Getting unlost and staying found – a practical framework for interpreting elastic parameters

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Introduction

Geophysicists are increasingly using seismic AVO inversion to generate elastic parameter estimates. But it is not always clear how to make sense of this information. From pre-stack seismic data we can estimate elastic moduli – bulk modulus, Lamé's Lambda parameter, and shear modulus (Mu), scaled by density (Rho) – but what do they mean? This visual poster presentation uses well log and laboratory data to extend rock physics knowledge of reservoir properties to seismic attributes. The goal is to understand how a reservoir's material properties are expressed by its elastic parameters. This offers a secure framework to interpret seismically-derived elastic moduli in terms of rock properties such as lithology, fluid, and porosity.

Seismic waves and elastic moduli: assumptions stated

Subsurface rocks present various scales of heterogeneity. At the atomic scale, we see the orderly atomic arrangement of pure minerals. But in real life we are not faced with a homogeneous pure mineral; a rock is made up of different minerals, held together by grain contact and/or cement, and including pores occupied by fluids. All these constituents influence the rock's elastic properties.

The rock scale is the realm of core and wireline measurements [cm]. Seismic waves, however, 'see' sequences of rocks on the order of metres. Seismology is based on continuum mechanics, but at the rock scale, there will always be some averaging. That is, it is the average or effective elastic parameters that seismologists must deal with. In this presentation, when we say that the rock and fluid properties of a reservoir affect its elastic parameters and in turn, its seismic expression, we are talking about the effective or average elastic parameters. The presentation assumes rocks are isotropic and elastic. Further, the discussion is restricted primarily to how mineralogy, porosity, and fluid content influence the rock's elastic moduli. Clearly, many other inter-related factors also influence elastic moduli (*Table 1*).

Rock properties and elastic moduli

The study of rocks is broken into studying the different constituents: the solid rock (lithology), the rock matrix (porosity), and the pore fluids.

Lithology and elastic parameters

A pure mineral is uniquely described by its elastic parameters, but we rarely deal with pure minerals. A real-life rock matrix is a naturally occurring mixture of minerals. Predicting the moduli from the constituent minerals is complex. The elastic properties of a rock depend on the elastic properties of the components, the relative volumes of the components making up the rock, and the microstructure.

There are theoretical relations describing how to calculate the elastic parameters of a medium composed of a mixture of minerals. But in an actual rock, additional factors such as grain contacts and cementation come into play and theoretical relations are inadequate. However, bounds describing the upper and lower elastic parameter values may be calculated in a straightforward fashion. Then to get more usable estimates we often go to empirically-derived relations.

Empirical relations are generally some simple polynomial fit to measured observations for a particular data set, often guided by some theoretical insight. Empirical relations most often work very well for the data they were derived from, but fail outside the sample range. With empirical relations one must be careful about ascribing physical meaning to what are essentially generic mathematical formulae.

Deterministic models are another approach to establish relations between elastic moduli and reservoir properties. Typically some simplifying assumptions about the geometry or microstructure are made (for example, spherical pores may be assumed). Note that these assumptions may be simplifying, but not necessarily geologically realizable.

As stated, reality is complex, but we can at least calculate boundary values of elastic parameters. Theoretical bounds rigorously derived from basic physical principles are widely applicable, but only provide upper and lower bounds on elastic properties rather than single estimated values. Well-established bounds theories are those of Voigt (1928); Reuss (1929); and Hashin and Shtrikman (1963).

The Voigt upper bound is a linear interpolation between the elastic moduli of two constituents of a two-phase composite. Consider a mixture of quartz and calcite (*Figure 1*). At zero percent calcite, the volumetric concentration of quartz is one, and the modulus of the composite is that of quartz. At 100% calcite, the modulus of the composite is that of calcite. For other mixtures, the bound is a line connecting the two end members. The influence of fractional changes in the mineralogy is nonlinear, so a small change in composition can influence the elastic parameters significantly. Multi-mineral mixtures can have ambiguous elastic parameter values, but quartz, calcite, and shale are end-members and can be identified reasonably well.

Porosity and elastic parameters

Extending mixture theory, a porous rock can be thought of as a two phase mixture: void space and rock matrix. Upper and lower bounds may be calculated, but there are certain constraints on how to add compressibilities. For closed systems we must account for fluid effects, leading us to the more complicated Biot-Gassmann theory. For simplicity, we first consider the effect of porosity in an open system where we do not need to consider fluid effects. That is, we first consider the dry measurements of the rock. We see that both Lambda and Mu are decreased by porosity, when the pores are dry.

Pore shape is a very important influence on seismic properties, but very difficult to quantify. It is observed (Zimmerman, 1991) that

- a crack is more compressible than a round pore.
- spherical pores are more incompressible, which means high Lambda values.
- flat pores like fractures and microcracks are less resistant to compression, which means lower Lambda values.
- Vp tends to be more sensitive to pore fluid saturation for flat pores than spherical pores.
- Cracks close as the effective pressure increases. The influence of cracks lessens as a function of depth. This is one of the reasons velocity generally increases with depth.

Critical porosity

The critical porosity model (Nur, 1992) is derived from empirical observations, but is similar in form to other theoretical relations. For most rocks, there is a critical porosity ϕ_c which separates the rock's mechanical and acoustic behavior into two distinct domains. For porosities less than ϕ_c, the mineral grains are load-bearing; for porosities greater than ϕ_c the mineral grains are in a suspension, with the fluid phase load-bearing. Most reservoir rocks are in the grain- or frame-supporting state. In this state, porosity varies from zero to critical porosity. Many effective medium models relate the elastic properties of rocks to porosity over the range of porosities from 0 to 100%, and should be modified to recognize the critical porosity divider.

The bounds can be re-scaled so that the high porosity end member is at critical porosity, not at 100% porosity. The upper HS bound can be re-scaled so that the porosity interval is between 0 and ϕ_c rather than between 0 and 1. That is, the end members will be the pure mineral modulus at zero porosity, and zero modulus at critical porosity. The elastic parameters vary linearly between the mineral end point and critical porosity (*Figure 2*).

Fluids and elastic parameters

In order to calculate the elastic properties of a saturated rock, we need to calculate the elastic properties of the pore fluids themselves. The Gassmann equation (1951) can be used to model how a fluid will influence the elastic moduli of the saturated rock. The shear modulus for a liquid or gas is zero. The bulk modulus can be measured in the lab and/or can be calculated using empirical relations. Remember that fluid properties will be functions of such things as chemical makeup, temperature, and pressure.

Generally, the rock's incompressibility is lower when the pore fluid is gas than when it is brine, and the rock's rigidity (resistance to shearing force) is relatively unaffected. The gas effect is larger at higher porosities (*Figure 3*), and in rocks with lower bulk moduli (weak rock framework).

Summary of effects for interpreting seismically-derived elastic parameters

As noted earlier, seismic properties are affected in complex ways by many factors, such as temperature, saturation, pressure, porosity, pore shape, fluid type, … the list goes on. These factors are often inter-related or coupled so that many also change when one factor changes. The complexity of how then to interpret seismically-derived elastic parameters can be overwhelming; some framework is needed. The scope of investigation of this paper is limited to three key rock and fluid properties pertinent to hydrocarbon exploration: lithology, porosity, and fluid type. The effects on elastic parameters are summarized *(Figure 4):*

Mineralogy
: For multi-mineral mixtures, the mixture occupies an ambiguous cloud in Lambda, Mu or LambdaRho, MuRho crossplot space. Quartz, calcite, and shale occupy the vertices and so are less ambiguous and can be identified reasonably well.

Porosity
: Lambda and Mu behave in exactly the same way in response to porosity, when the pores are dry. The effect of porosity is a shift toward the origin in cross-plot space.

Fluid
: Lambda is decreased by the presence of fluid; Mu is relatively unaffected by fluid. The effect is larger with increasing porosity.

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With increasing:	Compressional velocity	Shear velocity	Density	Incompressibility	Rigidity
Temperature	↓	↓	↓	↓	↓
Effective Pressure	↑	↑	↑	↑	↑
Pore Pressure	↓	↓	—	↓	↓
Porosity	↓	↓	↓	↓	↓
Clay content	↓	↓	—	↓	↓
Gas Saturation	↓	↑	↓	↓	—

Table 1: How some factors influence elastic parameters

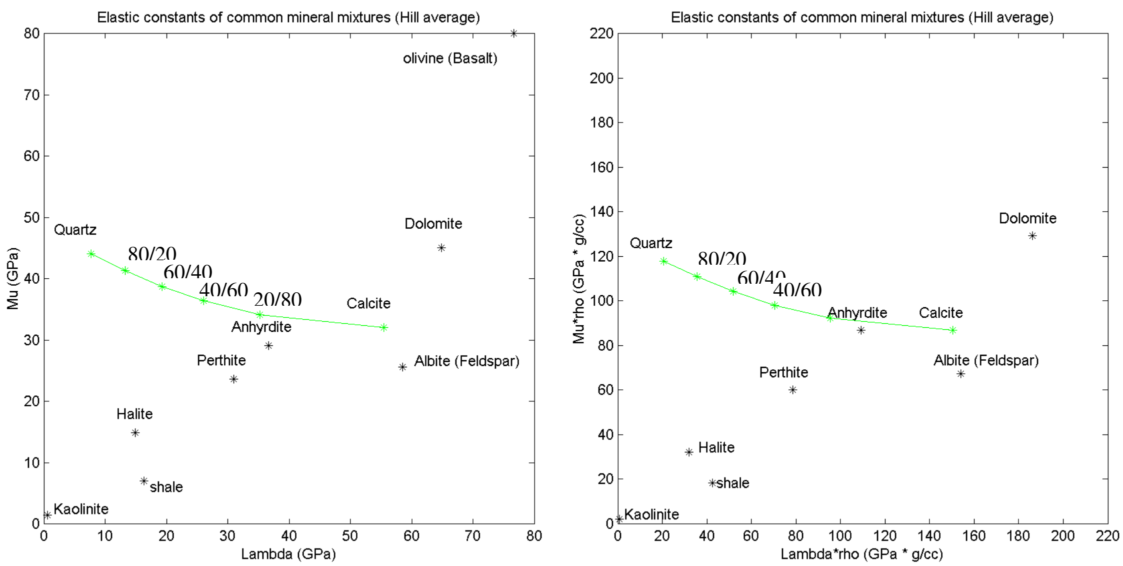

Figure 1: Elastic constants of common mineral mixtures (Hill average): Quartz-Calcite example. Note there is a nonlinear response to linear fractional changes. Therefore, it is possible that a small amount of the 2nd mineral can have a large influence on the effective elastic parameters of the mixture.

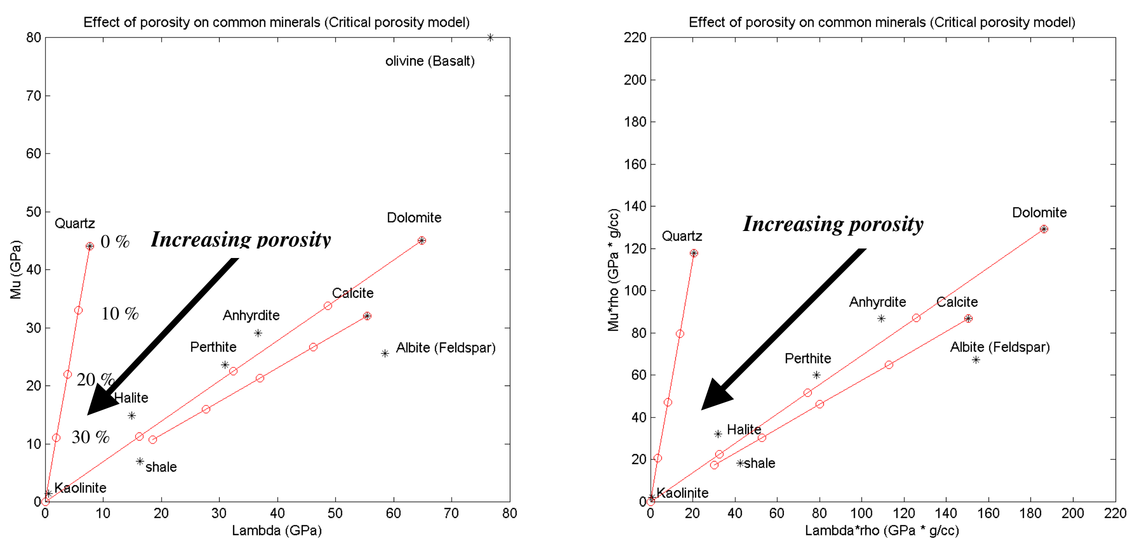

Figure 2: Effect of porosity on elastic moduli using critical porosity model: porosity values overlain. Note that increasing porosity moves toward the origin. That is, Lambda and Mu are both decreased by increasing porosity (when the pores are dry)

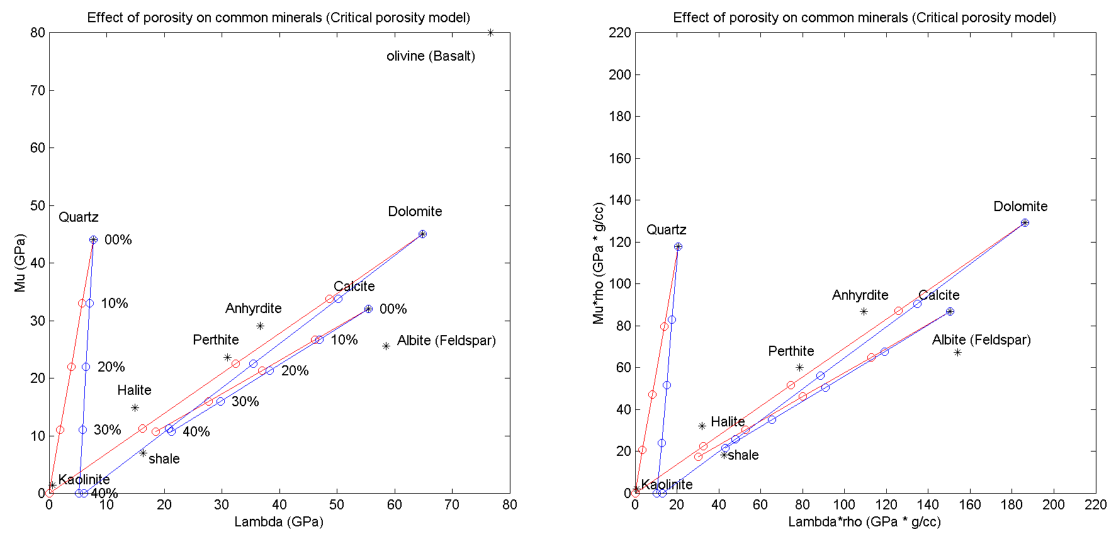

Figure 3: Effect of porosity for fluid-filled minerals using critical porosity model. Note the effect of porosity for gas (red) vs. brine (blue) filled sandstones: better fluid detection is possible at high porosity values. Note also that dolomite has better gas-brine separation than limestone

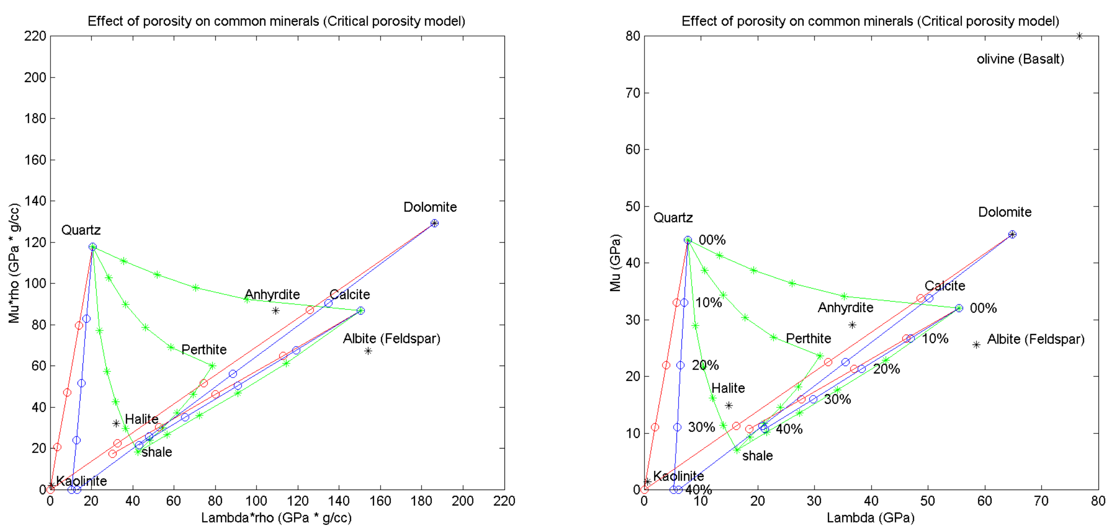

Figure 4: Interpretation template: composite display of lithology, porosity, and fluid effects discussed.