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Rock Physics of Reservoir Monitoring: Effects of Stress and Saturation Changes

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Summary

Conventional rock physics models based on porosity and clay content alone are not well suited to model the effects of stress and saturation changes commonly encountered in reservoir monitoring studies. In this paper we describe alternative models that can address these issues and discuss the pros and cons of these models.

Introduction

The increasing acceptance of time-lapse reservoir monitoring requires a rock physics model that allows us to better understand the distinction between the stress and fluid effects in our data, and allows us to monitor the flow through reservoirs at the seismic scale, not just at discrete well locations. The increased complexity in our data requires an increased complexity in our rock models, the chief requirement being the parameterization of the pore space by more than the single porosity value. In this paper we will be discussing the effects of pore space geometry on the velocities of rocks undergoing stress and pore fluid saturation changes.

Pore Space Models

There are a number of ways to parameterize the pore space, in addition to the porosity, a commonly use parameter is the aspect ratio. Instead of modeling the pore space as a sphere or a number of spheres, we model the pores as oblate ellipsoids, (also known as penny shaped cracks). These are geometrical bodies with two of the large axes identical, and the cross-section that of an ellipse. The ratio of the small to large axis is known as the aspect ratio. The effects of these ellipsoidal shapes on velocities with different pore filling fluids are given in Kuster and Toksöz (1974). An example is shown in Figure 1.

Several important point can be seen from Figure 1. One is that the effect of aspect ratio is large. For a given pore size (porosity), a smaller aspect ratio pore has a much larger effect on the velocities. This is because the smaller aspect ratio pore will have a larger surface area, thus causing more "defect" in the solid rock matrix. Another point is that contrary to the often accepted and used assumption from Gassmann, shear modulus is not independent of fluid content. This is because of the indirect coupling of a shear wave propagating across a microcrack at an oblique angle. This has an obvious effect on Vs prediction and fluid substitution studies.

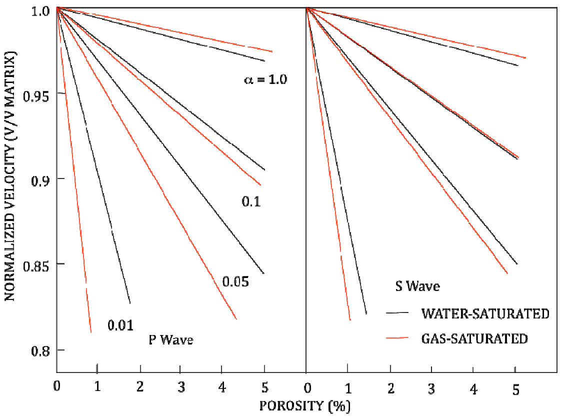

Figure 1: Effect of aspect ratio and saturation on P and S wave velocities (Toksöz et al., 1976)

One application of such pore shapes is the modeling of pressure dependence of the P and S wave velocities. We consider the pore space as a collection of individual pores of different aspect ratios (see Figure 2). Under pressure, the small aspect ratio (flatter) cracks close first, the larger

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aspect ratio cracks will have their aspect ratios reduced. The rate of this is controlled by the rock compressibility (see Toksöz et al., 1976).

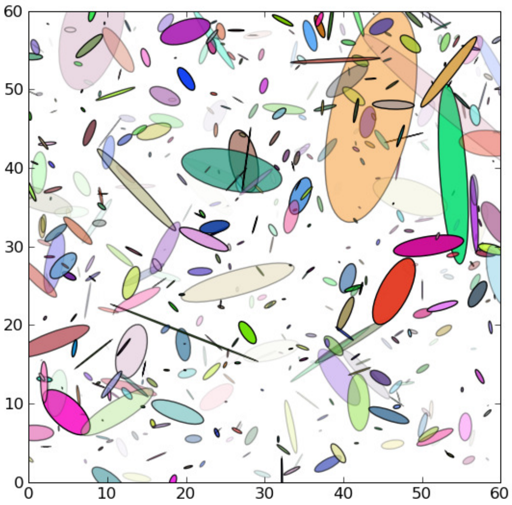

Figure 2: Rendition of pore space with different aspect ratio pores and a log normal distribution in size

With this approach and a distribution of different aspect ratio pores, we can model the P and S wave velocity changes as a function of pressure. Furthermore, we can invert the velocities to obtain an aspect ratio spectrum of the pore space, and this inverted spectrum has predictive values for fluid substitution (Cheng and Toksöz, 1979). An example on Navajo sandstone is given in Figures 3 and 4.

However, this approach has several limitations, some of them severe. The most obvious one is that the pores are not connected. This may work OK in seismic applications, but not for resistivity or permeability calculations. In addition, the invert spectrum has too many parameters to make it useful for seismic well ties and seismic petrophysics. We need to simplify these models to in order for them to be useful seismic well ties. An example is by the use of a single aspect ratio (see Ruiz and Dvorkin, 2009).

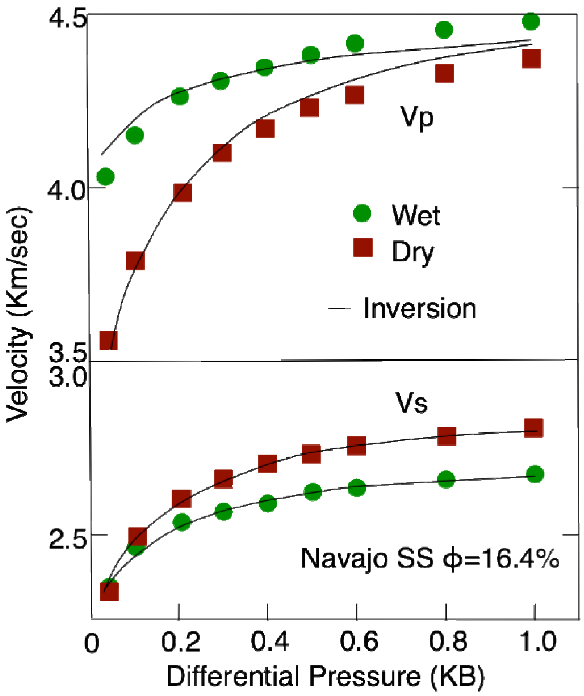

Figure 3: Fit to dry and wet P and S wave velocities for Navajo sandstone as a function of pressure (Cheng and Toksöz, 1979)

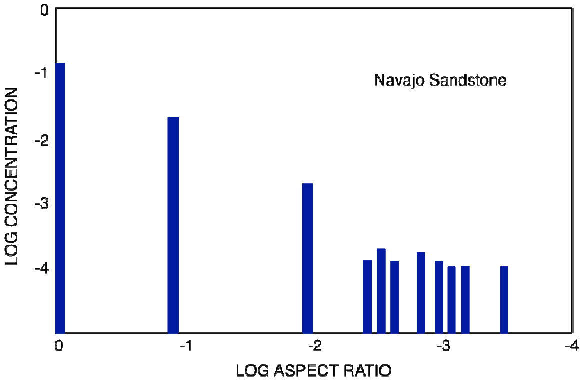

Figure 4: Pore aspect ratio spectrum obtain from inverting the data in Figure 3 (Cheng and Toksöz, 1979)

There are other different other approaches to model the complex pore space. One approach is through the contact-asperity approach, used by Walsh and Grosenbaugh (1979). A schematic of the asperity model is shown in Figure 5.

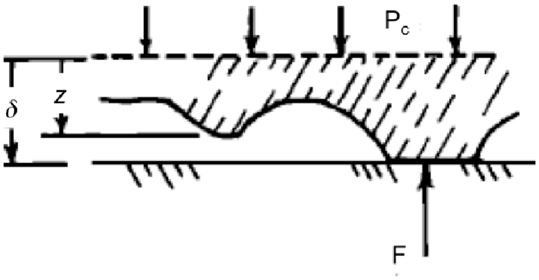

Figure 5: Coordinates for evaluating the compliance of an asperity. When height of a given asperity is z. For a given stress s_c, there is a displacement d where all asperities with height more than d is in contact.

This approach, like others, has advantages and disadvantages. One advantage is that we can combine this with flow model since there is an inherent size to the asperity heights. The disadvantage is that we need to get an estimated distribution for the asperity heights. However, if we assume an exponential distribution of the heights, Walsh and Grosenbaugh (1979) found that the inverse of the difference in measured compressibility β and the solid rock matrix compressibility βs will be linearly proportional to the applied stress. A plot of $1/(\beta\text{-}\beta s)$ for four different rocks is shown in Figure 6.

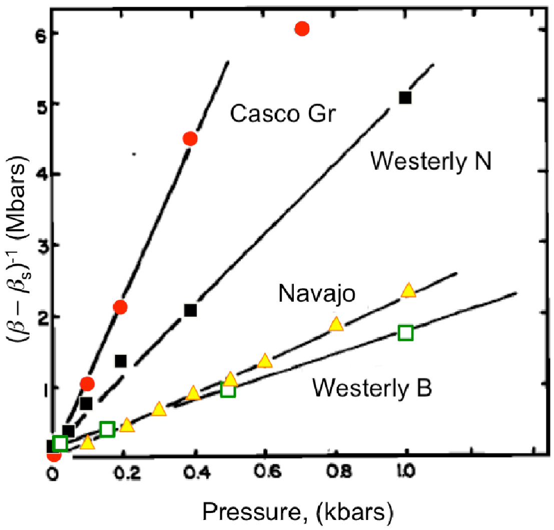

Figure 6: Plot of $1/(\beta\text{-}\beta s)$ versus effective pressure for different rocks. Westerly N and Westerly B are two different sets of data, both on Westerly granite, collected by A. Nur and B. Brace, respectively. Navajo is the sandstone data shown in Figure 3. Data from Walsh and Grosenbaugh (1979).

Summary

Stress dependent rock physics models are necessary for us to understand the changes in physical properties in time-lapse reservoir monitoring studies. We have shown two models that can predict seismic velocities as a function of pressure. Work still needs to be done to simply these models for routine applications to seismic rock properties studies.

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