AN AVO INDICATOR BASED ON THE IMPEDANCE CONCEPT

V. Grosfeld and L. T. Santos

email: *lucio@ime.unicamp.br*
keywords: *Seismic Attributes, Reflection Coefficient, AVO.*

ABSTRACT

In the last two decades, many approximations for the PP reflection coefficient have been proposed in the literature. Basically, all of them are derived from the classical approximation of Aki & Richards, using additional assumptions on the medium parameters. The aim of constructing such approximations is to establish reliable attributes that can be capable to indicate the presence of oil or gas. In this work we review some well known approximations and their respective attributes, We also introduce a new indicator based on a impedance-type of approximation for the reflection coefficient. Numerical examples are also provided.

INTRODUCTION

The variation of amplitude with offset (AVO) is a powerful tool to discriminate rocks containing gas and oil. Several approximations of the PP reflection coefficient (R) have been proposed and different AVO indicators can be extracted from them. However, there is no agreement about which is the best attribute and in which situation it would be better applied. The aim of this work is to present a general approach of the well-known approximations of the reflection coefficient and its respective attributes. The starting point for all the approximations is the classical approximation of Aki and Richards (see, e.g., Aki and Richards (2002)), which is based on a weak contrast in the media parameters and a small angle of incidence. Recently, impedance-type approximations for the reflection coefficient have been introduced. See, e.g., Connolly (1999), Santos and Tygel (2004) and Pang et al. (2006). Based on this kind of approximation we introduce a new indicator. Numerical examples demonstrate the ability of the attributes to discriminate between gas and oil.

AVO INDICATORS

Let us consider two isotropic homogeneous elastic media separated by a smooth interface. Each medium has a P-wave velocity α, a S-wave velocity β and a density ρ. Further, let us consider an incident compressional plane wave impinging upon this interface. The PP reflection coefficient (R) for a compressional reflected wave has an exact expression given by the well known Zoeppritz-Knott formula. This formula is very hard to handle and it is difficult to extract the physical sense of their terms.

For a small contrast between the properties of the two media and a small angle of incidence, the well known first-order approximation of Aki and Richards (2002) is given by

$$R \approx \frac{1}{2}\left[1 - 4\frac{\beta^2}{\alpha^2}\sin^2\theta\right]\frac{\Delta\rho}{\rho} + \frac{\sec^2\theta}{2}\frac{\Delta\alpha}{\alpha} - 4\frac{\beta^2}{\alpha^2}\sin^2\theta\frac{\Delta\beta}{\beta}\ , \tag{1}$$

where we have used the notation $u = (u_2 + u_1)/2$, $\Delta u = u_2 - u_1$ for $u = \theta, \alpha, \beta, \rho$, and the subindices 1 and 2 refer to the incidence and transmission sides of the interface, respectively. Moreover, θ_1 and θ_2 are such that $\alpha_2\ \sin\theta_1 = \alpha_1\ \sin\theta_2$ (Snell's law). Shuey (1985) rewrote expression (1) as a function of the angle θ,

$$R \approx A + B\sin^2\theta + C[\tan^2\theta - \sin^2\theta], \tag{2}$$

where the parameters A (Intercept), B (Gradient) and C are given by

$$A = \frac{1}{2}\left[\frac{\Delta\rho}{\rho} + \frac{\Delta\alpha}{\alpha}\right], \quad B = \frac{1}{2}\frac{\Delta\alpha}{\alpha} - 2\frac{\beta^2}{\alpha^2}\left[\frac{\Delta\rho}{\rho} + 2\frac{\Delta\beta}{\beta}\right], \quad \text{and} \quad C = \frac{1}{2}\frac{\Delta\alpha}{\alpha}\,. \tag{3}$$

Shuey was further on: for incidence angles smaller than 30 degrees, $\tan^2\theta \approx \sin^2\theta$ and then, equation (2) turns to be

$$R \approx A + B\sin^2\theta\,. \tag{4}$$

Equation (4) is the most used AVO formula. Castagna and Smith (1994) presented a large study using A and B, $A \times B$ and $(A+B)/2$ as AVO indicators. In that work they have shown that the difference between the normal incidence PP and SS reflection coefficients can be well approximated by the average indicator $(A+B)/2$. Moreover, it is also a robust indicator for clastic section to separate brine sands and gas sands, as shown in the top of Figure 1. In this figure, we have ploted the values $(A+B)/2$ for a set of 25 measurements of the Gulf of Mexico and Gulf Coast, given in Castagna and Smith (1994). However, as already mentioned in that work, for the model number 17 the average indicator failed. We can also observe that $A \times B$ attribute is not a good discriminator either, as depicted in the center of Figure 1.

Smith and Gidlow (1987) used Gardner's relationship for water-saturated rocks (Gardner et al., 1974), $\rho = a\,\alpha^{1/4}$, to obtain the following approximation for R,

$$R \approx \left[\frac{5}{8} - \frac{1}{2}\frac{\beta^2}{\alpha^2}\sin^2\theta + \frac{1}{2}\tan^2\theta\right]\frac{\Delta\alpha}{\alpha} - 4\frac{\beta^2}{\alpha^2}\frac{\Delta\beta}{\beta}. \tag{5}$$

Using the mudrock line of Castagna et al. (1985), $\alpha = 1.36 + 1.16\,\beta$ (in km/s), which relates P- and S-wave velocities for water-saturated sandstones, siltstones and shales, Smith and Gidlow (1987) define the "fluid factor" indicator ΔF as

$$\Delta F = \frac{\Delta\alpha}{\alpha} - 1.16\,\frac{\beta}{\alpha}\,\frac{\Delta\beta}{\beta}, \tag{6}$$

where the contrasts for α and β can be estimated from equation (5). The fluid indicator ΔF will be close to zero for water-bearing and shales rocks and nonzero for other type of rocks or fillings. Fatti et al. (1994) rewrote equation (5) in terms of $R_P = \Delta I_P/I_P$ and $R_S = \Delta I_S/I_S$, where $I_P = \rho\alpha$ and $I_S = \rho\beta$. This modification allow them to redefine the fluid factor as

$$\Delta F = R_P - 1.16\,\frac{\beta}{\alpha}\,R_S. \tag{7}$$

Smith and Sutherland (1996) substitute the term $g = 1.16 \times \beta/\alpha$ in the above equation to obtain the "best" separation. The estimated value was $g = 0.63$. The bottom of Figure 1 depicts the behavior of the fluid factor for the same set of 25 measurements used previously, using this value of g.

IMPEDANCE-TYPE INDICATOR

Following the simple cases of normal incidence in elastic media and general oblique incidence in acoustic media, two new approaches for approximating the reflection coefficient have appeared recently in the literature. The main idea is to write the reflection coefficient as a function of a "angular" impedance functions, $I_j = I(\rho_j, \alpha_j, \beta_j, \theta_j)$, $j = 1, 2$. Such approximation is given by

$$R \approx \frac{I_2 - I_1}{I_2 + I_1} = \frac{1}{2}\frac{\Delta I}{I}, \tag{8}$$

where $\Delta I = I_2 - I_1$ and $I = (I_2 + I_1)/2$.

Since the introduction of the *elastic* impedance of Connolly (1999), different authors have suggested alternative impedance functions, under different assumptions on the parameters involved. See, e.g., Santos and Tygel (2004) and Pang et al. (2006). For any choice of the impedance function, we now define a new attribute J, as the ratio of the impedances,

$$J = \frac{I_1}{I_2} \approx \frac{1-R}{1+R}. \tag{9}$$

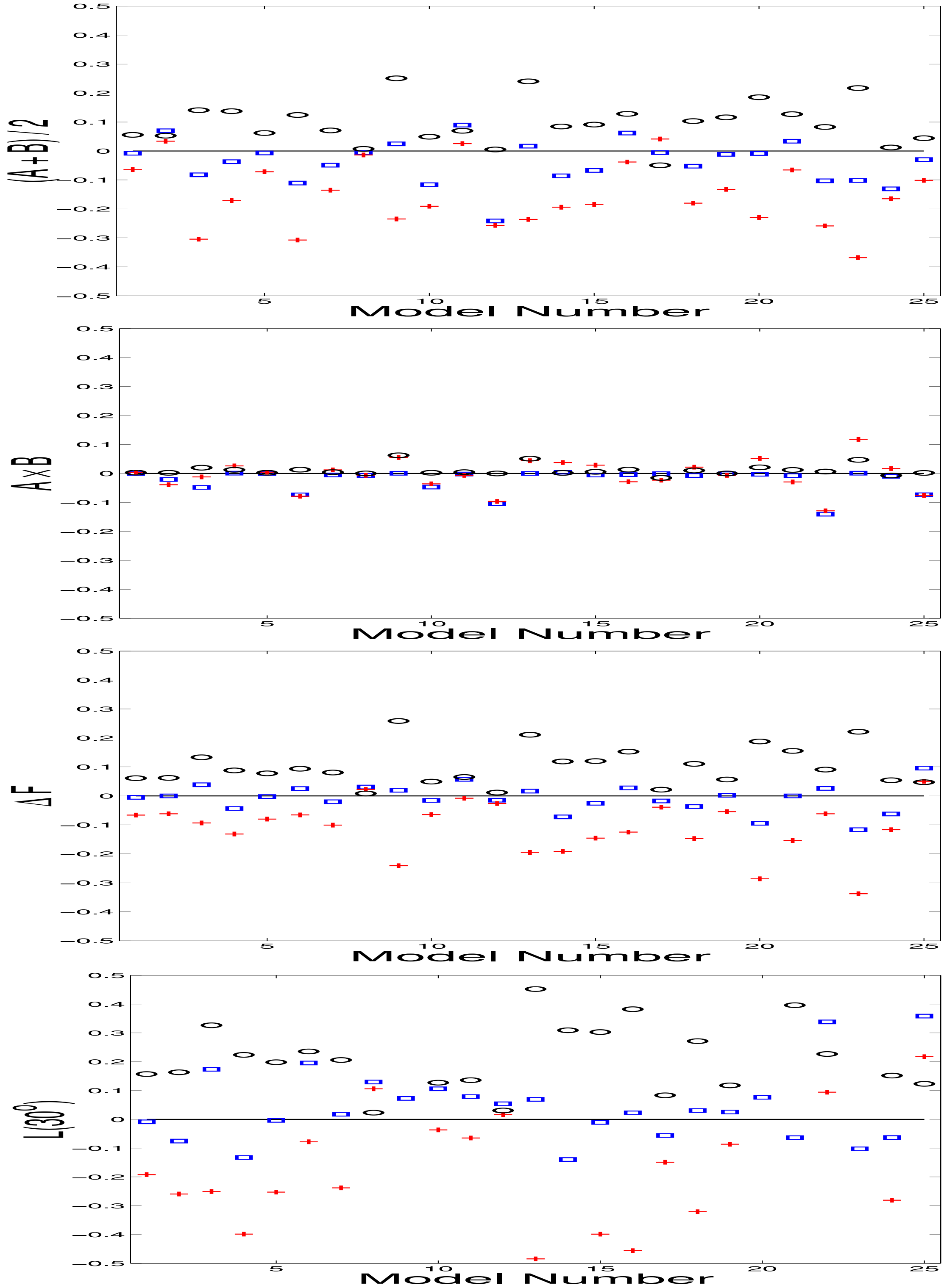

Figure 1: Four different attributes for 25 measurements of shale over brine-sand (□), shale over gas-sand (+) and gas-sand over brine-sand (○): $(A + B) / 2$, $A \times B$, Fluid Factor ΔF, and $L(30^o)$.

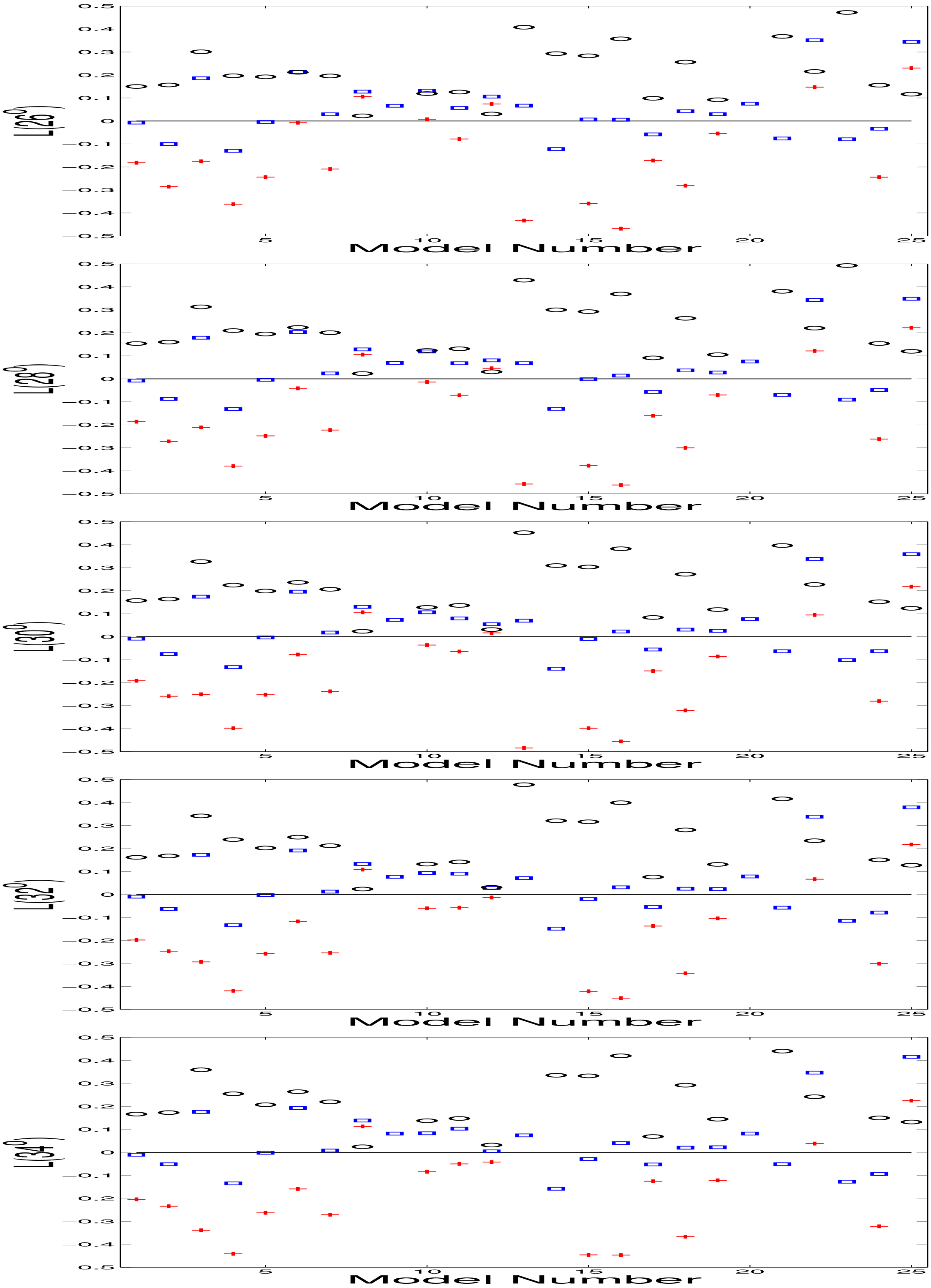

Figure 2: Impedande-type indicator L for diferent values of θ near 30^o for 25 measurements of shale over brine-sand (□), shale over gas-sand (+) and gas-sand over brine-sand (○).

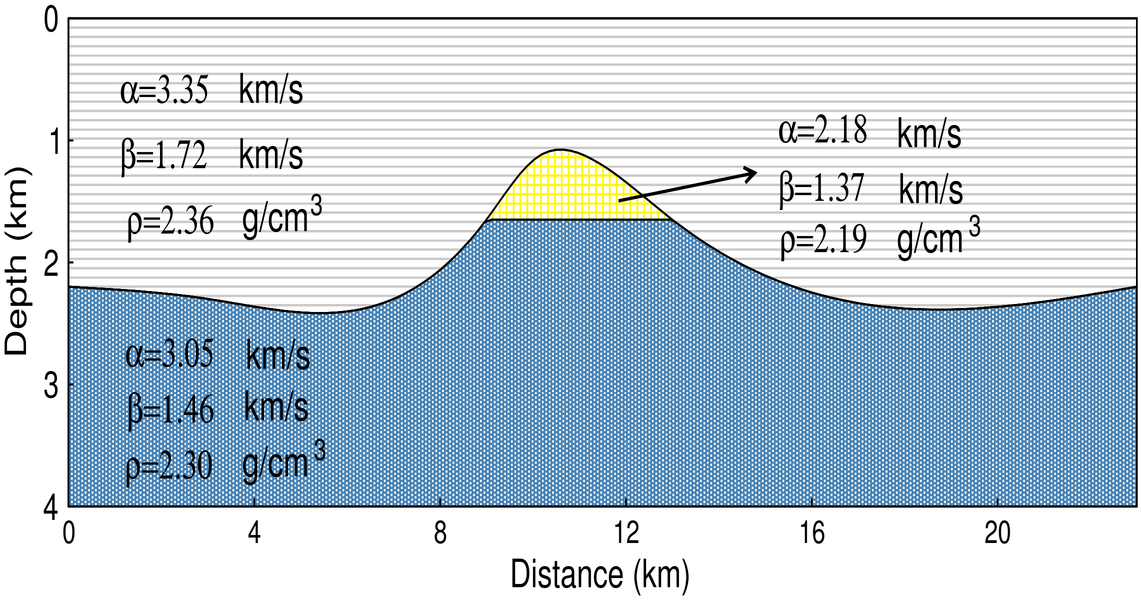

Figure 3: Synthetic model for the experiments: a shale layer over a brine-sand dome, with a small layer of gas-sand in the top.

Clearly, this indicator depends on the angle (or ray parameter). To accomplish the first two highly desirable characteristics of a good indicator, according Castagna and Smith (1994), we take as the indicator

$$L = 1 - J, \quad \text{or} \quad L \approx \frac{2R}{1+R}. \tag{10}$$

Figure 2 shows the behavior of L for diferent values of θ near 30^o. In the bottom of Figure 1 it is depicted $L(30^o)$, where we can observe that the new attribute separates well gas sand from brine sand for all the 25 measurements, including Model 17.

SYNTHETIC DATA

In order to test the efficiency of our new indicator L for identifying interfaces with different fluids, we computed the discussed attributes for the model depicted in Figure (3). It consists of a shale layer over a brine-sand dome, with a small layer of gas-sand in the top. The seismic processing was done using `PROBE`, from Paradigm, and we have used the following standard relations,

$$\rho = 0.6\,\alpha^{1/4}, \quad \text{and} \quad \beta = 0.86\alpha - 1.17. \tag{11}$$

Our indicator L was extracted from the stacked angle sections, computed for each 5 degrees. The atributes extracted are show in Figure 4.

The average $(A+B)/2$ does not provide a good identification of the shale/gas-sand interface. Moreover, the sign of the attribute for the second interface is wrong. The product $A \times B$ separates well shale/gas-sand from shale/brine-sand, but the sign of the last one is positive instead of negative, as in the case of gas-sand/brine-sand. The fluid factor ΔF and our $L(30^o)$ separate well shale/gas-sand from shale/brine-sand, with the correct sign for both interfaces. Comparing the four attributes, our indicator had the best performance in separating the fluid interfaces. However, observe that there is a missing section of L for the second interface, due to the ausency of incidence angles near 30^o in that area.

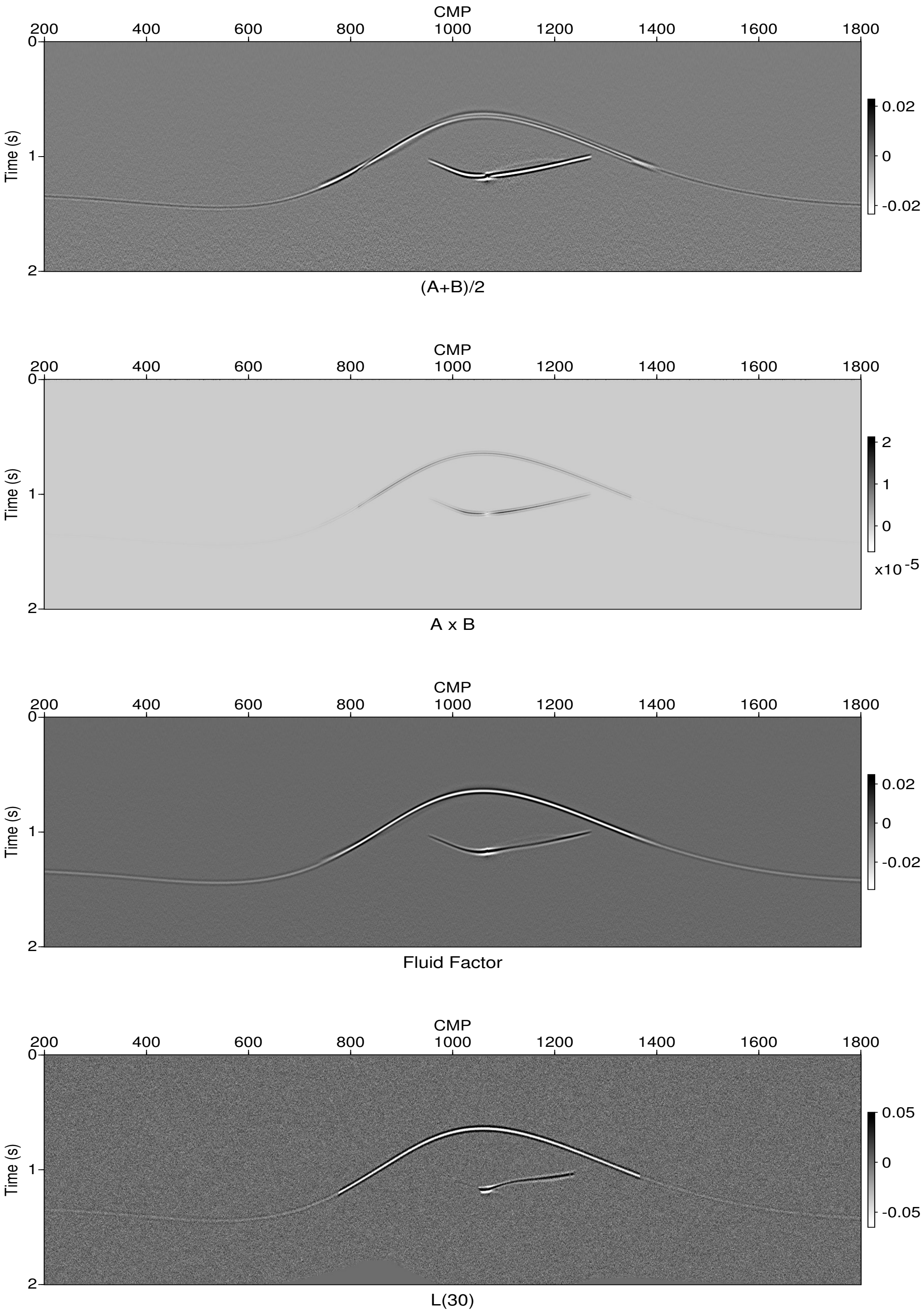

Figure 4: Four different attributes for the synthetic model depicted in Figure 3: $(A\ +\ B)\ /\ 2$, $A \times B$, Fluid Factor ΔF, and $L(30^o)$

CONCLUSIONS

Different approximations for the PP reflection coefficient provide different indicators to discriminate gas and oil. When applied to a set of data, some of them are able to separate gas sand from brine sand. We introduced a new attribute which was more efficient in discriminate gas and oil for the same data. Further investigation is being carried to test the potential of the new attribute for well-log analysis.

ACKNOWLEDGEMENTS

This work has been partially supported by the *National Council of Scientific and Technological Development (CNPq)*, Brazil (307165/2003–5), the *Research Foundation of the State of São Paulo (FAPESP)*, Brazil (02/08544–5) and the sponsors of the *Wave Inversion Technology (WIT) Consortium*, Germany.

REFERENCES

Aki, K. and Richards, P. G. (2002). *Quantitative Seismology*. University Science Books.

Castagna, J., Batzle, M. L., and Eastwood, R. L. (1985). Relationship between compressional and shear-wave velocities in clastic silicate rocks. *Geophysics*, 50:551–570.

Castagna, J. and Smith, S. (1994). Comparison of AVO indicators: A modeling study. *Geophysics*, 59:1849–1855.

Connolly, P. A. (1999). Elastic impedance. *The Leading Edge*, 18:438–452.

Fatti, J. L., Vail, P. J., Smith, G. C., Struss, P. J., and Levitt, P. R. (1994). Detection of gas in sandstone reservoirs using AVO analysis: A 3-D seismic case history using Geostack technique. *Geophysics*, 59:1362–1367.

Gardner, G. H. F., Gardner, L. W., and Gregory, A. R. (1974). Formation velocity and density – The diagnostic basis for stratigraphic traps. *Geophysics*, 39:770–780.

Pang, D., Liu, E., and Yue, J. (2006). Comparison of accuricies of elastic impedances. *Journal of Seismic Exploration*, 14:303–317.

Santos, L. T. and Tygel, M. (2004). Impedance-type approximations of the P-P elastic reflection coefficient: Modeling an AVO inversion. *Geophysics*, 69:592–598.

Shuey, R. T. (1985). A simplification of the Zoeppritz equations. *Geophysics*, 50:609–614.

Smith, G. C. and Sutherland, R. A. (1996). The fluid factor as a n AVO indicator. *Geophysics*, 61:1425–1428.

Smith, S. and Gidlow, P. M. (1987). Weighted stacking for rock property estimation and detection of gas. *Geophysical Prospecting*, 35:993–1014.