# Q and the Quest for Heavy Oil Viscosity

Fereidoon Vasheghani*
University of Calgary, Calgary, Alberta, Canada
vashegha@ucalgary.ca

Larry R. Lines and Joan Embleton
University of Calgary, Calgary, Alberta, Canada

## Introduction

Shear properties of heavy oils have been researched by geophysicists in recent studies (e.g. Behura et al. 2007, Vasheghani et al, 2009). It is now believed that shear properties of the heavy oils can change the seismic response. For this reason, heavy oils are considered viscoelastic materials rather than just purely elastic which means that their response to variations of stress is time dependant. In viscoelastic rock physics theories, unlike the traditional elastic models which consider only the elastic properties of the material, the viscosity is taken into account; therefore, the seismic behavior is influenced by viscosity of fluids. This gives geophysicists the necessary foundation for characterizing heavy oil fluids using seismic data. In the presence of heavy oil viscosities, energy of the passing seismic waves is converted in an irreversible fashion, into heat and therefore is lost. This loss of energy is measurable from seismic data through an attribute called quality factor, Q. Both models and data show similar Q vs. viscosity variation, and that there can be ambiguity in defining viscosity from Q.

## Viscosity and Q

To formulate the viscoelastic behavior, combination of springs and dashpots can be used. These components are responsible for elastic and viscous responses, respectively. The combination known as the Zener or standard linear solid model is the most appropriate for exploration seismology. In this model a spring is attached to a parallel connection of a dashpot and another spring (Figure 1).

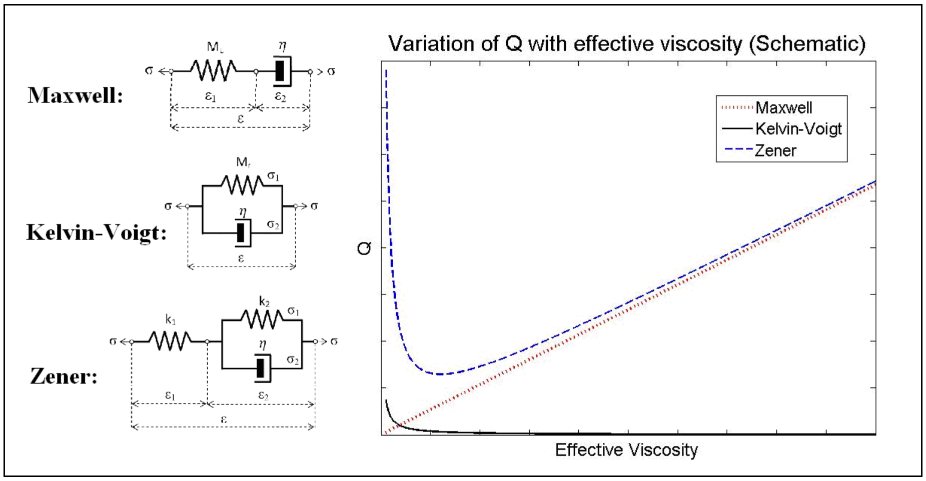

Figure 1: Different viscoelastic models with corresponding behaviors (modified from Vasheghani and Lines, 2009).

While viscoelastic models are necessary for the purpose of heavy oil reservoir characterization, they are not sufficient, because they only provide the relationship between Q and effective viscosity of the material but not the heavy oil inside the pores. Another approach is to use poroviscoelastic formulation. In such theory, fluid inside the pores is distinguished from the solid frame surrounding it. Therefore, the behavior of the material can be attributed to fluid properties and solid properties separately.

Biot-squirt flow model (BISQ) is one of the poroviscoelastic theories that explain the effect of reservoir parameters on P-wave attributes (Dvorkin et al, 1993). The relationship between Q and heavy oil viscosity is given in equation (1) which is valid at seismic frequencies.

$$Q_p = \frac{\operatorname{Re}\left(\sqrt{Y}\right)}{2\operatorname{Im}\left(\sqrt{Y}\right)} \tag{1}$$

where in the above,

$$Y^{-1} = M + F_{sq}\frac{\alpha^2}{\varphi} \tag{2}$$

$$M = K_d + \frac{4}{3}\mu_d \tag{3}$$

$$F_{sq} = F\left[1 - \frac{2J_1(\xi)}{\xi J_0(\xi)}\right] \tag{4}$$

$$\xi = \sqrt{i}\sqrt{\frac{R^2\eta\varphi\omega}{kF}} \tag{5}$$

$$F = \frac{\varphi}{\dfrac{\varphi}{K_f} + \dfrac{1-\varphi}{K_m} - \dfrac{K_d}{K_m^2}} \tag{6}$$

$$\alpha = 1 - \frac{K_d}{K_m} \tag{7}$$

In these equations, $\eta$ is fluid viscosity, $\varphi$ is porosity, k is permeability, $J_n$ denotes a Bessel function of type n, $K_f$, $K_m$ and $K_d$ are fluid, matrix and dry frame bulk modulus, respectively, $\mu_d$ is dry shear modulus, $\omega$ is angular frequency, and R is characteristic squirt flow length.

The relationship between $Q_p$ and fluid viscosity is shown in figure 2 for the parameters given in the table. This curve can be used for estimating heavy oil viscosity from seismic attributes.

This type of behavior, decreasing-increasing is typical of Zener model. Maxwell and Kelvin-Voigt models are not able to predict such trend. That is one of the reasons it is believed that Zener component is the most appropriate for modeling the Earth's seismic response.

Experiments confirm that Q shows the same behavior (Behura et al, 2007). Figure 3 shows the results of lab measurements. The curve of Q versus temperature for rock with oil shows a decreasing-increasing trend.

| Reservoir and fluid properties | |
|---|---|
| Fluid Density | 1000 kg/m$^3$ |
| Fluid bulk modulus | 1 GPa |
| Fluid viscosity | Variable |
| Frequency | 300 Hz |
| R | 1 mm |
| Oil saturation | 1 |
| Matrix Bulk modulus | 35 GPa |
| Matrix Density | 2650 kg/m$^3$ |
| Porosity | 0.30 |
| Dry frame bulk modulus | 1.7 GPa |
| Dry frame shear modulus | 1.35 GPa |
| Permeability | 1 D |

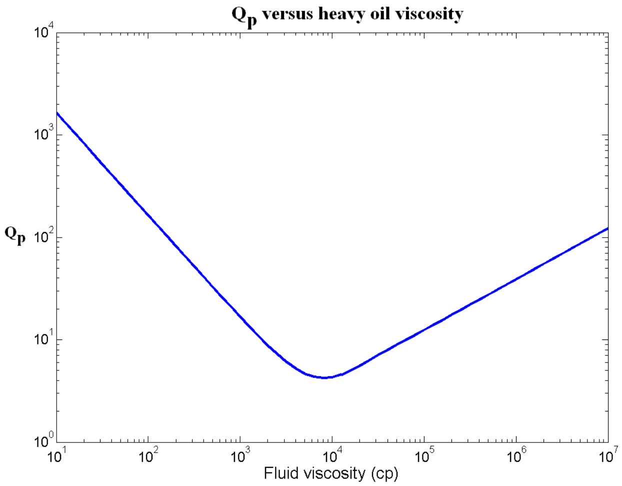

Figure 2: Changes in Q with respect to variations in viscosity.

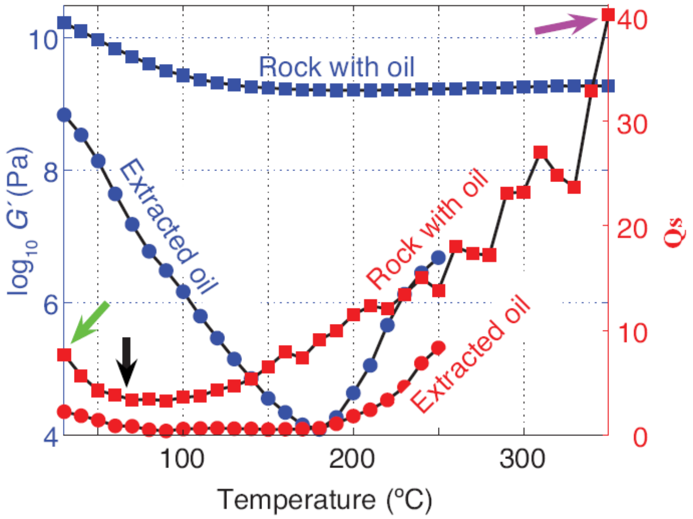

Figure 3: Changes in Q with temperature. Increasing temperature causes reduction in viscosity (modified from Behura et al, 2007).

It is important to note that the curves for Q in figure 3 show $Q_s$. to convert from $Q_p$ to $Q_s$ and vice versa, the following relation can be used (Udías, 1999):

$$\frac{1}{Q_p} = \frac{4}{3}\left(\frac{v_s}{v_p}\right)^2 \frac{1}{Q_s} \qquad (8)$$

It explains that the shape of both $Q_p$ and $Q_s$ curves are the same but the values are different and depend on the $v_p/v_s$ ratio.

Another important consideration is that changes in temperature not only changes the viscosity but also influences the other parameters such as compressibility and density. From equations (1) to (7), it is obvious that Q does not depend on density. However, the other parameters might change the relationship. It makes the sensitivity analysis an essential part in the estimation of viscosity from Q in heavy oil reservoirs. Figure 4 shows how 20% error in each parameter will influence the estimated viscosity.

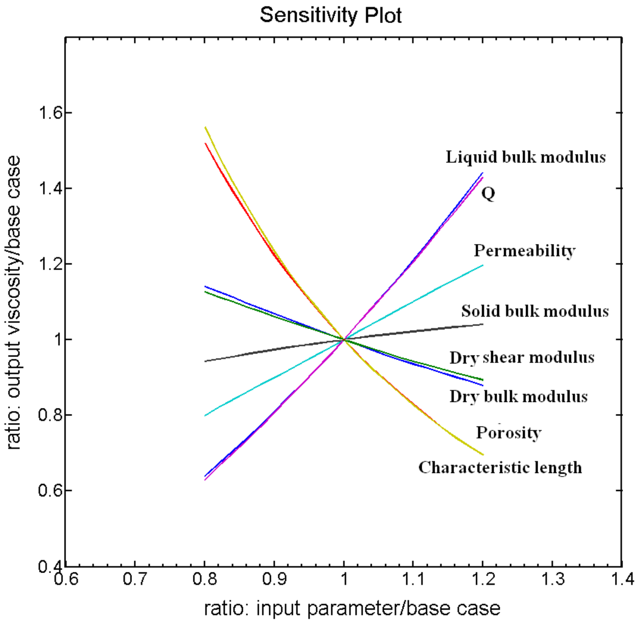

Figure 4: Sensitivity plot. Porosity and liquid bulk modulus should be as accurate as possible because their error has the most impact on the accuracy of estimated fluid viscosities.

## Conclusions

In traditional rock physics theories, it is assumed that the shear properties of fluids do not affect the seismic response. Recent studies show that this is not correct for heavy oils. Heavy oils are considered viscoelastic materials and their shear properties are important. This is shown by viscoelastic rock physics theory. While viscoelastic formulation relates viscosity to measurable seismic attributes, viscosity in those models is the effective viscosity of rock and fluid combined.

Poroviscoelastic theories relate seismic attributes to fluid properties; therefore, can be used for heavy oils reservoir characterization. Both theory and measurements show that Q has a decreasing-increasing behavior with viscosity.

Some reservoir parameters have more influence on the accuracy of the estimated viscosities and should be know to a good degree of accuracy. Liquid bulk modulus and porosity are two of those. Q does not change with density. The Q-viscosity behavior in Figures 1-3 unfortunately demonstrates that there can be nonuniqueness (ambiguity) in determining viscosity from Q.

## Acknowledgements

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