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Brittleness revisited

David Cho[1] *and Marco Perez*[2]
[1]*Qeye Labs Canada,* [2]*Apache Canada*

Summary

The concept of brittleness plays a crucial role in the development of tight oil and gas as it reflects a rock's ability to fail and maintain a fracture in a hydraulic fracture experiment. Conventional methods that attempt to quantify the degree of brittleness associated with a rock mass have a few shortcomings. For example, failure criteria are not used and only the effective moduli are considered, leading to an incomplete description of the problem. In this paper, we address some of these issues by including failure criteria and rock physics models in the brittleness definition.

We propose that petrophysical parameters such as porosity and mineralogy play a more fundamental role in determining a rock's brittleness. This is the result of fractures being supported by the rock frame and hence, the matrix composition must be considered. Furthermore, porosity variations result in a redistribution of stress concentrations, leading to areas that are more susceptible to failure and ultimately reducing the rock's overall strength.

Introduction

A material is brittle if, when subjected to stress, breaks without significant deformation or strain. This concept of brittleness has great implications for the development of tight oil and gas, where a brittle rock is desired for its ability to fail upon hydraulic fracture stimulation to enhance permeability. Furthermore, a rock must be stiff enough to maintain a fracture for proppant placement. Consequently, methods have been developed in an attempt to quantify the degree of brittleness in a given rock formation. One widely used methodology comes from Rickman et al. (2008), where the authors suggest that a brittleness index (BI) can be computed by a renormalization of the Poisson's ratio and Young's modulus in some zone of interest. The claim is that a low Poisson's ratio reflects the rock's ability to fail under stress and a high Young's modulus reflects the rock's ability to maintain a fracture once the rock fractures (Rickman et al., 2008). Although this method has been proven useful in many circumstances, some fundamental issues remain. First, the renormalization process is somewhat arbitrary in defining the upper and lower bounds. This results in a BI that provides information only in a relative sense. Second, the BI only covers part of the brittleness definition. This relates to the elastic moduli and hence the stress and strain in the above definition. The concept of failure is ignored. Third, Poisson's ratio and Young's modulus are two of many elastic moduli and are related through the material constitutive relations. Changes in other elastic moduli can thus influence the Poisson's ratio and Young's modulus. Consequently, consideration of just Poisson's ratio and Young's modulus is insufficient. Lastly, the elastic moduli used in the BI are essentially the effective moduli. Changes in the matrix and pore properties must also be considered.

In this paper, we address the above issues by including the use of failure criteria in the brittleness definition. Additionally, rock physics models are used to investigate how changes in petrophysical parameters such as porosity and mineralogy can affect the elastic moduli. These are used to identify the more favorable conditions under which fractures can form.

Failure criteria

Various failure criteria can be used to determine the conditions under which a material will fail when subjected to stress. These can be used to relate elastic properties and failure. In the following, we briefly discuss some of these relationships.

The uniaxial strain model and Mohr-Coulomb failure criterion can be used to understand the formation of shear fractures under compression. According to the uniaxial strain model, the horizontal stress is related to the vertical stress through a scalar quantity given by $\nu/(1-\nu)$, where ν is the Poisson's ratio. Therefore, a lower Poisson's ratio translates to a larger deviatoric stress under the conditions of uniaxial strain. This results in a larger Mohr circle in Mohr-Coulomb space and thus represents more favorable conditions for failure. This result is consistent with Rickman et al. (2008).

Now consider the Griffith energy-balance criterion (1920), which can be used to understand the propagation of joints under tension. The critical tensile stress required to propagate a three-dimensional penny-shaped crack is given by

$$T_C = \sqrt{\frac{\pi\gamma E}{4(1-\nu^2)c}}\,, \tag{1}$$

where E is Young's modulus, c is the crack radius and γ is the surface energy per unit area. Equation 1 suggests that a decrease in Poisson's ratio or a decrease in Young's modulus will lower the critical tensile stress required to initiate crack growth. According to Rickman et al. (2008), a high Young's modulus is required to maintain a fracture; however, lowering the Young's modulus represents more favorable conditions for failure. Therefore, the highest values of Young's modulus should not represent the optimal conditions for hydraulic fracturing. Furthermore, consider the constitutive relation given by

$$E = 3K(1-2\nu)\,, \tag{2}$$

where K is the bulk modulus. Equation 2 is linear for constant K. Therefore, a low Poisson's ratio is necessarily accompanied by a high Young's modulus. However, by lowering the value of K, a lower value of Young's modulus can be achieved. This suggests that a low bulk modulus should be another condition in the brittleness definition.

The two failure criteria discussed above relate elastic properties and failure; however, a proper calibration is still required to fully determine the failure properties. The calibration process is beyond the scope of this paper but can be achieved through determination of the failure envelope in Mohr-Coulomb space and the energy term in the Griffith criterion.

Rock physics analysis

In the above section, a homogeneous material was assumed and the elastic moduli under consideration are essentially the effective moduli. As petrophysical parameters such as porosity and mineral fractions affect the effective moduli, these must also be considered to understand the brittleness concept. In this section, we present a rock physics model to illustrate how changes in petrophysical parameters affect a rock's brittleness.

First, consider a rock with a three phase mineral composition consisting of varying fractions of quartz, clay and limestone and varying porosity. As each mineral end member has a distinct set of elastic properties, we can use Hashin-Shtrikman (1963) to provide a relationship between the mineral fractions and effective moduli of the rock matrix. Furthermore, we can use the non-interacting approximation (Kachanov, 1992; Kachanov et al., 1994; Shafiro and Kachanov, 1996) to include the effects of porosity. Rock physics trends are then generated as in Perez (2013) to investigate how changes in mineralogy and porosity affect the effective elastic moduli. Figure 1 shows the rock physics trends in Poisson's ratio and Young's modulus space with constant lines of bulk modulus. From Figure 1 we can draw a few general conclusions. An increase in quartz content will lower the Poisson's ratio and increase the Young's modulus. In addition, an increase in porosity will lower the bulk modulus and hence the Young's modulus. The associated implications for brittleness are then as follows. Since we are after a rock that is more easily fractured and is capable of maintaining a fracture, we must have some optimal range of values for the Poisson's ratio, Young's modulus and bulk modulus, where these optimal values are ultimately related to the petrophysical parameters. Fractures in a rock mass are supported by the matrix; therefore, the ability to maintain a fracture should be associated with the rock frame and hence the mineralogy. A greater volume of quartz therefore represents both an increased ability to fail under stress and to maintain a fracture. Furthermore, an increase in porosity will enhance the rock's ability to fail under stress. This is the result of a redistribution of stress concentrations when pores are introduced, resulting in areas of increased stress and leading to more favorable conditions for failure.

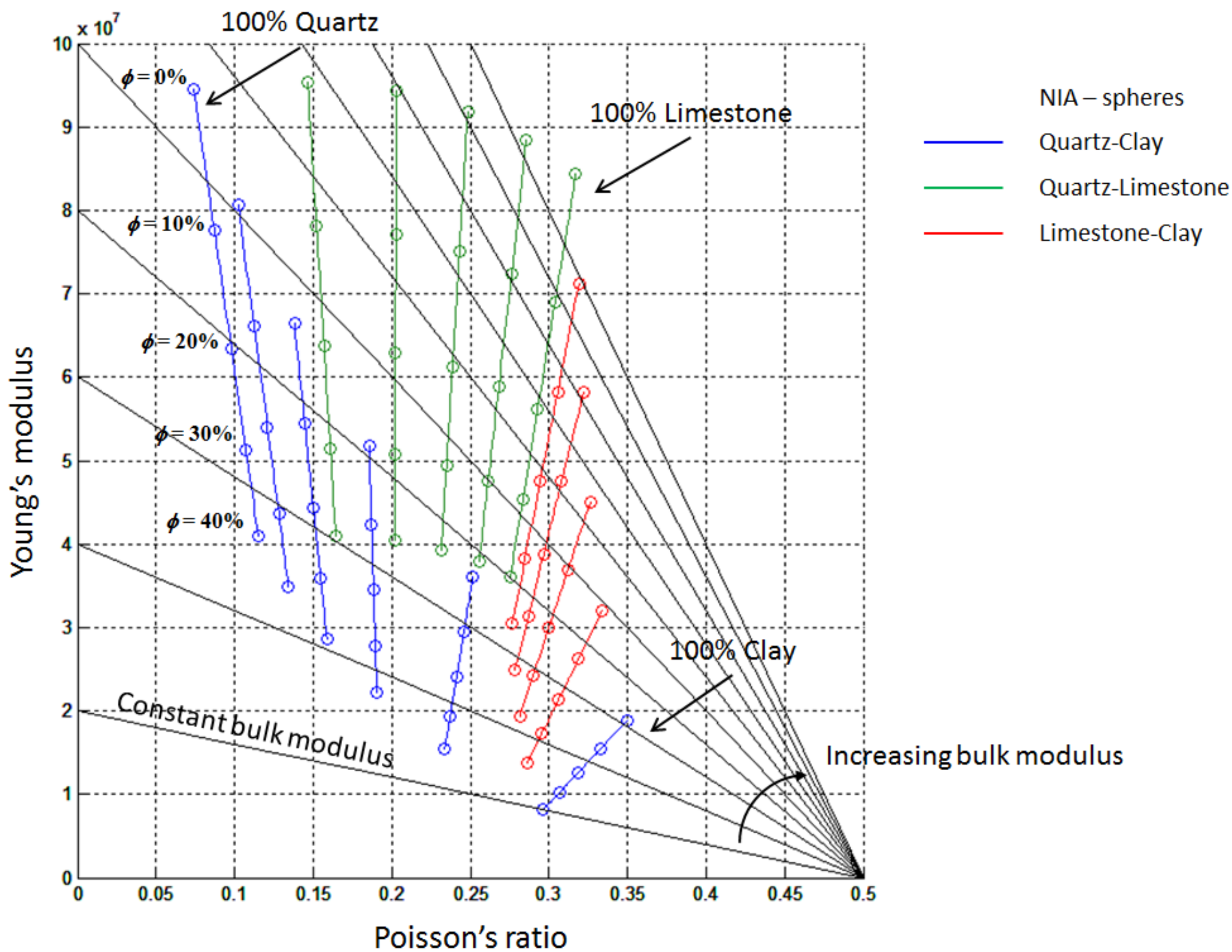

Figure 1: Rock physics trends for varying mineralogy and porosity.

Discussion and conclusions

Brittleness is an important concept for the development of tight oil and gas, as it plays a crucial role in the degree of success associated with a hydraulic fracture experiment. Conventional methods used to quantify brittleness have been proven useful in many circumstances, but lack a few more fundamental considerations, leading to an incomplete description of the problem. The optimal conditions for hydraulic fracturing require a rock mass that is relatively easy to fracture. In addition, the rock mass must be able to maintain a fracture for proppant placement. Therefore, failure properties as well as elastic properties must be considered to understand how the rock mass fails and deforms when subjected to stress.

Elastic moduli that can be estimated from a seismic experiment are essentially the effective moduli and describe the deformational behavior of the rock mass as a whole. However, we propose that petrophysical parameters such as porosity and mineralogy play a more fundamental role in the brittleness concept as presented here. This is due to the fact that fractures are supported by the rock frame, hence the matrix composition and corresponding elastic moduli of the rock frame should be considered for the rock's ability to maintain a fracture. Nonetheless, the rock frame is what fractures and therefore, the matrix properties also represent the rock's ability to fail. Furthermore, the introduction of pores results in a redistribution of stress concentrations in the rock frame. Porosity variations therefore lead to areas that are more susceptible to failure and ultimately reduce the rock's overall strength.

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