Foolproof AvO

Dr. Ron Masters, Geoscience Advisor, Headwave, Inc

This paper was prepared for presentation during the 75th EAGE Conference & Exhibition incorporating SPE EUROPEC held in London, UK, June 10 – 13, 2013.

Abstract

Interpreters can sometimes directly identify reservoirs and hydrocarbons by observing Amplitude v. Offset anomalies in seismic data. The underlying science is mature [Castagna & Backus 1993]. Many forms of attribute analysis have been used routinely for a long time, including AvO cross plotting [Masters, 1989]. Typically AvO analysis has been applied by multi-disciplinary experts to confirm prospects already identified by conventional interpretation. Their work always depended on prior knowledge of which prospective horizon to investigate, and what combination of AvO attributes would provide the appropriate recognition criteria in each case, until now.

In this paper, we present a method that can *unequivocally* identify AvO anomalies, even if they have not previously been recognized as prospects, even if they have not been mapped. It does not require any prior knowledge about local conditions in the subsurface, or about which AvO class is locally likely to indicate reservoirs and hydrocarbons. Of course, quantitative interpretation of vital reservoir characteristics like porosity and saturation remains essential and still requires deep expertise.

Introduction

Why are we interested in seismic amplitude as a function of offset? The key point is that offset dependence measures mode conversion from compressional to shear waves. Seismic sources generate pressure waves that reflect from impedance contrasts in the subsurface. At normal incidence, no mode conversion occurs. At oblique incidence, both compressional and shear waves are reflected and transmitted at the interface. It’s easy to see why. Compressional wave particle motion is along the direction of propagation, shear wave motion is transverse. Coupling from P to S only occurs at wide angles. In isotropic media the angle of incidence θ is the only geometric parameter.

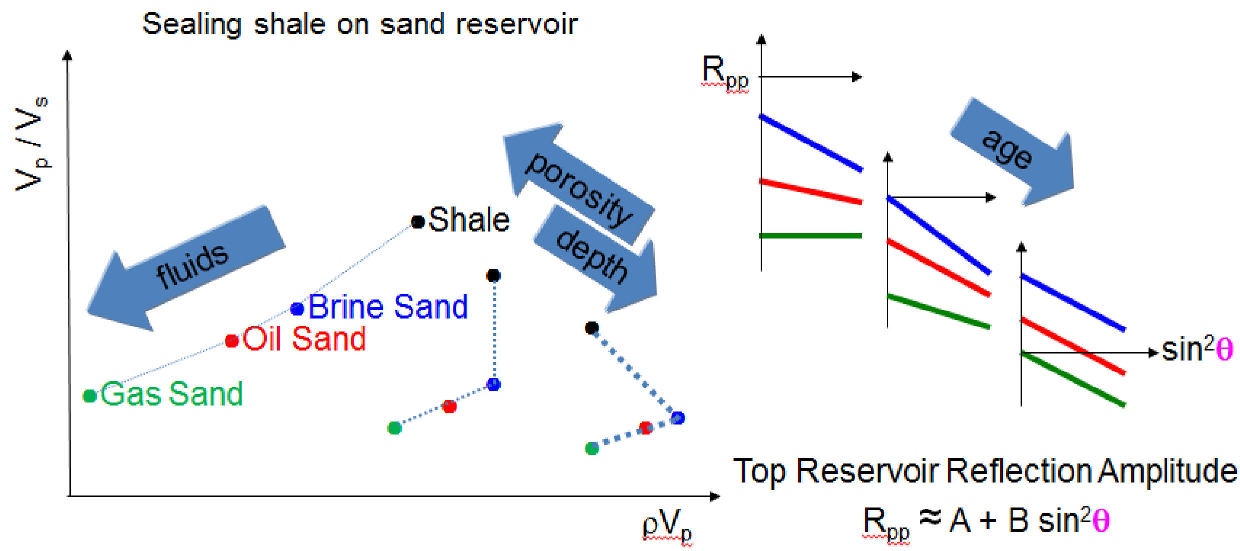

Figure 1 *Left: V_p/V_s ratio as a function of acoustic impedance, for reservoir sand with various fluids and the associated top seal. Three sets, connected by dotted lines, illustrate the variation due to porosity changes with depth and age. Right: Top reservoir P-wave reflection amplitude as a function of the angle of incidence, for the three fluid types, at each of the illustrated burial ages.*

Material properties also matter. On the left, in Figure 1, we plot the ratio of compressional and shear velocities, V_p/V_s, against the acoustic impedance, ρV_p. Two points represent the properties of a shale seal (black) over a brine-filled sand reservoir (blue). If we consider the variation due to reservoir fluid fill, we see that lighter hydrocarbons reduce impedance and V_p/V_s relative to brine. At right, we plot the amplitude of the compressional-wave reflection from an incident compressional wave, R_{pp}, for this seal and reservoir with 3 different fluids. The offset dependence is approximately linear in the parameter $\sin^2\theta$. A is just the impedance contrast. B is more complicated, but depends on the shear modulus and the V_p/V_s ratio. As the reservoir-seal pair compacts with burial, the sand and shale properties change. The reservoir becomes harder relative to the seal, and the fluid effects are smaller. With further burial and diagenesis, porosity reduction continues and the reservoir becomes even harder. The parameters change continuously over geologic time.

The best tool for interpreting this AvO behavior is a cross plot of intercept A and slope or gradient B, show in Figure 2 at left. The three triplets of color-coded points are the reflectivity attribute vectors for the three fluid types and ages in Figure 1. On the cross plot, roman numerals I, II, & III indicate the AvO classes defined by Rutherford & Williams (1989) to describe top reservoir reflectivity. The cartoons at right illustrate the normal incidence response of a prospect at each of the three ages and burial depths.

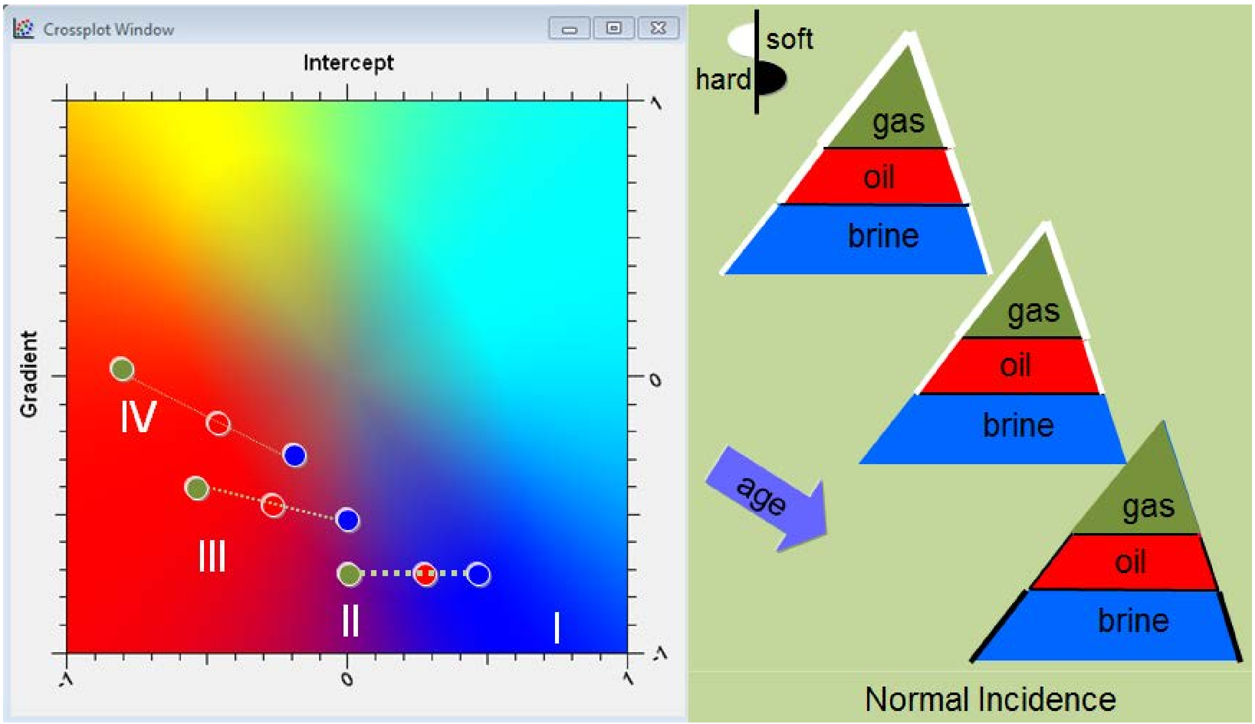

***Figure 2** Left: cross plot of intercept A and slope or gradient B for each of the P-wave reflection coefficients in Figure 1, again connected by dotted lines indicating common age. Roman numerals indicate AvO classes. Right: cartoons representing the normal incidence reflection from a reservoir model with gas, oil, and brine legs, at the three successive depths shown in the cross plot. The wiggles at the top indicate the polarity convention.*

Reflectivity varies with age. In young unconsolidated sands, the brine leg of the top reservoir generates a soft reflection, and the oil & gas legs are successively softer. With age, the brine sand may become a hard reflection, and at successive times each of the legs becomes non-reflective at normal incidence, and later, hard. Gas over oil over brine always shows increasing impedance in a uniform reservoir. These three snapshots might correspond to a bright spot, a polarity reversal and a dim spot for the oil leg on the full stack seismic data. Each may occur successively, at some arbitrary moment in geologic time. The AvO behavior changes continuously with depth and age. Boundaries between classes are of no interest. The appropriate pay signature must be determined by the interpreter in each individual case.

Method

The central feature of the method is the colored background in the cross plot. By using complementary color scales on two axes and interpolating along ellipses, we assign a unique color to each attribute vector (A,B). Co-visualizing a pair of seismic attribute volumes with this coloring shows the location in the cross plot for each voxel in the volume. Weak reflections are dull greys, strong ones have bright colors, and every AvO class is represented simultaneously. If some particular subsurface feature is anomalous, it will have a different color than nearby reflections, vertically and laterally. One may simply pan through the data and see them. One cannot miss an anomaly because it was not considered likely in a preconceived earth model.

As with other AvO cross plot applications, we can display a 2D histogram of the data vectors from a reference region, which may or may not include anomalies. Scaling and rotating the color axes can improve discrimination between the anomalous behavior and a background trend. For volume visualization, weak amplitudes can been made transparent, revealing high amplitudes for every AvO class simultaneously, even before horizons have been picked. Of course horizons may also be useful for sculpting the view, if they are available. Interpreters can make judgments about reservoir and fluid calls based on the structural fit, geomorphology, and comparisons at analog wells.

Example

Figure 3, left, shows a cross plot in which the color axes have been scaled to approximate a reference data distribution. Although the histogram does not show an obvious lump that could be captured by a polygon in the cross plot, nonetheless there is a clear discrimination in the volume view at right between horizons following the yellow-to-blue background variation and that obvious cyan-over-red doublet. (The data shown here has the opposite polarity from the cartoons in the earlier figures, so cyan is appropriate for a top reservoir.) Viewing the anomaly in context against conventional sections reveals that it is fault-bounded on the left. The boundary near the viewer is the edge of the survey, and the far edge is a stratigraphic pinch-out against an unconformity. Part of the perimeter at right shows a common down-dip termination.

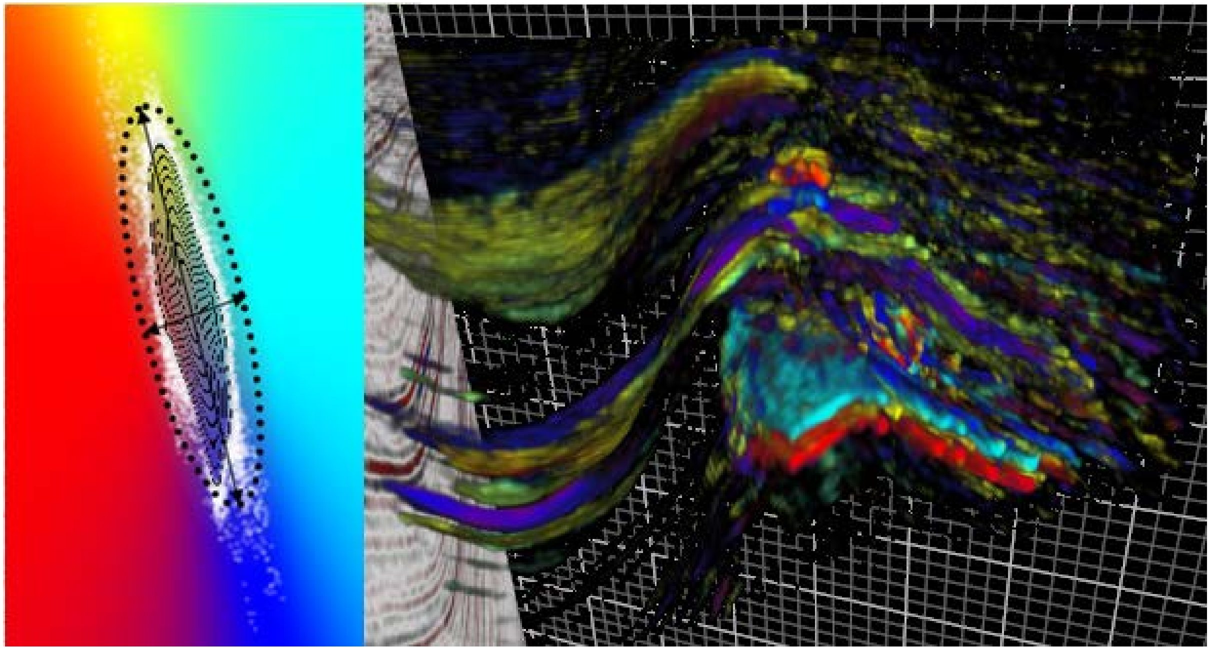

Figure 3 *Left: Cross plot with histogram of data vectors from a region of interest, after rotating and scaling the color axes. The most common vectors are contoured, and the least common included as individual points. Right: Intercept and Slope attribute volumes co-visualized with the color scheme at left. Opacity indicates distance from the origin.*

Conclusions

Gradational color variation shows the data as it is. Anomaly detection is foolproof because one cannot miss an anomaly by an unfortunate AvO class prediction, attribute combination, reference histogram selection, or cross plot polygon choice. Because there are no sharp boundaries in the cross plot, and all AvO classes are visible at once, all the color boundaries in the subsurface view must be due to lithology and/or fluid anomalies.

Acknowledgements

The authors are grateful to Headwave for encouragement to publish.

References

Castagna, J. P., and M. M. Backus, eds. 1993, Offset-Dependent Reflectivity – Theory and Practice of AVO Analysis, Society of Exploration Geophysics, Tulsa.

Masters, A. R., 1989, "Methods for processing and displaying seismic data" US Pat. 5001677

Rutherford, S.R. and, R.H. Williams,1989, "Amplitude-versus-offset variations in gas sands" Geophysics, 54, 680-688.