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A Rock Physics Model for Exploring Heavy Oil in Infra-Cambrian Bilara Carbonates of the Bikaner-Nagaur Basin.

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Summary

We developed a rock physics model to aid exploration of heavy oil in Infra-Cambrian Bilara carbonates of the Bikaner-Nagaur basin. From rock physics modeling, it has been observed that the major contribution to porosity in recrystalized Bilara carbonates is from cracks with aspect ratio ~0.04. In general, heavy oil in Bilara carbonate has minor effect on elastic properties of the rock. But in a clean carbonate, the presence of cracks significantly reduces the elastic moduli of the rock. Thus, identifying regions of high crack density would serve as a plausible model for heavy oil exploration in Bilara carbonates.

Introduction

In spite of several proven hydrocarbon plays worldwide, Infra-Cambrian rocks have not been adequately explored. In a recent article, Singh and Tiwari (2011) summarized global occurrences of hydrocarbon plays and finds in Infra-Cambrian rocks from a plate tectonic viewpoint. They argued strongly in favor of aggressive search for hydrocarbons in sedimentary rocks of India belonging to this age. Discovery of heavy oil from the Baghewala structure in the Bikaner-Nagaur basin (Figure 1) provides new exploration opportunity in western India. Heavy oil (~ 18o API) has been encountered in the Infra-Cambrian Jodhpur formation in Baghewala field.

The overlying Bilara carbonate also shows presence of heavy oil but was not tested because of lower porosity and permeability of the formation. Due to non-availability of shear velocity measurements in this well, the elastic properties of the heavy-oil-bearing rocks could not be characterized adequately. We used wireline-measured density and shear sonic velocity in Bilara carbonates from wells in a neighboring field to develop a rock physics model. The rock physics model provides an understanding about the interrelationship between elastic and petrophysical properties of Bilara carbonate. It also helps to develop a model for exploring hydrocarbons using seismic data. The results of rock physics modeling shows that the elastic properties of Bilara carbonate are more sensitive to the pore geometry than to the fluid properties. Thus, exploration for heavy oil in Bilara carbonate should target areas of high fracture density by using elastic properties derived from 3D seismic amplitude and amplitude variation with offset (AVO) analyses.

Theory

Differential effective medium theories (Ruiz et al., 2010) have been successfully used to model elastic properties of rocks with various idealized pore shapes. These inclusion methods incorporate pore shapes in addition to volumes of constituent minerals of the rock. Pore geometry is a critical parameter that significantly influences the elastic properties of a a rock. Following Kuster and Toksoz, 1974 (K-T), the effective elastic properties of a medium embedded with inclusions of a specific geometrical shape can be written as

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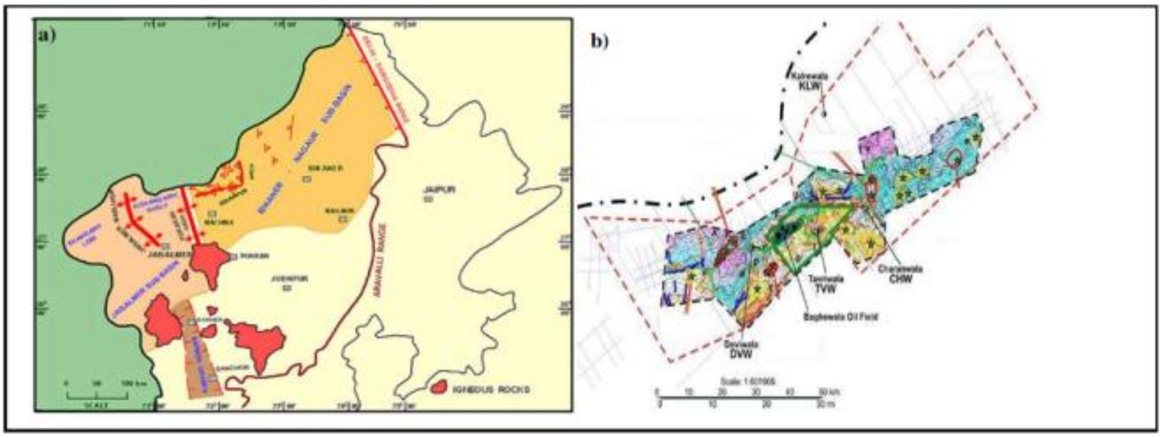

Figure 1 : a) Maps showing location of Bikaner-Nagaur basin b) heavy oil is encountered in Baghewala structures in Bikaner-Nagaur basin.

$$(K_{KT} - K_m)\frac{\left(K_m+\frac{4}{3}\mu_m\right)}{\left(K_{KT}^{*}+\frac{4}{3}\mu_m\right)} = \sum_{i=1}^{N} x_i (K_i - K_m) P^{mi} \ , \qquad (1)$$

$$(\mu_{KT} - \mu_m)\frac{(\mu_m+\delta_m)}{\left(K_{KT}^{*}+\frac{4}{3}\delta_m\right)} = \sum_{i=1}^{N} x_i (\mu_i - \mu_m) Q^{mi} \ , \qquad (2)$$

Where K_{KT} and μ_{KT} are the bulk and shear moduli of effective media and K_m and μ_m are the bulk and shear moduli of minerals K_i and μ_i are the bulk and shear moduli of an inclusion and x_i represents the volume fractions of inclusions P^{mi} and Q^{mi} can be written as (Mavko et al., 1998)

$$P^{mi} = \frac{K_m+\frac{4}{3}\mu_m}{K_i+\frac{4}{3}\mu_i+\pi\alpha\beta_m} \ ,$$

$$Q^{mi} = \frac{1}{5}\left(1 + \frac{8\mu_m}{4\mu_i+\pi\alpha\beta_m} + 2\frac{K_i+\frac{2}{3}(\mu_i+\mu_m)}{K_i+\frac{4}{3}\mu_i+\pi\alpha\beta_m}\right),$$

Where

$$\beta = \mu_m \frac{(3K_m+\mu_m)}{(3K_m+4\mu_m)},$$

and α , is the aspect ratio (ratio of minor to major axis) of elliptical inclusions.

For spherical inclusions, these terms are given by

$$P^{mi} = \frac{K_m+\frac{4}{3}\mu_m}{K_i+\frac{4}{3}\mu_m},\ Q^{mi} = \frac{\mu_m+\delta_m}{\mu_i+\delta_m} \text{ with } \delta_m = \frac{\mu_m}{6}\frac{(9K_m+8\mu_m)}{(K_m+2\mu_m)}.$$

This model has been extensively used to explain elastic properties of rocks of wide depth ranges (Xu and White, 1995). We used this model to explain observed elastic properties of Bilara carbonate rocks, assuming the rock is a mixture of carbonate and shale with different embedded pore geometries. A conceptual rock model with different aspect ratios is presented in Figure 2.

We used the following steps for rock physics modeling of elastic properties.

i) Compose grain properties of the carbonate and shale mixture using the Reuss (1929) mixing method.
ii) Apply the Kuster-Toksoz (1974) equations to get the effective elastic properties of the dry rock skeleton.
iii) Incorporation fluid modulus is as inclusions in the rock for crack facture porosity.

Examples

We selected a wet Bilara carbonate to build a rock physics model. Figure 3 shows the wireline logs for Bilara formation. The conceptual rock model (Figure 2) is composed with pores of different geometries. We have considered two types of pores: i) spherical pores (i.e., primary inter-granular pore geometry considered to be rounded) and ii) pores with aspect ratio 0.04 representing the presence of cracks in the rock. Mineral parameters (Mavko et al., 1998) used in rock physics modeling are given in Table 1.

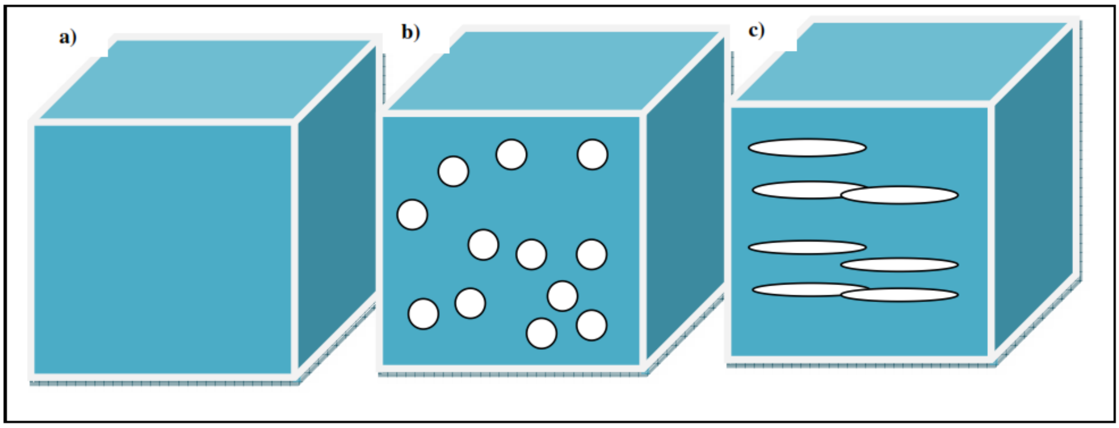

Figure 2: Conceptual rock model: a) rock with no porosity b) rock with spherical pores c) rock with fractures.

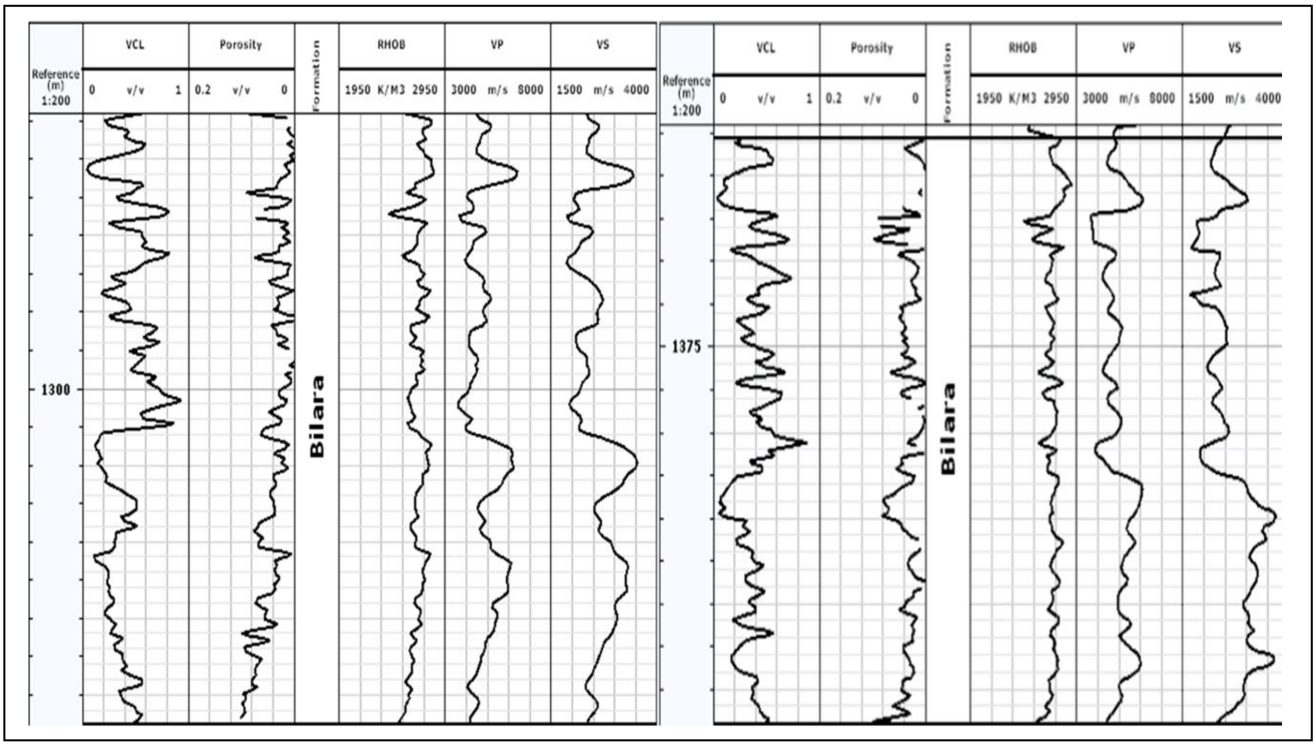

Figure 3: Log data for Bilara formation in 3a) Well 1 and 3b) Well 2. Tracks 1 through 5 display clay volume, porosity, bulk density, compressional velocity and shear velocity respectively.

Table 1 : Elastic parameters in model

Mineral	Bulk Modulus (GPa)	Shear Modulus (GPa)	Bulk Density (g/cc)
Dolomite	94.9	45	2.87
Shale	22	10	2.62
Brine	2.7	0	1.01

Rock physics modeling

To determine the distribution of pore geometries in clean Bilara carbonate, we inverted measured velocities to estimate pore aspect ratio using Equations 1 and 2. Figure 4 shows the distribution of pores with different aspect ratios. It can be seen that cracks with aspect ratio 0.04 are dominant rock population in clean Bilara carbonate. We modeled elastic properties of Bilara formation (Figure 5) for various types of pore shapes and change in clay volume to analyze their effects. The effects of different pore aspect ratios on the bulk and shear moduli are presented in Figure 5a and 5b respectively. It can be seen that for a specific porosity, the elastic moduli increase with increase in aspect ratio of the cracks. On the other hand, these moduli decrease with increase of clay volume (Figures 5c and 5d).

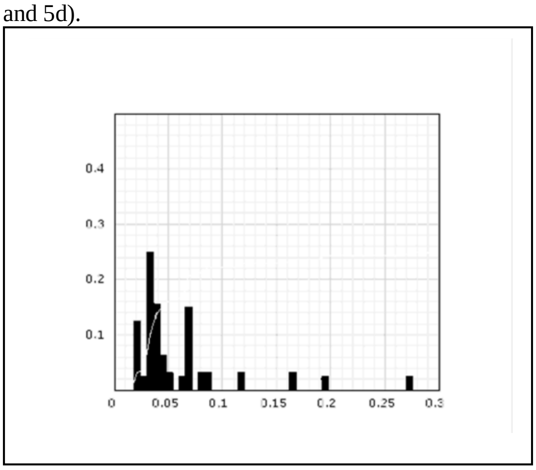

Figure 4: Frequency of aspect ratio derived from measured velocities.

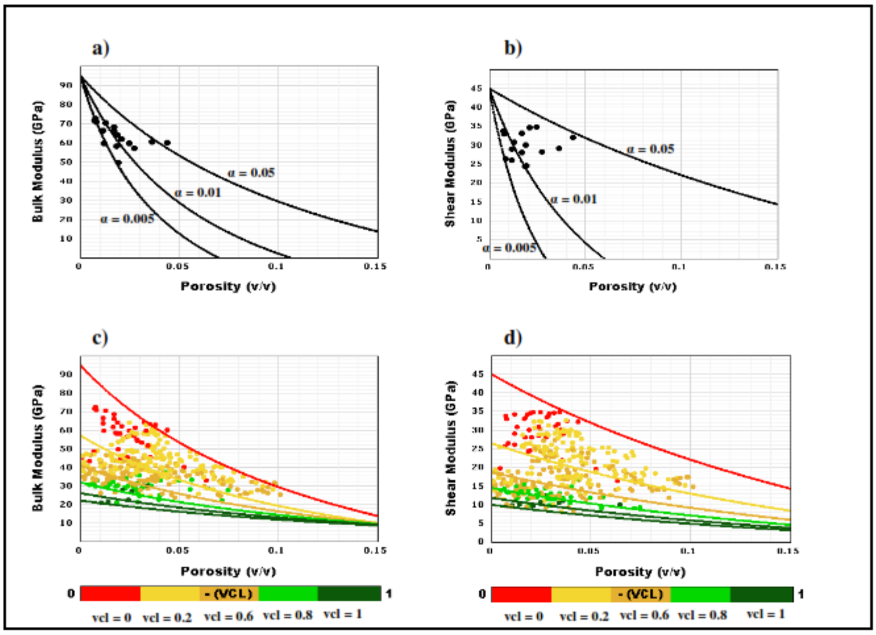

Figure 5: Elastic moduli vs porosity for measured (solid circles) and modeled data (solid lines). a) and b) Measured data for clean reservoir (clay volume: VCL<0.15) and modeled data at various pore aspect ratio. c) and d) Measured data for the entire Bilara formation and modeled data for various VCL values and pore aspect ratio=0.05.

We also analyzed sensitivity of elastic properties of Bilara carbonates to the presence of heavy oil through inclusion of the fluid modulus in Kuster-Toksoz model. Table 2 shows the physical properties of heavy oil characteristic of this area. The results (Figure 6) show that replacement of water by heavy oil in the pores has an insignificant effects on elastic moduli. To investigate the effect of pore shape and clay volume on the ratio of compressional and shear wave velocity (Vp/Vs), we used equations 1 and 2 to estimate Vp/Vs for different aspect ratio and clay volume combinations (Figure 7). It has been found that Vp/Vs increases with clay volume and it decreases with decrease in aspect ratio of pores, the difference increasing with increasing porosity.

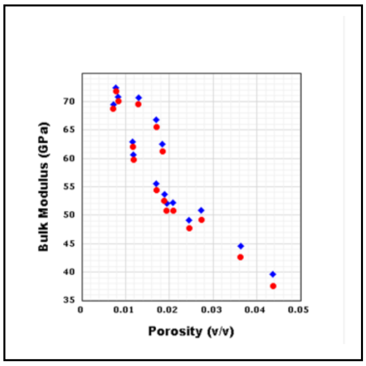

Figure 6: Bulk modulus vs. porosity of a clean reservoir (VCL<15%) saturated with brine (blue diamond) or with heavy oil (red circles).

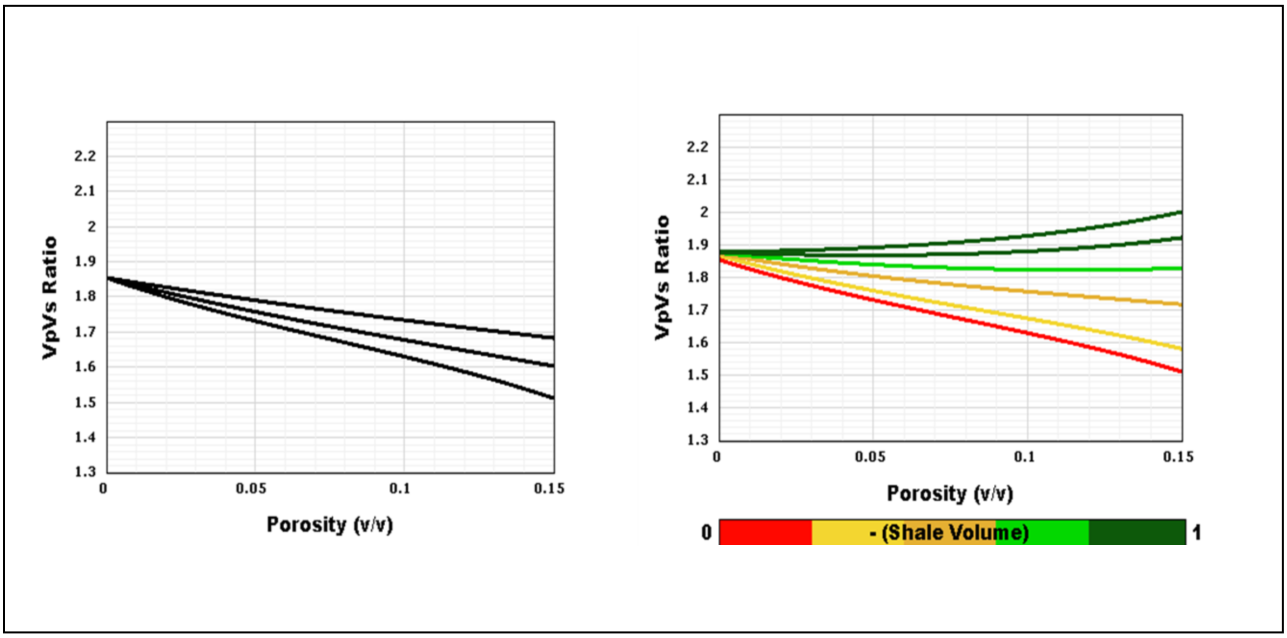

Figure 7: Variation of Vp/Vs ratio with porosity for different a) aspect ratios and b) various clay volumes.

Table 2 : Heavy oil properties

Temp (degF)	Pressure (psi)	GOR	API (degree)	Bulk Modulus (GPa)	Density, (Kg/m3
100	1400	17	15	2.2	930

Conclusions

Rock physics modeling results suggest that clean reservoir facies in Bilara carbonate rock is dominated by fracture or crack porosity. The elastic moduli in the Bilara carbonate rock are not sensitive to the presence of heavy oil at low porosities where elastic moduli decrease due to two factors: i) a change in pore shape in a reservoir facies, which means that porosity is predominantly fracture porosity; and ii) an increase in clay volume in nonreservoir facies. Whereas the shaly facies has higher Vp/Vs ratios, the fractured clean reservoir facies has a low Vp/Vs ratio, thus providing a means to discriminate between good- and poor-quality reservoirs. The presented model suggests that the mapping of areas of high fracture density by using seismic-derived elastic rock properties is a viable tool for exploring for heavy oil in the Bilara carbonates.

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Acknowledgments

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