Comparison of AVO indicators: A modeling study

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ABSTRACT

A worldwide collection of 25 sets of velocity and density measurements from adjacent shales, brine sands, and gas sands was acquired with full-waveform sonic, dipole sonic, and conventional well logging devices and/or in the laboratory. These data provide theoretical shale over brine-sand and shale over gas-sand P-wave and S-wave normal-incidence reflection coefficients \( R_p \) and \( R_s \), AVO intercepts (A), AVO gradients (B), the AVO indicators \( R_p - R_s \) (reflection coefficient difference), and \( A \times B \) (AVO product). The reflection coefficient difference is found to be a more universal indicator than the AVO product in clastic stratigraphic intervals. For shale over brine-sand reflections, the average \( R_p - R_s \) tends to be near zero and relatively invariant with depth. Irrespective of gas-sand impedance, \( R_p - R_s \) is always negative for shale over reservoir quality gas-sand reflections and more negative than for the corresponding brine-sand reflections. In comparison, the AVO product may be positive, near zero, or negative for gas-sands depending on the impedance contrast with the overlying shale. These measurements also verify that \( R_p - R_s \) is well approximated by a simple linear combination of \( A \) and \( B \).

INTRODUCTION

In contrast to conventional seismic interpretation, amplitude variation with offset (AVO) analysis involves the management and interpretation of additional dimensions and much greater volumes of data. To reduce AVO information to a more readily interpretable form, various "indicators" have been proposed (see Swan (1993) for an excellent review and discussion). Ideally, a single AVO indicator would be displayed as a color seismic section with "red" being indicative of hydrocarbons. However, in practice, this approach often yields disappointing results. The objective of this paper is to demonstrate that it is critical to select an AVO indicator that is well-suited to the problem at hand. In particular, the AVO product indicator \( A \times B \) is often inappropriate for hydrocarbon detection. Alternatively, we propose that in clastic stratigraphic sections, the normal incidence P-wave and S-wave reflection coefficient difference \( R_p - R_s \) is more universally applicable when appropriately corrected for overburden effects. A suite of velocity measurements in brine sands, gas sands, and shales are used to illustrate these claims.

THEORY

Following Shuey (1985), the P-wave reflection coefficient as a function of angle of incidence \( R_{pp}(\theta) \) may be expressed as:

\[
R_{pp}(\theta) = A + B \sin^2 \theta, \tag{1}
\]

where \( A \) is the normal incidence P-wave reflection coefficient, \( R_{pp} \), and the AVO gradient (slope) is given by

\[
B = \left( -2 \frac{V_p^2 \Delta \rho}{V_p^2 \rho_p} + \frac{1}{2} \frac{\Delta V_p}{V_p} - 4 \frac{V_s^2 \Delta V_s}{V_p^2 V_s} \right), \tag{2}
\]

where

\[
\begin{align*}
V_p &= (V_{p2} + V_{p1})/2, \\
V_s &= (V_{s2} + V_{s1})/2, \\
\rho &= (\rho_2 + \rho_1)/2, \\
\Delta V_p &= V_{p2} - V_{p1}, \\
\Delta V_s &= V_{s2} - V_{s1}, \\
\Delta \rho &= \rho_2 - \rho_1, \\
V_{p2} &= P\text{-wave velocity in underlying medium}, \\
V_{p1} &= P\text{-wave velocity in overlying medium}, \\
V_{s2} &= S\text{-wave velocity in underlying medium}, \\
V_{s1} &= S\text{-wave velocity in overlying medium}, \\
\rho_2 &= \text{density in underlying medium}, \text{ and} \\
\rho_1 &= \text{density in overlying medium}.
\end{align*}
\]

The product of "A" and "B" \( (A \times B) \) is often used to verify classical bright spots. This is based on the observation that a low-impedance gas sand encased in shale will have a
larger negative AVO intercept (A) and a larger negative AVO gradient (B) than will associated reflectors not associated with gas. Thus, \( A \cdot B \) should be an excellent indicator of Class III type gas sands [we use the nomenclature of Rutherford and Williams (1989)]. Furthermore, as shown by Swan (1993), certain product indicators have excellent S/N characteristics and may exhibit some degree of immunity to mild phase and velocity errors. On the other hand, \( A \cdot B \) will very effectively screen out Rutherford Class I ("A" positive, "B" negative) and Class II ("A" near-zero, "B" negative) gas sands. This unfortunate attribute is generally not well understood by interpreters who often expect only large \( A \cdot B \) ("red") to be indicative of hydrocarbons. What is needed is an AVO indicator that will work for gas sands of all impedances, not just classical bright spots. The "fluid factor" of Smith and Gidlow (1987) satisfies this need as does the reflection coefficient difference \( R_p - R_s \) discussed by Castagna (1993). From an interpretation standpoint, the latter is appealing for its simplicity and physical intuitiveness. Physical insight is derived directly from the reflection coefficient definitions:

\[
R_p = (\Delta V_p/V_p + \Delta p/p)/2, \tag{3}
\]

\[
R_s = (\Delta V_s/V_s + \Delta p/p)/2, \tag{4}
\]

and

\[
R_p - R_s = (\Delta V_p/V_p - \Delta V_s/V_s)/2. \tag{5}
\]

Inspection of equations (3), (4), and (5) reveals that the dependence on pore fluid content is large for \( R_p \), small for \( R_s \), and large for \( R_p - R_s \). The lithology and porosity dependence is large for both \( R_p \) and \( R_s \). However, to first order for brine sands and shales, variations in lithology and porosity affect \( \Delta V_p/V_p \) and \( \Delta V_s/V_s \) similarly, and tend to cancel out when these quantities are subtracted. Thus, in clastic sections, nonpay \( R_p - R_s \) exhibits a fairly constant mean value and provides a well behaved background against which gas-sand related \( R_p - R_s \) clearly stands out. In addition, the effect of gas is always to make \( R_p - R_s \) more negative.

Following Wiggins et al. (1983) we have

\[
R_p - R_s = (A + B)/2, \tag{6}
\]

which is exact when \( V_p/V_s = 2 \). Thus, assuming appropriate measurement and calibration, \((A + B)/2\) should be an excellent hydrocarbon indicator in clastic sections. In practice, one would apply a time and space varying offset gain function to "zero out" mean \((A + B)/2\) in known nonpay intervals. The resulting quantity could then be expressed as a linear combination of \( A \) and \( B \), \( \alpha A + \beta B \), where \( \alpha \) and \( \beta \) are empirical constants that simultaneously calibrate amplitudes and remove "local" petrophysical biases. The resulting "calibrated" \((A + B)/2\) is equivalent to Smith and Gidlow's (1987) fluid factor.

Figure 1 shows mean shale over sand \( R_p - R_s \) as a function of depth for Gulf Coast clastics calculated using the data of Gregory (1977) and the mudrock trend of Castagna et al. (1985). Shale over brine-sand \( R_p - R_s \) is near zero and about constant. Shale over gas-sand \( R_p - R_s \) is always negative. Although the separation between brine sands and gas sands decreases with increasing depth, the difference is slowly varying and may be assumed to be constant for a given target interval. The least-squares fit for shale over gas-sand \( R_p - R_s \) is:

\[
(R_p - R_s)_{gas} = -0.1310 \log^2 z + 1.253 \log z - 3.0616, \tag{7}
\]

where \( z \) is depth in feet.

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**Fig. 1.** Average Gulf Coast \( R_p - R_s \) for brine sands and gas sands from Gregory (1977) and Castagna et al. (1985). The solid line is a second-order logarithmic polynomial fit to the gas-sand data.
DATA

We have collected a suite of 25 sets of $V_p$, $V_s$, and $\rho$ measurements in adjacent shales, gas sands, and brine sands, from which we have derived reflection coefficients and AVO parameters. The velocities were derived primarily from monopole and dipole full-waveform sonic logs or from laboratory pulse-transmission measurements on cores. In a few instances, the Greenberg and Castagna (1992) method was used to perform fluid substitution when both gas-sand and brine-sand measurements were not available. Densities were obtained from conventional density logs or were estimated from lithology and porosity information. Velocities marked with an asterisk were estimated.

RESULTS

Figure 2a shows the resulting P-wave reflection coefficients for shale over brine sand and shale over gas sand for all 25 sets of measurements. Class I (large positive gas-sand $R_p$), Class II (near-zero gas-sand $R_p$), and Class III (large negative gas-sand $R_p$) are all represented. Gas-sand $R_p$ is almost always more negative than brine-sand $R_p$ and may be “brighter” or “dimmer” in magnitude. The AVO gradient “$B$” for gas sands may also be positive, near-zero, or negative. Relative to brine sands, gas-sand $R_p$ is more negative, but the magnitude of a gas-sand P-wave reflection coefficient may increase or decrease with offset. The corresponding AVO gradients (slopes) are shown in Figure 2b. In absolute terms, there is a great deal of overlap between brine-sand and gas-sand AVO gradient. However, in a relative sense, a gas sand will usually have a more negative gradient than its corresponding brine sand.

A * B (see Figure 3) may be positive, near-zero, or negative for both brine sands and gas sands. Gas-sand A * B may be more positive, more negative, or about equal to brine sand A * B. A * B is strongly positive only when “A” and “B” are both strongly negative. Thus, one cannot simply relate $A * B$ to hydrocarbon content unless it is known a priori that Class III behavior is expected.

In contrast, Figure 4 shows $R_p - R_s$ for brine sands and gas sands. In absolute terms, the more negative the $R_p - R_s$, the greater the probability of hydrocarbons. More important, however, is the relative behavior of $R_p - R_s$. Goldman (1979) showed that in a particular horizon is followed onto a structure. Excepting sandstones with abnormally small gas effect, $R_p - R_s$ is always more negative for gas sands than it is for brine sands. Furthermore, reservoir quality gas-sand $R_p - R_s$ is always negative. This is a distinct advantage over $R_p$ or $R_s$, which all may be positive, zero, or negative for gas sands.

As shown in Figure 5, $R_p - R_s$ is well approximated by $(A + B)/2$. This approximation can be improved by applying corrections using “background” $V_p/V_s$ and $\rho$ derived from

<table>
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<tr>
<th>Table 1. $P$-wave and $S$-wave velocities and densities for 25 sets of brine sands, gas sands, and shales that occur in close in-situ proximity. The velocities are from full-waveform sonic logs, dipole sonic logs, or were measured in the laboratory. The densities are from compensated density logs or were estimated from lithology and porosity information. Velocities marked with an asterisk were estimated.</th>
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velocity analyses, well log control, trend curves, and/or other a priori information. Furthermore, excepting one anomalous brine sand in Figure 5 (we suspect a velocity measurement error), the largest deviations are such that they enhance the performance of \((A + B)/2\) as a hydrocarbon indicator; brine sands exhibit anomalously small \((A + B)/2\) while gas sands exhibit anomalously large \((A + B)/2\). It is evident from Figure 6 that, in absolute terms, about 90 percent of the gas sands exhibit \((A + B)/2\) more negative than \(-0.2\), while more than 75 percent of the brine sands have \((A + B)/2\) more positive than \(-0.05\). These statistics can be improved when the data are interpreted relatively along a single horizon. Clearly, \((A + B)/2\) (as seen in Figure 6) is petrophysically a more robust hydrocarbon indicator than \(A \times B\) (Figure 3).

**CONCLUSIONS**

\(R_P - R_S\) has some characteristics that are highly desirable for a hydrocarbon indicator in clastic sections:

1) Background (nonpay) mean \(R_P - R_S\) tends to be relatively constant and near zero. Thus, amplitude calibration can be performed by “zeroing” mean derived \(R_P - R_S\) over known nonpay intervals.

2) \(R_P - R_S\) is almost always negative for shale over gas-sand interfaces and significantly more negative than for shale over brine-sand interfaces, and

3) \(R_P - R_S\) will work for any gas-sand impedance providing there is a strong gas effect on P-wave velocity.

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**Fig. 2.** (a) P-wave reflection coefficients for 25 sets of shale, brine-sand, and gas-sand \(V_p, V_s,\) and \(\rho\) measurements given in Table 1. The reflection coefficients are for shale over brine sand (square) and shale over gas sand (plus sign). (b) The AVO gradients corresponding to the reflection coefficients in (a).
Fig. 3. A * B corresponding to the reflection coefficients in Figure 2a.

Fig. 4. $R_P - R_S$ corresponding to the reflection coefficients in Figure 2a.
Fig. 5. $R_P - R_S$ versus $(A + B)/2$ for all 25 sets of measurements.

Fig. 6. $(A + B)/2$ corresponding to the reflection coefficients in Figure 2a.
In comparison, $A \cdot B$ may be positive, near zero, or negative depending on the impedance of the gas-sand relative to that of the overlying shale. When "A" is zero, all AVO information in $A \cdot B$ is lost. Typically, $A \cdot B$ is a useful indicator only for Class III gas sands.

$(A + B)/2$ provides a good approximation to $R_p - R_s$ and may actually enhance hydrocarbon detectability in some cases.

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REFERENCES


