

Optimal hydrocarbon indicators

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Summary

The best combination of rock properties as hydrocarbon indicators is currently under debate. For many rocks, the increase in saturated bulk modulus is approximately linearly related to the fluid modulus ($\Delta K = G(\phi) * K_f$). This ΔK can be extracted from seismic data and therefore serve to indicate fluids. For sandstones and clay-rich sandstones, the difference of the bulk and shear modulus ($K-\mu$) may prove best. Combinations of Lamé's constant (λ), shear modulus, and density (ρ), have also been proposed. However, many of these extracted moduli combinations are basically similar in sensitivity to hydrocarbon saturation. Starting with normal reflectivity and slope (A-B) plots, the indicators can be tuned to the properties of the contained pore fluids.

Introduction

Extensive effort is now being spent to extract rock and fluid properties from prestack offset seismic data. 'Bright spots' and amplitude versus offset (AVO) have been used for many years as hydrocarbon indicators (e.g. Smith and Gidlow, 1987) with varying degrees of success. Recently, attempts have been made to focus the analysis by converting the observed offset response directly to rock and fluid properties. In some cases, this has provided a good tool to identify hydrocarbon zones quickly (Fatti et al., 1994). Extraction of various rock moduli have been used or proposed (Goodway et al., 1997, Chen et al., 1998, Berryman et al., 1999) but the best method is still under debate. Calibration of hydrocarbon indicators for specific locations and rock types is needed.

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A common simplification to Zoepritz equation good for angles, Θ , less than about 30 degrees is

$$R(\Theta) = A + B \sin^2\Theta$$

Here, A is the normal incidence reflectivity, and B would be the slope or angle dependence. Sheuy (1985) gives a simple form for B

$$B = A_0 A + \Delta v / (1 - \nu)$$

A_0 is related to the average Poisson's Ratio, ν , compressional velocity, and density. If we assume that the

background Poisson's ratio is 0.3, and density changes with velocity, we get

$$B = -1.26 A + 2.04 \Delta v$$

The change in Poisson's ratio, Δv , was calculated with the Gassmann substitution. In Figure 1, the calculated slope and intercept is plotted for a shallow case using different fluids.

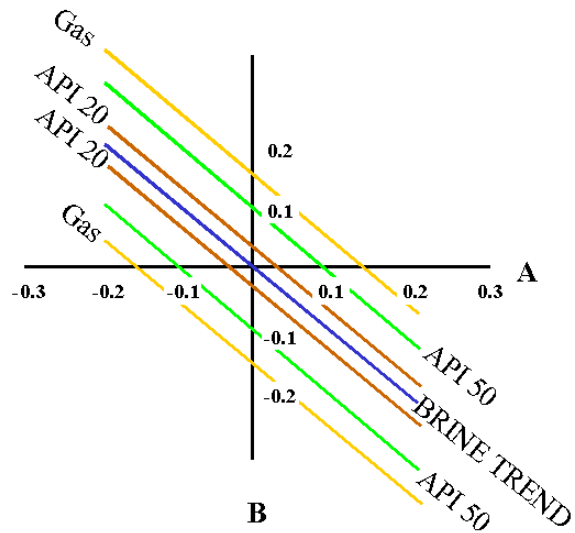


Figure 1: Calculated slope versus intercept relation for different pore fluids.

Reflections involving the brine saturated case along the 'brine trend' which pass through the origin. We see no strong normal reflection or angle dependence. As successively lighter hydrocarbons are substituted, our lines relating the A and B coefficients moves further from the brine trend. For our light live oil, we get a response almost the same as gas. Although the normal incidence reflection can be near zero, we get expect a strong angle dependence (B). Foster and Keys (1999) see a similar response systematically changing with all gas sand classifications.

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Other fluid indicators have been suggested recently. Shear and Bulk moduli (μ and K respectively) are commonly derived seismic data.

$$\mu = V_s^2 \rho$$

$$K = V_p^2 \rho - 4/3 \mu$$

Where V_s and V_p are shear and compressional velocities and ρ is density. Shear modulus is often independent of pore fluid content. Focus historically has then been on bulk modulus as a hydrocarbon indicator.

Goodway et al. (1999) and Berryman et al. (1999) point out that Lamé's constant, λ , is an available term that may be better suited as a fluid indicator.

$$\lambda = K - 2/3 \mu$$

Combinations of λ , λ/μ , and λ/ρ are all suggested. Goodway et al. (1997) demonstrated the improved appearance of sections processed for λ/ρ .

These relations can also be tested by plotting all calculated values where enough data is available. In Figure 2, velocities, densities, and lithologies are seen from a North Sea well made available by Keys et al. (1998).

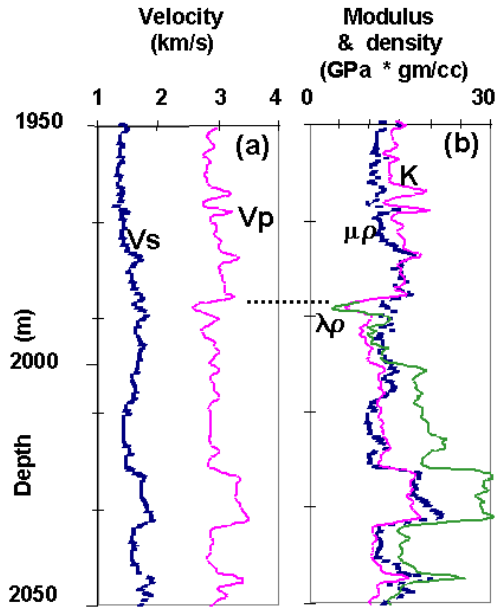


Figure 2: Shear and Compressional velocities (a) and moduli-density relations for well A

A hydrocarbon zone occurs at 1985 meters and is indicated on the velocity logs by a decrease in V_p . Shear velocity is almost unaffected as is the shear-density product $\mu\rho$. Both the bulk modulus and Lamé-density term, $\lambda\rho$, show a strong decrease entering the hydrocarbon zone. However, in hydrocarbon zones below about 1990 meters, the response is relatively weak.

Alternatively, the brine line of Castagna et al. (1985) suggests another factor. For gas saturated (dry) clastics they found that the bulk modulus is approximately equal to the shear modulus. This is consistent with the laboratory data of Han (1986) seen in Figure 3.

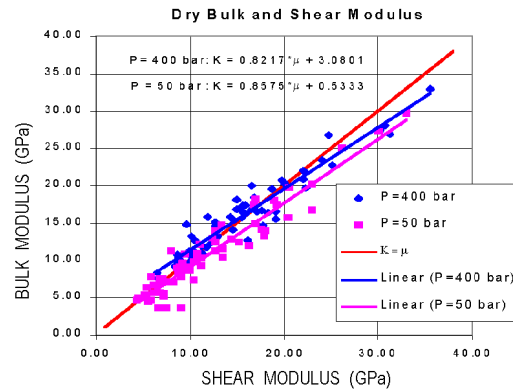


Figure 3: Laboratory data of Han (1986) showing the relation between dry rock bulk and shear moduli.

Taking the difference between the dry moduli gives

$$K_{\text{dry}} - \mu = 0.$$

Thus, if the hydrocarbon or gas modulus is small, this difference will approach zero.

Saturation effects

The change in rock bulk moduli with saturation can be written in the form:

$$K_{\text{sat}} = K_{\text{dry}} + \Delta K$$

Here, ΔK is increment due fluid saturation. It is approximately proportional to fluid modulus as

$$\Delta K = G(\phi) * K_f$$

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where $G(\phi)$ is a constant saturation gain function for a dry rock and K_f is fluid modulus. Hence, ΔK is a direct indicator for fluid modulus.

Pore fluids in gas, oil and water formations usually have distinct ranges of modulus

Gas	0.01 to 0.4 Gpa
Oil	0.4 to 2.0 Gpa
Water	2.2 to 4.0 Gpa

Clearly, if we can derive ΔK accurately, we have a chance to evaluate pore fluid directly. For partial hydrocarbon saturated reservoirs, fluid modulus distributes in between those for gas, oil and water.

The sensitivity of a rock to liquid saturation is strongly dependent on the ratio of the dry rock (K_{dry}) to mineral (K_s) moduli

$$Kn = K_{dry}/K_s$$

where Kn is the normalized dry modulus. Substituting this term into Gassmann's equations and keeping only the dominant terms gives us

$$G(\phi) = (1-Kn)^2 / \phi$$

For a deep water reservoir rock with 30% porosity and over pressured condition, Kn can be small as 0.05.

The saturation gain function, $G(\phi)$, is then equal to 0.3.

We can then use this value to estimate the range of this $K-\mu$ hydrocarbon indicator:

Gas (Gpa)	Oil (Gpa)	Water (Gpa)
0.01 to 0.4	0.4 to 1.2	2.2 to 4.0
0.03 to 1.2	1.2 to 3.6	6.6 to 12.0

If we compare our $K - \mu$ with the extracted K and λ we see the consistently lower values below 1985 meters (Figure 4). Plotting the difference between the bulk and shear modulus whenever it passes over a threshold of about 8 GPa, we get a good correlation to the hydrocarbon saturated zones. It should be noted however, that all the terms K , λ , and $K-G$ are giving approximately the same result, but with slight offsets in value. This is because of the nearly constant value of shear modulus μ . Adjusting the threshold for each curve would give basically the same result.

From seismic velocities, if we can approximate the shear modulus from compressional-wave modulus

$$V_p^2 * \rho = M = K_{sat} + 4/3 \mu$$

We can derive fluid indicator as

$$K_{sat} - \mu = M - 7/3 \mu.$$

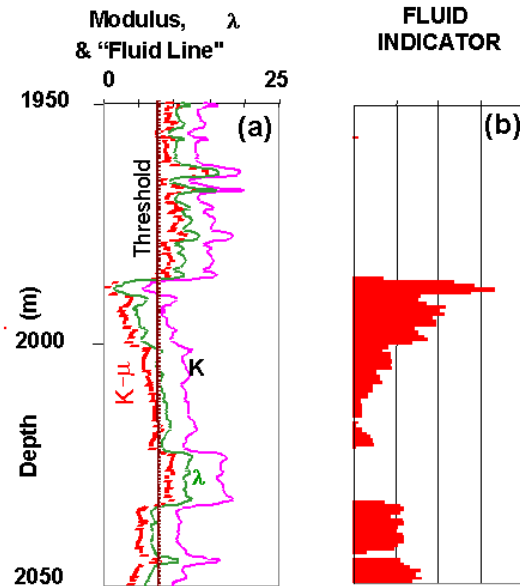


Figure 4: Extracted moduli (a) and 'Fluid Indicator' (b) for well A

Using the results of Figure 3 gives us more specific relations:

$$K_{dry} = 0.822 * \mu + 3.08 \text{ (Gpa)}$$

Using this equation we can adjust the hydrocarbon indicator as

$$K_{sat} - \mu = M - 2.155 * \mu + 3.08 \text{ (Gpa)}.$$

Conclusions

Various combinations of rock properties have been proposed as hydrocarbon indicators. Bulk modulus, K , lame's, λ , constant, and products of shear modulus, μ , and λ with density ρ . For sandstones, the difference $K-\mu$ may be the most sensitive in absolute terms. However, most of

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these indicators give similar results in magnitude. The best indicator will need to be calibrated and tested for the local situation.

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Acknowledgments

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