Under this regular column titled 'Expert Answers', we pose questions of both general and technical interest to well-known geophysicists who are considered authorities in a certain area within the geophysical domain and get their 'expert' answers. As these answers could have an individualistic tone, we request the answers from more than one expert in any area.

In this issue, we have selected the following general question and include the answers given by Brian Russell (GeoSoftware), and Miguel Bosch (Info Geosciences, Houston, USA). We thank them for encouraging us with their responses. Readers are encouraged to send us their feedback and even the questions they would like to get answered by experts.

The order in which the answers appear below is the order in which we received them.

- *Satinder Chopra*

Are we able to estimate the subsurface elastic properties quantitatively?

Expert Answer – 1 by Brian Russell*

INTRODUCTION

To answer this question, we first need to define what we mean when we say subsurface elastic properties. Let's start with the *P*-wave and *S*-wave velocities, V_P and V_S, which can be expressed either as a function of the bulk modulus *K*, shear modulus μ, and density ρ, or as a function of the Lamé coefficients λ, μ, and density, which are written as

$$V_P = \sqrt{\frac{K + (\frac{4}{3})\mu}{\rho}} = \sqrt{\frac{\lambda + 2\mu}{\rho}}, \qquad (1)$$

and

$$V_S = \sqrt{\frac{\mu}{\rho}}, \qquad (2)$$

In equations 1 and 2, the shear modulus μ is identical to the second Lamé coefficient μ, and the following relationship holds between the bulk modulus and the first and second Lamé coefficients

$$K = \lambda + \left(\frac{2}{3}\right)\mu. \qquad (3)$$

Equations 1 and 2 are the velocities of compressional and shear seismic waves travelling in an isotropic earth (that is, the properties do not vary as a function of angle) and are fundamental to reflection seismology. Castagna et al. (1985) have shown that there is a roughly linear relationship between the P- and S-wave velocities in wet sands and shales, but that this relationship needs to be modified in hydrocarbon-bearing rocks.

We are also interested in the P- and S-impedances, I_P and I_S, which are the product of density and P- or S-wave velocity, since these are the parameters extracted using seismic inversion:

$$I_P = \rho V_P = \sqrt{K\rho + \left(\frac{4}{3}\right)\mu\rho} = \sqrt{\lambda\rho + 2\mu\rho} \qquad (4)$$

and

$$I_S = \rho V_S = \sqrt{\mu\rho} \qquad (5)$$

Finally, we are interested in the V_P/V_S ratio, which can be written as

$$\frac{V_P}{V_S} = \sqrt{\frac{K}{\mu} + \frac{4}{3}} = \sqrt{\frac{\lambda}{\mu} + 2}. \qquad (6)$$

Notice that the V_P/V_S ratio is independent of density and contains the ratio of the bulk to shear modulus or

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the two Lamé coefficients plus an additive constant under the square root sign.

To understand the importance of these elastic constants in quantitative interpretation, let's consider the rock physics template, or RPT, which was introduced by Ødegaard and Avseth (2004) and involves the identification of geological facies on a cross-plot of V_P/V_S ratio against *P*-impedance. The template can be applied to both well log datasets and the results of elastic inversion of pre-stack seismic data. Figure 1(a), taken from Ødegaard and Avseth (2004), shows a modelled set of points, where colour represents porosity, and the term acoustic impedance is synonymous with the terms *P*-impedance and I_P discussed above. Note the various clusters: shale, brine sands, gas sands, and cemented sands, and trends: pressure, porosity, gas, clay content, and cement.

Next, Figure 1b shows a real data example from the North Sea, with the facies shown in colour. It shows an excellent fit to the modelled points of Figure 1a. Notice that the oil sand facies, shown in green, plot in the lower left-hand part of the rock physics crossplot, with both low V_P/V_S ratio and P-impedance.

But how do we extract this information from seismic data? The first attempts were able to extract P-impedance from stacked seismic data (Lindseth, 1979). This was based on the following simple relationship between P-impedance and the zero-offset seismic reflection coefficients:

$$R_{P_i} = \frac{I_{P_{i+1}} - I_{P_i}}{I_{P_{i+1}} + I_{P_i}} = \frac{\Delta I_P}{2 I_P}, \qquad (7)$$

where R_{Pi} represents the reflection coefficient between the i^{th} and i+1st geological layers, ΔI_P is the difference and I_P is the average P-impedance across the interface separating these two layers. Mathematically, we can integrate equation 7 to get the P-impedance, but there are some limitations in doing this. First, the seismic trace represents the convolution of the reflection coefficients with a seismic wavelet and deconvolution will never fully remove the effects of the wavelet. To get around this problem, a low frequency trend is usually estimated from either well log curves or seismic velocities and is added to the resulting inverted trace. Second, the seismic data is usually corrupted with noise, so adequate processing must be done first. This usually involves stacking a CDP gather, but although this will improve the signal-to-noise ratio it also smears out the amplitudes over a range of offsets or angles, which means we are not estimating the true zero-offset amplitude.

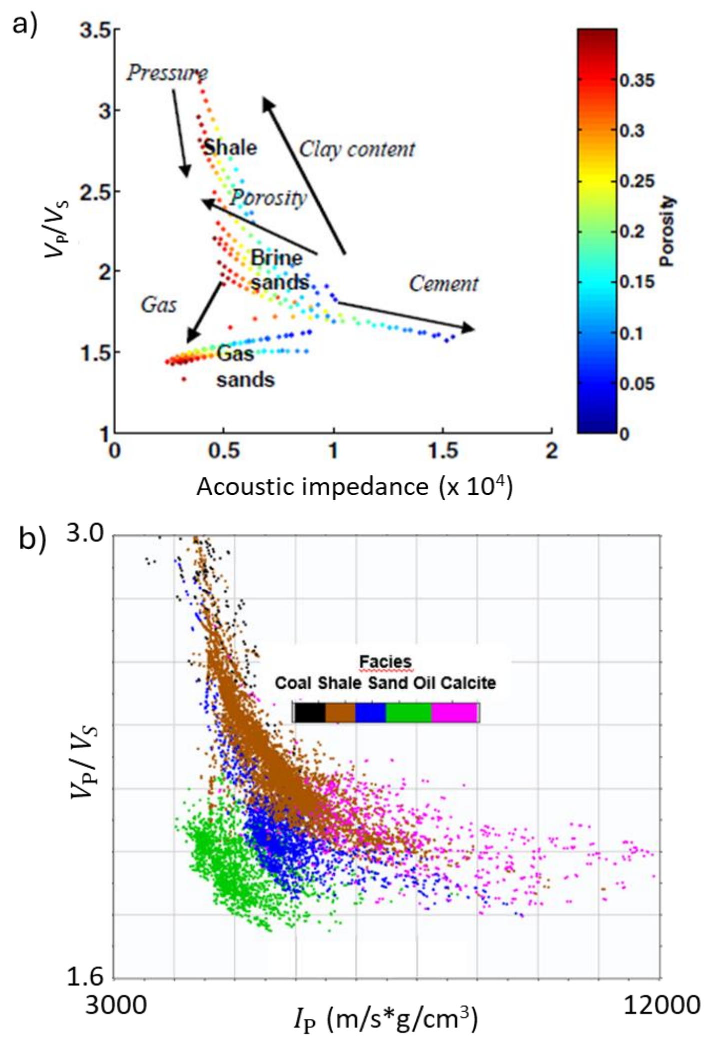

Figure 1. *The rock physics template, where (a) shows a modelled example ((Ødegaard and Avseth, 2004) and (b) shows a real data example from three wells in the North Sea.*

The limitations of poststack data were overcome when the AVO method was invented (Ostrander, 1984), which analyses the data as a function of angle of incidence. Although the full equations for computing the amplitudes have been known for over one hundred years (Zoeppritz, 1919), the AVO method is based in the linearized approximation of Aki and Richards (2002)

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which, as reformulated by Fatti et al. (1984), can be written as

$$R_P(\theta) = a\frac{\Delta I_P}{2I_P} + b\frac{\Delta I_S}{2I_S} + c\frac{\Delta\rho}{2\rho}, \qquad (8)$$

where $a = 1 + \tan^2\theta, b = -8\left(\frac{V_S}{V_P}\right)^2 \sin^2\theta, and\ c = 4\left(\frac{V_S}{V_P}\right)^2 \sin^2\theta - \tan^2\theta$, and we have introduced an S-impedance reflectivity term $\frac{\Delta I_S}{2I_S}$ and a density reflectivity term $\frac{\Delta\rho}{2\rho}$. This means that we can use equation 8 to perform pre-stack inversion on a *P*-wave angle gather. As in post-stack inversion, this involves the incorporation of a low frequency trend, but also includes the addition of constraints between *P*-impedance, *S*-impedance, and density. Details of this technique are presented in Hampson et al. (2005). Once we have inverted for *P* and *S*-impedance, we can compute the ratio of the two results to get the V_P/V_S ratio (since the density term cancels out) and can produce a cross-plot of the real data like the RPT cross-plots shown in Figure 1.

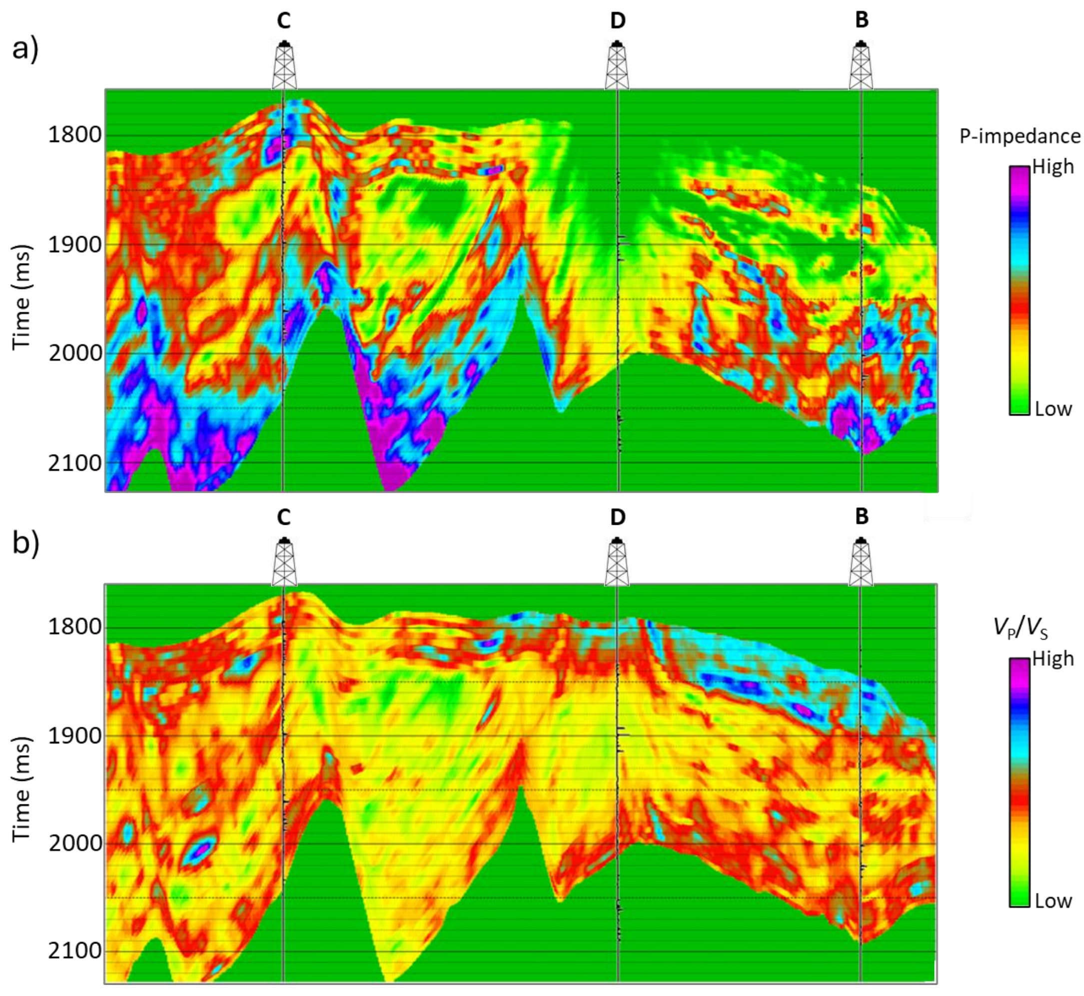

Figure 2*: The inverted seismic results, where (a) shows the inverted P-impedance and (b) shows the inverted V_P/V_S ratio.*

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Continuing with the real data example shown in Figure 1(b), the pre-stack inverted results of the seismic data that was intersected by the three wells used to compute this cross-plot are shown in Figure 2. Note that this is a line that has been reconstructed from a 3D seismic volume that includes the three wells. Figure 2(a) shows the inverted P-impedance and Figure 2(b) shows the inverted V_P/V_S ratio. Also shown are the locations of the three wells used to create the cross-plot in Figure 1(b).

In Figure 2(a) notice that there is an area of low acoustic impedance shown by the green colour that is between wells C and D. This same region shows an area of low V_P/V_S ratio in Figure 2(b), again coloured in green. If you go back to Figure 1(b), you will see that low V_P/V_S ratio and low P-impedance on the Rock Physics Template corresponds to the oil sand facies. Using a statistical technique described by Doyen (2007) we are then able to transform the seismic results shown in Figure 2 into an estimate of facies distribution in the subsurface. This technique involves fitting probability density functions to the facies from the well logs shown in Figure 1(b) and then applying these probability density functions to the extracted V_P/V_S ratio versus P-impedance results from the seismic data using Bayesian classification.

The results of the classification applied to the data shown in Figure 2 are shown in Figure 3 and indicate that there is an area of bypassed oil sand pay between wells C and D, as shown by the green oil sand facies. This map shows most likely facies, but we can also make plots of the actual probability of finding the facies.

In summary, *not only are we able to estimate subsurface elastic properties such as P-impedance, S-impedance and V_P/V_S ratio from seismic data, we are able to transform these elastic properties into geological facies estimates*. As discussed here, this involves analyzing well data using a V_P/V_S versus P- impedance rock physics cross-plot, inverting the pre-stack seismic data for P-impedance and S-impedance, and then applying the results learned from the well log data to the inverted seismic data. *G*

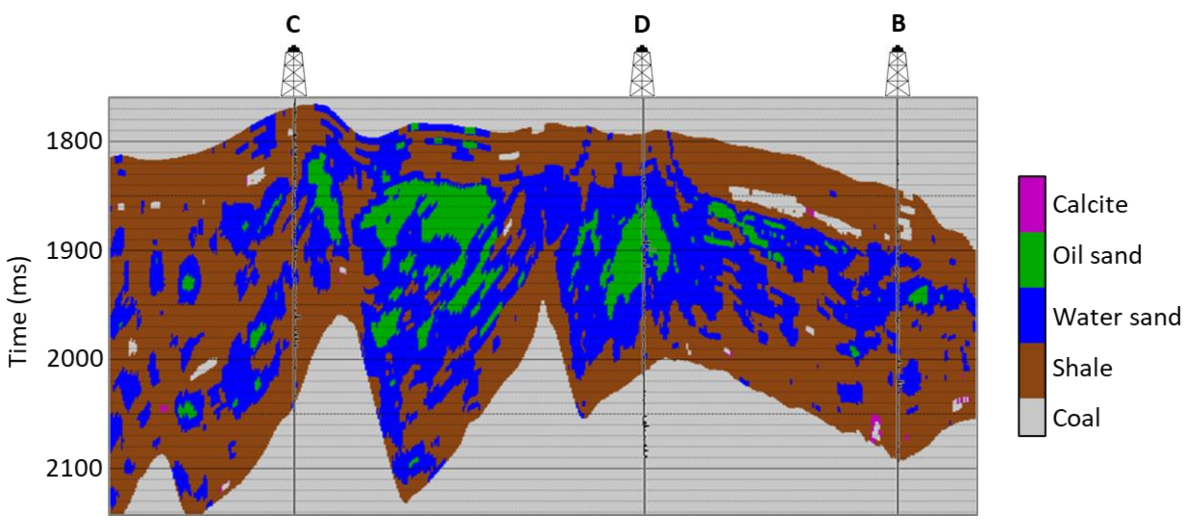

Figure 3: *Predicted facies using the rock physics cross-plot of Figure 1 and the inverted seismic data of Figure 2. Note the area of bypassed oil sand pay between wells C and D.*

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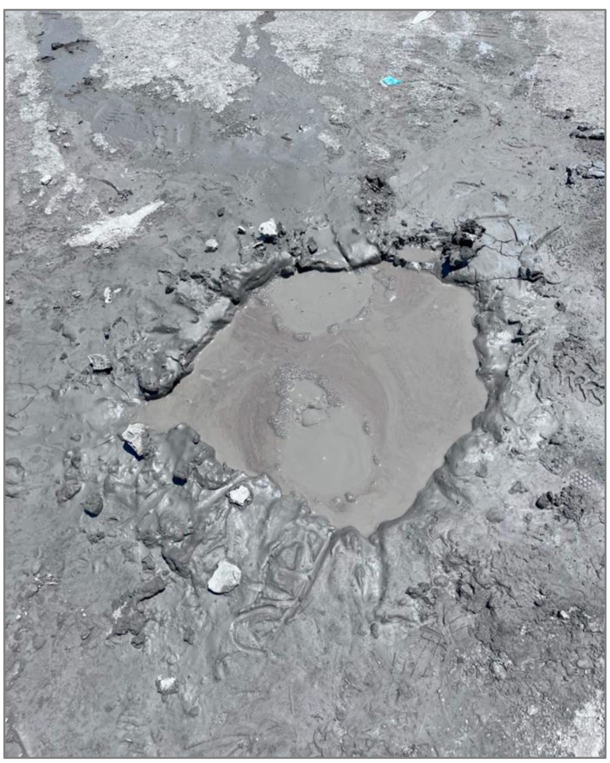
BIOGRAPHY

Brian Russell joined Chevron Standard as an exploration geophysicist in Calgary 1975 and worked for Chevron Geophysical in Houston, and Teknica Resources and Veritas in Calgary before co-founding Hampson-Russell Software with Dan Hampson in 1987. Hampson-Russell is now a subsidiary of GeoSoftware in Calgary, where Brian is Vice President. He is a Past-President of both the CSEG and SEG and has received Honorary Membership from both societies, as well as the Cecil Green Enterprise Award from SEG and the CSEG Medal. Brian holds a B.Sc. from the University of Saskatchewan, a M.Sc. from Durham University, U.K., and a Ph.D. from the University of Calgary, all in geophysics. He is an Adjunct Professor at the University of Calgary and affiliated with the CREWES Consortium.



Gobustan, Azerbaijan, is renowned for its mud volcanoes. With the highest number of mud volcanoes found in any country, Azerbaijan is home to 350 of the world's 700 mud volcanoes. Locals have various names for them such as "yanardagh" (burning mountain), "pilpila" (terrace), "gaynacha" (boiling water), and "bozdag" (grey mountain), in addition to the geographical term "mud volcanoes." *Photo courtesy: Ritesh M. Joshi.*

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