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Mapping Brittleness and Stress

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Summary

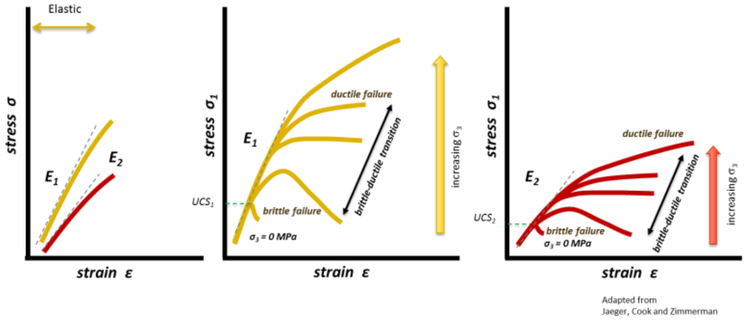
Seismic methods, as they pertain to the development of unconventional reservoirs, have frequently focused on mapping “brittle” reservoir – which has been variously defined. Brittle failure has been linked to hydraulic fracture effectiveness as it is thought that permeability enhancement is a function of rock brittleness. Here, a method is presented to estimate a rocks propensity for brittle failure as a function of mineralogy and stress state. Seismic interpretation templates for brittleness are generated based on a rock physics model, the concept of brittle to ductile transition and stress estimation models.

Introduction

Laboratory experiments investigating the relationships between rock elastic properties and their failure mechanism have shown that the mode of rock failure is a function of both rock composition and the state of stress. Therefore, attempts to predict how a material will fail are incomplete without some knowledge of the stress state.

An attempt to quantify brittleness was presented by Rickman et al. (2008), which high graded reservoir with high Young’s modulus (E) and low Poisson’s ratio (ν). The rationale was that Poisson’s ratio expressed the rocks ability to fail under stress while Young’s modulus represents the ability to maintain a fracture. In addition, it is known that the elastic properties of the rock correlate to mineralogical constituents. For example, a low Young’s modulus and a high Poisson’s ratio is usually related to clay rich rocks which are typically ductile. However, without a rock physics model that accurately relates elastic properties to mineralogy, incorrect estimates of clay volume and thus brittleness can be made.

Nevertheless, even with a calibrated rock physics model, using only mineralogical and elastic property data is insufficient to determine rock brittleness. Figure 1 shows this schematically for two different hypothetical rocks, where depending on the confining stress on the rock, the rock strength and the manner in which the rock fails varies (Adapted from Jaeger et al, 2009, Plumb, 1994). To determine relationships between elastic and/or lithologic properties to failure properties, stress tests are performed on the rocks of interest. Applying an increasing stress to different rocks until the rock strength is exceeded enables empirical relationships that correlate mineralogy and elastic properties to failure parameters to be determined. Such laboratory experiments are conducted to ascertain relationships between elastic moduli of rocks and the strength and failure mechanisms of the rock.



Adapted from
Jaeger, Cook and Zimmerman

Figure 1. Schematic diagram illustrating dependence on failure on confining stress for a given Young’s modulus.

This schematic shows that even with knowledge of mineralogy and elastic properties it would be difficult to determine how a rock would fail. The following outlines a method that incorporates both mineralogy (through elastic property mapping) and in-situ stress into mapping brittleness.

Method

The construction of a seismic interpretation template for brittleness consists of four main elements:

1. Establishing a brittle to ductile transition model
2. Constructing a rock physics model relating elastic properties to mineralogical properties
3. Determine an empirical relationship between mineralogical and/or elastic properties to failure properties
4. Use stress estimation models to determine in-situ stress

Each element is briefly discussed below.

Brittle to ductile transition

Various models have been proposed to explain conditions under which the brittle to ductile transition occurs. One such model suggests that the transition occurs when the stress necessary for fracture is similar to that necessary for sliding with friction, while another suggests that the transition occurs when the Mohr envelope of peak strength reaches a point of zero gradient (Hashemi et al., 2009). Hoek and Brown (1980) suggest that the transition occurs when the minimum principle stress is equal to the unconfined compressive strength (UCS) of the rock. The Hoek and Brown models is utilized primarily as it allows for calibration between elastic moduli and UCS and the ability to measure and estimate σ_3. Figure 2 shows the brittle to ductile transition in the Mohr-Coulomb space. When the stress circle intersects the failure envelope, if the minimum principal stress, σ_3, is less than the UCS, the material will tend towards brittle failure whereas if σ_3 is greater than the UCS the material will tend toward ductile failure.

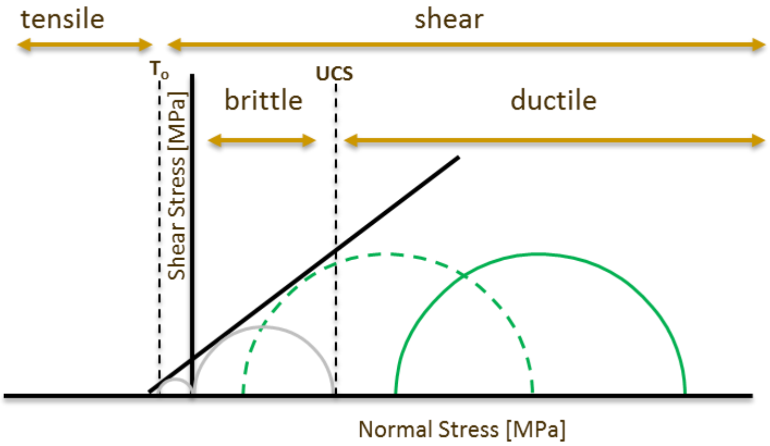


Figure 2. Mohr Coulomb diagram outlining brittle to ductile transition. Adapted from Hashemi et al. 2009.

Rock physics model

Rock physics models can be used to increase understanding of the relationship between elastic properties and mineralogy, texture and diagenetic changes. Given that clay volume does not correspond linearly or consistently with Poisson’s ratio (different clay properties, fabric, texture, stress dependence etc.) it is important to construct rock physics models that are properly calibrated to petrophysical and/or core data. Here, the non-interacting approximation, NIA, (Kachanov et al. 1994) is used to model the influence of clay and porosity in unconventional reservoirs. The basic model consists of three minerals constructed with end members of quartz, limestone and clay. Since a three mineral model can be combined in a number of different ways, the elastic estimate of clay volume estimate is non-unique. Figure 3 shows a combination of three different mineral mixtures: quartz, limestone and clay dominated. Trendlines are computed for each set of mineral recipes and interpolated to populate the possible elastic parameter space, lambda-rho and mu-rho (LMR) in this case. The average and standard deviation of volumes of clay quartz and limestone are computed. The standard deviation is evidence that the same combination of elastic parameters can be derived from various mineralogical combinations. Figure 4 shows the clay volume interpretation template, expressed in terms of the elastic properties of an LMR crossplot, where colors represent clay volume and expected deviation in clay estimates based on the three recipes chosen.

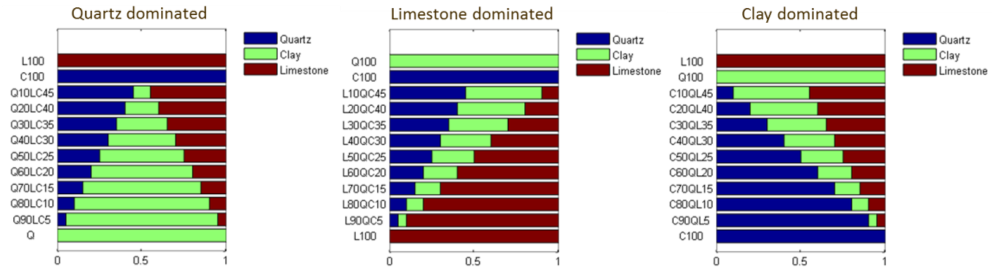


Figure 3. Three distinct mineral mixture recipes used to generate 3 sets of rock physics trends.

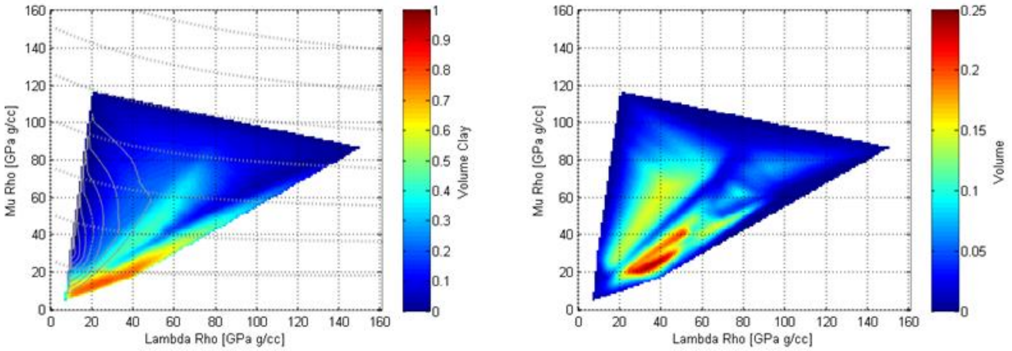


Figure 4. Volume of clay estimate in LMR space (left) and standard deviation of clay volume estimate (right). The deviation is an indication of ambiguity between elastic paramters and lithology prediction.

Empirical relationship to failure parameters

To determine σ_3 at failure, the UCS and coefficient of friction (μ_i) as well as the state of stress of the rock must be known. To estimate the failure parameters, UCS and μ_i are correlated to elastic parameters and/or lithology. Calibrating failure parameters to elastic moduli or mineralogy through laboratory experiments is important for accurate failure assessments. Published results (Plumb, 1994, Sone and Zoback, 2010, 2011) relating elastic and reservoir properties to failure parameters can be used when core data is unavailable for laboratory experiments (Figure 5).

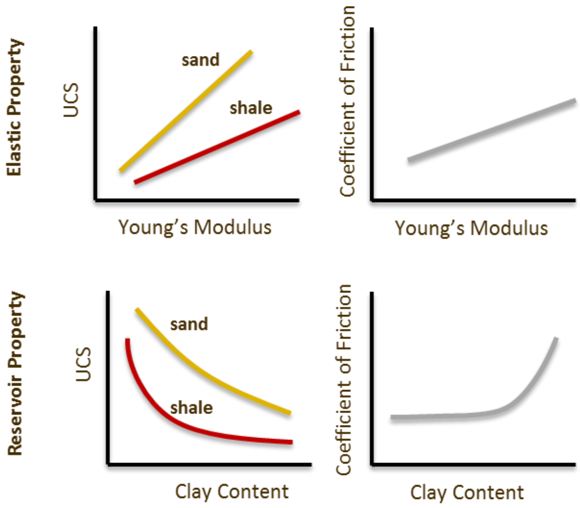


Figure 5. General trends of failure parameters as a function of elastic property and reservoir property (clay volume).

Once the trends are established, using an estimate of elastic property or lithology, the failure parameters can be estimated.

Stress estimation model

Poro-elasticity suggests that there is a relationship between rocks mechanical properties, stress and strain. The three equations below represent two models which relate elastic properties and overburden stress to lateral stresses (Sayers, 2010). Equation 1 imposes a no lateral strain boundary condition while the second set of equations, equation 2 and 3, allows for strain.

$$\sigma_h = \sigma_H = \frac{\nu}{1-\nu}\sigma_v \qquad 1.$$

$$\sigma_h = \frac{\nu}{1-\nu}\sigma_v + \frac{E}{1-\nu^2}\left(\varepsilon_h + \nu\varepsilon_H\right) \qquad 2.$$

$$\sigma_H = \frac{\nu}{1-\nu}\sigma_v + \frac{E}{1-\nu^2}\left(\varepsilon_H + \nu\varepsilon_h\right) \qquad 3.$$

In practice, the strain parameters are mostly used to fit stress estimates to measured data. Any estimates from this equation should be constrained by measured stress data and by the stress polygon introduced by Zoback et al.

If a suitable estimate is achieved, an elastic property dependence of stress can be mapped. For any given overburden stress, a stress map, which is a function of elastic properties, can be constructed. Figure 6 shows the stress estimate for a given overburden stress as a function of elastic parameters for the two models

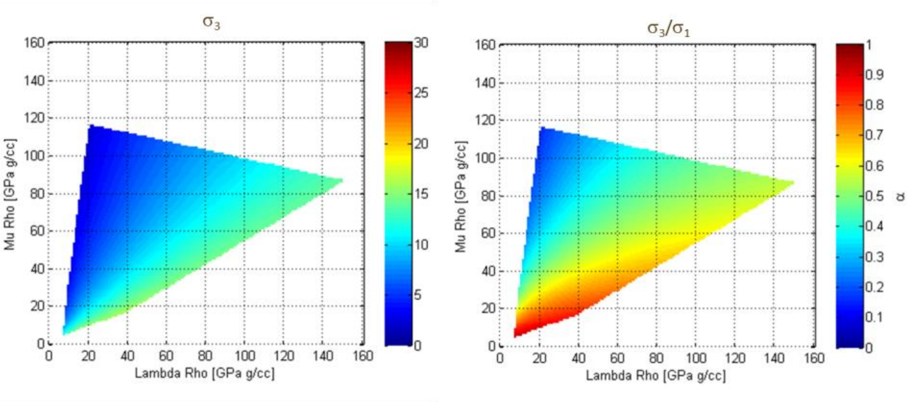


Figure 6. Manifestation of two different stress models, functions of elastic property, in LMR space. Passive basin assumption (left) showing σ_3 and lateral ratio ($\alpha = \sigma_h/\sigma_H$) resulting from allowing lateral strain.

Figure on the left shows how $\sigma_h = \sigma_H$ varies as a function of $\lambda\rho$ and $\mu\rho$ (equation 1), while the figure on the right is the σ_h/σ_H ratio as a function of $\lambda\rho$ and $\mu\rho$ (equations 2 and 3).

Examples

Consider the following data in the Horn River basin.

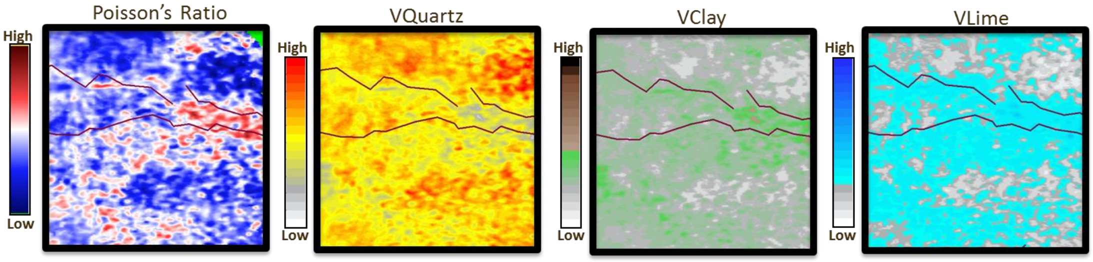


Figure 7. Seismic extractions of Poisson's ratio (left) and rock physics derived estimates of (left to right) quartz, clay and limestone.

The previously shown templates are used to help interpret the inversion results. Ultimately, for a given overburden stress, assessments can be made which high-grade areas of increased relative brittleness as a function of elastic properties and inferred lithology.

Figure 8 shows the brittle to ductile LMR template for a given overburden stress. The heavy black line separates the ductile region (hot colors) from the brittle region. Seimically derived $\lambda\rho$ and $\mu\rho$ attributes can be interpreted with this template. The template allows for proper reservoir development by focusing on the rocks which are most likely to exhibit brittle failure.

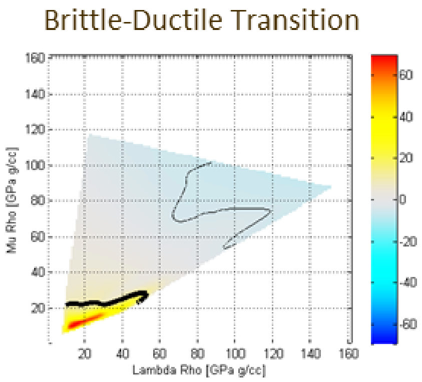


Figure 8. Brittle to ductile transition in LMR space for a given overburden stress. Heavy black line denotes when σ_3 is greater than UCS (hot colors) while cool colors denote brittle failure.

Conclusions

A method has been presented where seismic data have been used to estimate elastic properties of rock which when used in conjunction with rock physics models and empirical elastic to failure property transforms can be used to map brittleness. This method is intended to account for the stress dependence in assessing rock failure.

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