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Poisson's Ratio Contrast and AVO Responses: Model Study

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ABSTRACT

A critical element in the use of amplitude versus offset (AVO) for gas detection or lithological discrimination is to define a parameter that represents anomalous behaviour. Shuey's approximation to the Zoeppritz equations for the compressional wave reflection coefficient has been widely used as a basis for defining AVO anomalies. Shuey's approximation states the AVO response as a linear equation. The intercept and gradient from this equation have frequently been used as key parameters to quantify AVO response. Generally, large gradients are normally assumed to be related to gas saturation. In order to better understand the gradient term, 25 model pairs of shale over gas sand, and shale over brine sand, were used to analyse the gradient term as the sum of two functions. The first function is defined as the non-Poisson's ratio contrast term, and the second as the Poisson's ratio contrast term.

Three conclusions have been reached from this analysis.

1. The gradient may be significant even for a small Poisson's ratio contrast. This effect may be one of the reasons that AVO analysis is misleading in some geological settings.
2. Similar values of Poisson's ratio contrast may produce quite different gradients in different rocks.
3. In most cases the non-Poisson's ratio contrast term is constructive to the magnitude of gradient when the normal incidence reflectivity and Poisson's ratio contrast have opposite signs, while it is destructive to the magnitude of gradient when both have the same signs.

Keywords: AVO, Poisson's ratio, Poisson's ratio contrast, gradient, normal incidence reflectivity, Shuey's equation

INTRODUCTION

The use of AVO as a direct hydrocarbon indicator and seismic lithology discriminating tool is based on the principle that Poisson's ratio (or *Vp/Vs*) is different for varying gas saturation and for various lithologies. Commonly, as the gas content in a given rock increases, the Poisson's ratio becomes anomalously low.

Following Shuey (1985), the compressional wave reflection coefficient given by Zoeppritz equations can be approximated as:

$$R(\theta) = R_0 + G\sin^2\theta \ , \tag{1}$$

where:

$$G = A_0 R_0 + \frac{\Delta\sigma}{(1-\sigma)^2} \ , \tag{2}$$

$$R_0 = \frac{\dfrac{\Delta V_p}{V_p} + \dfrac{\Delta\rho}{\rho}}{2} \ , \tag{3}$$

$$B = \frac{\dfrac{\Delta V_p}{V_p}}{\dfrac{\Delta V_p}{V_p} + \dfrac{\Delta\rho}{\rho}} \ ; \text{and} \tag{4}$$

$$A_0 = B - 2(1+B)\frac{1-2\sigma}{1-\sigma} \tag{5}$$

The general elastic properties in equations (2) to (5) are related to the physical properties on each side of the interface, as shown below.

$$\Delta V_p = V_{p2} - V_{p1} \tag{6}$$

$$V_p = \frac{V_{p2} + V_{p1}}{2} \tag{7}$$

$$\Delta\rho = \rho_2 - \rho_1 \tag{8}$$

$$\rho = \frac{\rho_2 + \rho_1}{2} \tag{9}$$

$$\Delta\sigma = \sigma_2 - \sigma_1 \tag{10}$$

$$\sigma = \frac{\sigma_2 + \sigma_1}{2} \tag{11}$$

$$\theta = \frac{\theta_2 + \theta_1}{2} \tag{12}$$

The incident and reflected waves, with angle of incidence and reflection, θ_1, are above the reflecting interface and the transmitted wave with angle, θ_2, is below the reflecting interface. V_{p1}, ρ_1, σ_1 are the compressional wave velocity, density, and Poisson's ratio for the layer above the reflecting interface, and V_{p2}, ρ_2, σ_2 are the compressional wave velocity, density, and Poisson's ratio for the layer below the reflecting interface respectively. R_0 is the intercept term in equation (1) and also represents the P-wave normal incidence reflectivity. G is the gradient in equation (1) and is a complex function of ΔV_p, V_p, $\Delta\sigma$, σ, $\Delta\rho$, and ρ as shown in equation (2) through (5).

In this paper A_0R_0 is called the non-Poisson's ratio contrast term (nPRCT) and $\Delta\sigma/(1-\sigma)^2$ is called the Poisson's ratio contrast term (PRCT). Various assumptions have been made by many authors (Gelfand et al., 1986; Hilterman, 1990, among others) for the values of Poisson's ratio (or V_p/V_s) for different rock types to further simplify the gradient (G) from Shuey's equation. It is generally assumed that if the magnitude of Poisson's ratio contrast

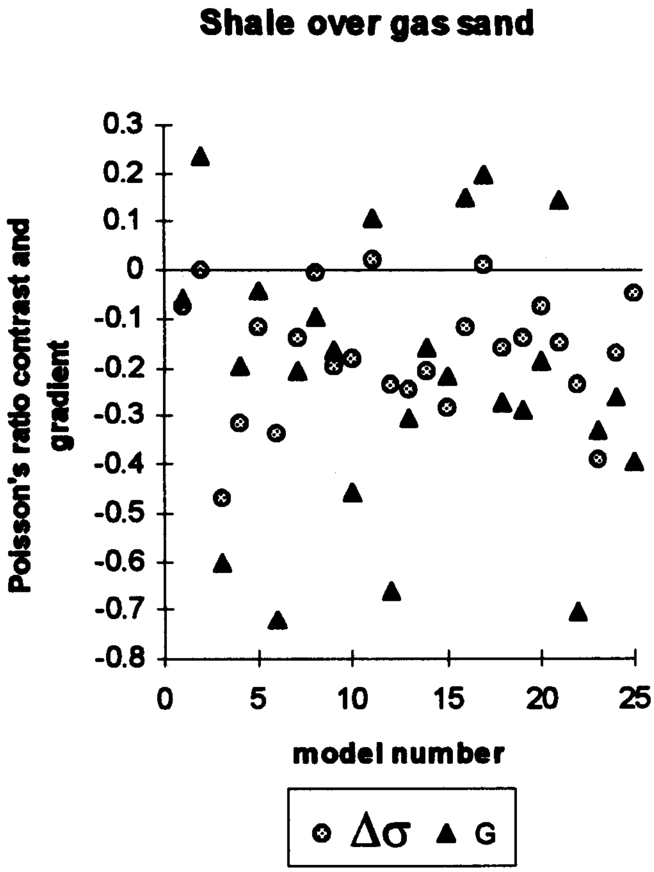

Figure 1. The gradient (G) and Poisson's ratio contrast ($\Delta\sigma$) for shale over gas models (Castagna and Smith, 1994). The vertical axis represents values for G (gradient) and $\Delta\sigma$ (Poisson's ratio contrast), and the horizontal axis represents the model number.

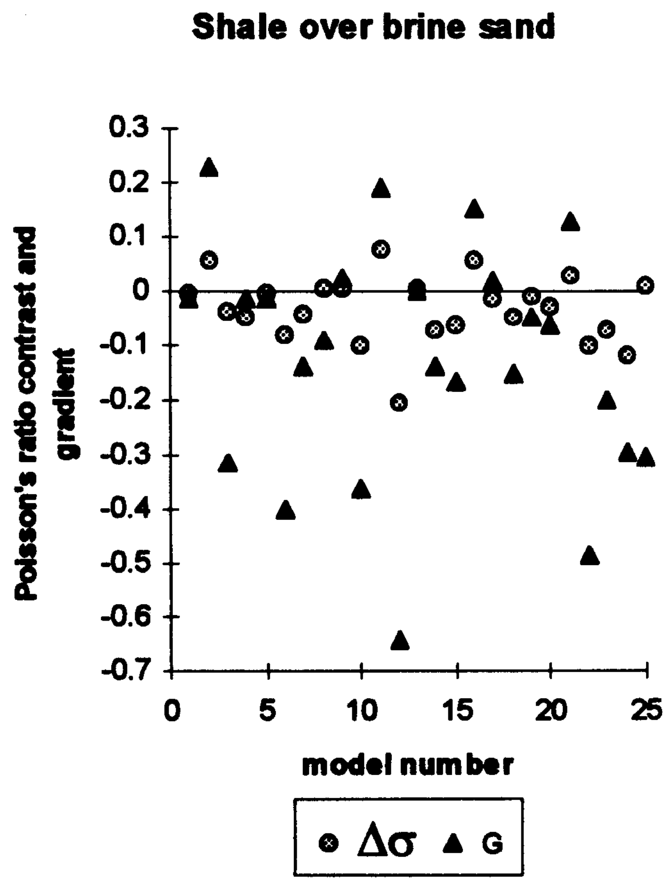

Figure 2. The gradient (G) and Poisson's ratio contrast ($\Delta\sigma$) for shale over brine models (Castagna and Smith, 1994). The vertical axis represents values for G (gradient) and $\Delta\sigma$ (Poisson's ratio contrast), and the horizontal axis represents the model number.

($\Delta\sigma$) is large, then the AVO anomaly indicator (the gradient, G) will be large. Based on this principle, many AVO studies have been conducted world-wide to discriminate seismic amplitude anomalies caused by gas or lithological changes. There are many examples in the literature (Rutherford and Williams, 1989; for example) of the application to hydrocarbon analyses, while Lu and Lines (1995) presented an example of using the AVO technology to study lithology for the Alberta Nisku reef prospect based on the Poisson's ratio contrast between shales and carbonates.

DISCUSSION

To investigate the relative importance of the two terms (nPRCT and PRCT) of the gradient (G), 25 rock models from around the world from Castagna and Smith (1994) were used. For these models the gradient (G) and Poisson's ratio contrast ($\Delta\sigma$) were computed. These values, plotted for each of the 25 models, are shown in Figure 1 (shale over gas sand) and Figure 2 (shale over brine sand). It is obvious that the gradient (G) may be significant even in some cases where the magnitude of Poisson's ration contrast ($\Delta\sigma$) is small (shale over gas sand models 2, 17, 25; shale over brine sand models 2, 3, 25). Figure 1 and Figure 2 also show that similar values of Poisson's ratio contrast ($\Delta\sigma$) may produce quite different gradients in different rocks (shale over gas sand models 4 and 6, 9 and 10, 12 and 13; and shale over brine sand models 3 and 4, 19 and 25 are some examples).

In most circumstances $A_0<0$ (Shuey, 1985). Hence:
when $R_0>0$ (class 1, class 2p) (using the nomenclature of Ross and Kinman (1995)), then the non-Poisson's ratio contrast term (nPRCT), $A_0R_0 < 0$;
and if $\Delta\sigma<0$, A_0R_0 is constructive to the magnitude of gradient (G);

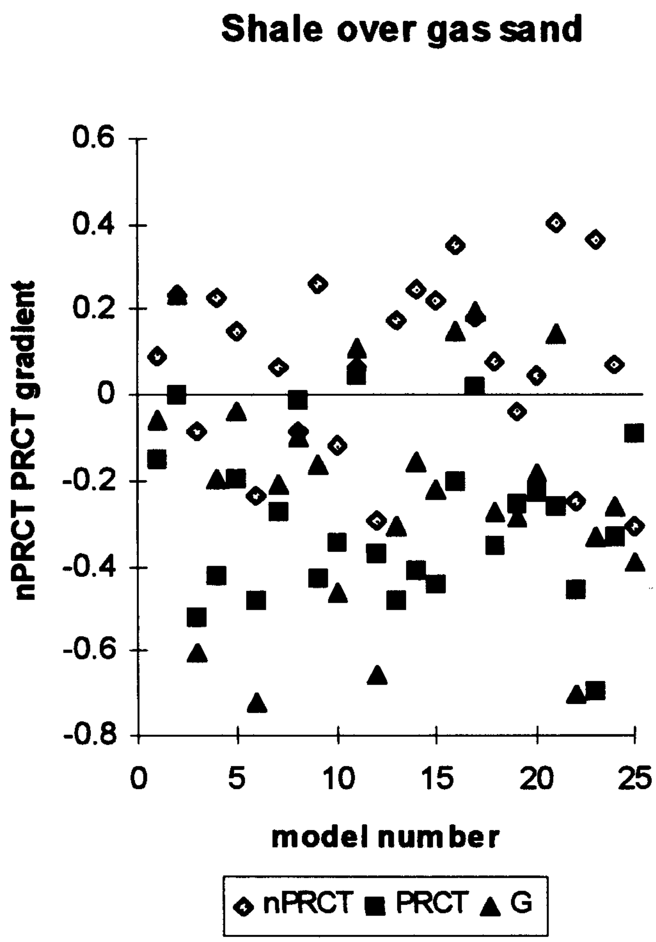

Figure 3. The gradient, non-Poisson's ratio contrast term, and Poisson's ratio contrast term for shale and gas sand models (Castagna and Smith, 1994). The horizontal axis represents the model number.

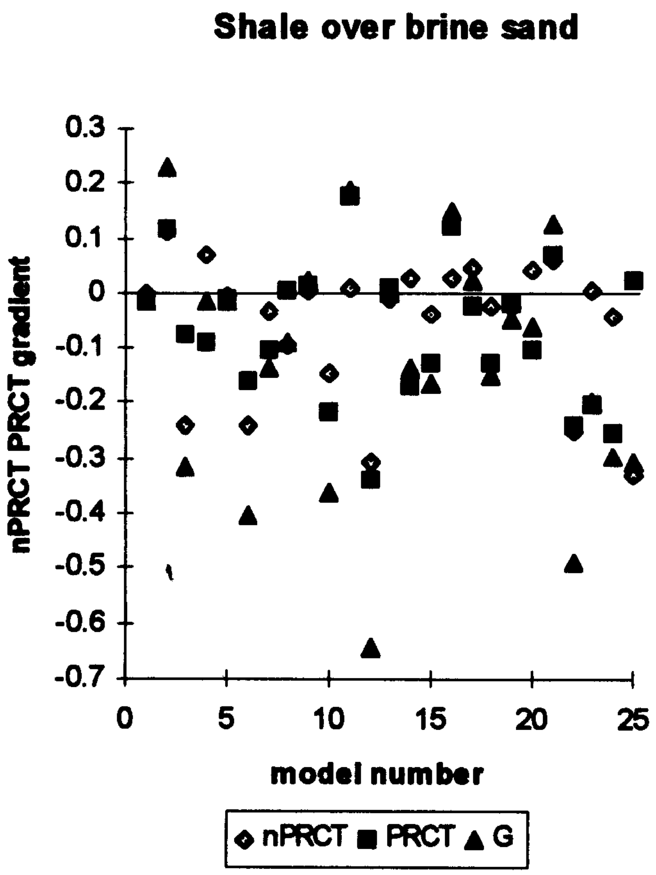

Figure 4. The gradient, non-Poisson's ratio contrast term, and Poisson's ratio contrast term for shale and brine sand models (Castagna and Smith, 1994). The horizontal axis represents the model number.

and if $\Delta\sigma > 0$, A_0R_0 is destructive to the magnitude of gradient (G).

When $R_0 < 0$ (class 2, class 3) (using the nomenclature of Ross and Kinman (1995)), then the non-Poisson's ratio contrast term (nPRCT), $A_0R_0 > 0$;
and if $\Delta\sigma < 0$, A_0R_0 is destructive to the magnitude of gradient (G);
and if $\Delta\sigma > 0$, A_0R_0 is constructive to the magnitude of gradient (G).

To quantify this, the non-Poisson's ratio contrast term (nPRCT) and the Poisson's ratio contrast term (PRCT) are calculated and plotted for each of the 25 models. Figure 3 shows these values for the shale over gas sand model, while Figure 4 shows these values for the shale over brine sand. These Figures show that the non-Poisson's ratio contrast term (nPRCT) is constructive to the magnitude of the gradient (G) significantly in a number of cases (model numbers 6, 12, 22, 25 for shale over gas sand; model numbers 3, 6, 10, 12, 22 for shale over brine sand), while it is destructive to the magnitude of the gradient (G) significantly in model numbers 4, 9, 15, 21, 23 for shale over gas sand. Therefore assumptions that are only based on the contributions of the Poisson's ratio contrast may be misleading.

CONCLUSION

The gradient term (G) of the Shuey's equation is a complex function of ΔV_p, V_p, $\Delta\sigma$, σ, $\Delta\rho$, and ρ. Analysing the models of Castagna and Smith (1994) shows that a small Poisson's ratio contrast ($\Delta\sigma$) may cause a large gradient for some rocks. On the other hand, similar values of Poisson's ratio contrast ($\Delta\sigma$) may produce quite different gradients for different rocks. In addition, the non-Poisson's ratio contrast term can be either constructive or destructive to the magnitude of the gradient depending on the polarity of normal incidence reflectivity (R_0) and the Poisson's ratio contrast. The simple assumption of a value for Poisson's ratio (or V_p/V_s) to simplify the gradient may not account for observed AVO anomalies. It is suggested that more accurate shear wave velocity information to accurately determine Poisson's ratio (or V_p/V_s) should be utilised in the modelling of AVO response. The results indicate that a better method is needed to isolate areas with anomalous AVO response. Current methods relying on the gradient may cause the explorationist to misinterpret some gas prospects. Once areas with an anomalous AVO responses are defined more careful modeling, using observed petrophysical properties, will allow more accurate assessment of the hydrocarbon potential.

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