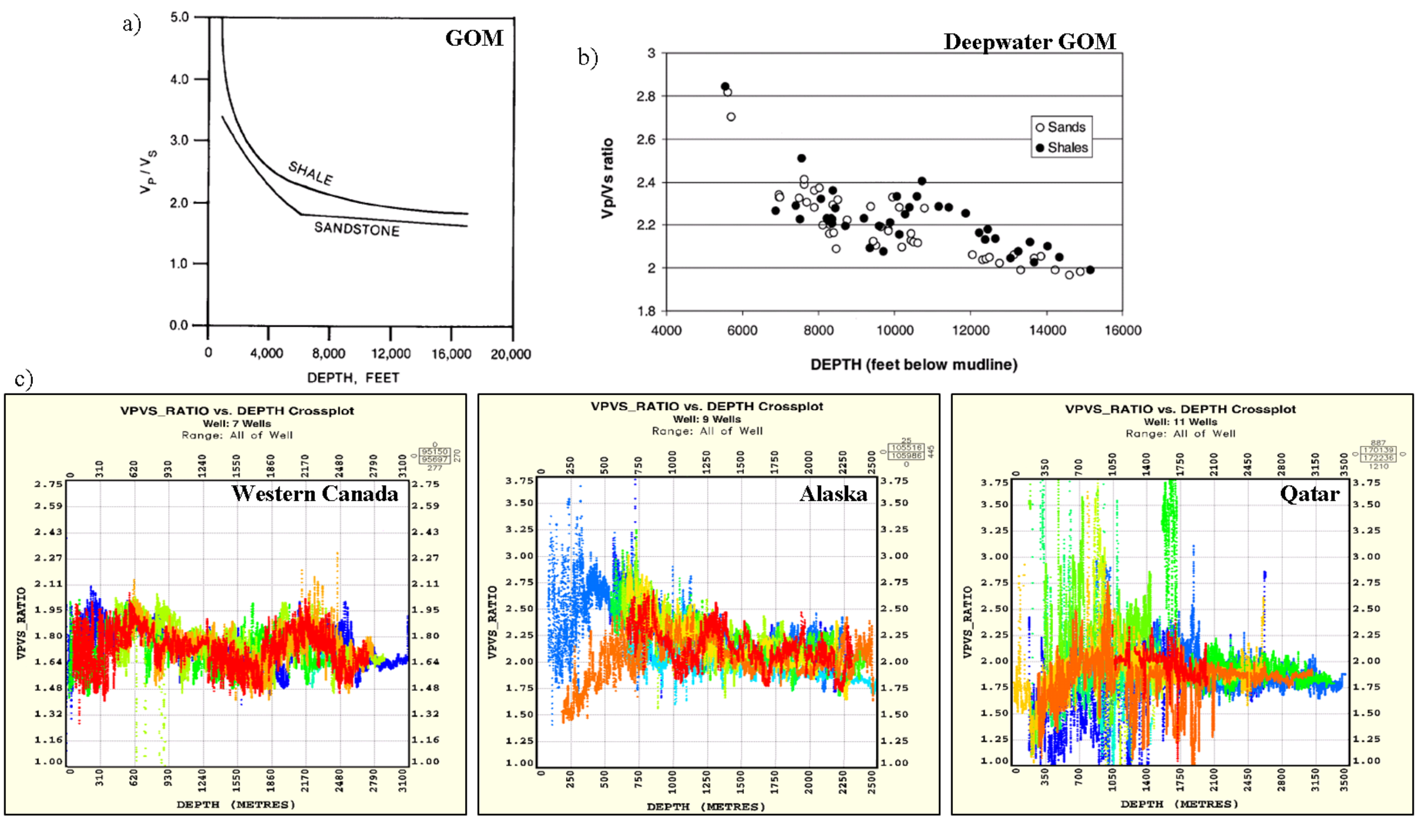


Figure 4. Vp/Vs plotted versus depth for 4 basins around the world. (a) The Gulf of Mexico (from Castagna et al. (1985)), (b) Deepwater Gulf of Mexico (from Smith and Sondergeld (2001)), (c) Western Canada, Alaska, and Qatar. Except for the unconsolidated shallow GOM sediments the vast majority of the Vp/Vs ratios are less than 2.25 which suggest we would expect relatively small deviations in crossplot fluid angle behavior.

Conclusion

AVO crossplotting techniques and applications have evolved over the last decade. Deciding which AVO crossplot template to apply in a given play requires a petrophysical understanding of the environment. It is also important to understand how calibrated the seismic data is beforehand when performing crossplot analysis. Background trend rotations observed in the seismic, as a function of time/depth, are typically not representative of the local geology. The AVO fluid angle experiences dramatic variations only in extremely low velocity environments, often producing polarity shifts in the AVO gradient. On the other hand, when logs are indicating a well compacted environment (Vp/Vs ratios of 1.6-2.4) a relatively small range of fluid angles (background trend rotations) can be expected in the seismic data during the course of an AVO investigation. This can allow for more latitude in crossplot analysis strategies. For example, larger time windows can be brought into crossplot space than previously considered.

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