Frequency dependent anisotropy with a multi-scale equant porosity model.


Abstract

We extend our earlier poroelastic model to the case of anisotropy and fractures of different scales. The anisotropy has a tendency to decrease with frequency. In contrast to earlier, single-scale, models the size of the fractures plays a key role in the analysis. When larger fractures are present, fluid viscosity becomes an important parameter for wave propagation at seismic frequencies, and fluid substitution calculations should take account of this.

Introduction

A great deal of interest exists in the development of theoretical models which can relate fracturing in rock to anisotropic seismic properties. The classical attempts to solve the problem (see Liu et al. 2000 for a thorough review) were derived under the assumption that no exchange of fluid took place, either between fractures themselves or between fractures and the rock matrix.

The importance of fluid exchange between different parts of the pore space during seismic wave propagation has long been recognized (Gassmann, 1951; Biot, 1956). Thomsen (1995) showed the relevance of these ideas to the interpretation of seismic anisotropy. His work allowed for the transfer of fluid between fractures and "equant porosity" in the rock matrix. Perfect pressure equalization, corresponding to a wave of very low frequency, was assumed. Such an effect was shown to greatly increase the magnitude of seismic anisotropy that a given fracture distribution would produce.

More recent models (Hudson et al., 1996; Pointer et al., 2000; van der Kolk et al., 2001) have attempted to extend Thomsen's (1995) work to the entire frequency range. Various geometries are considered, consisting of simple aligned fractures, distributions of fracture orientations or aligned fractures connected to equant porosity. In all cases the resulting anisotropy is frequency dependent. Otherwise, however, the results appear sensitive to the details of the geometry considered, emphasizing the need to work with the most general model possible.

In this paper we consider a model in which the pore space consists of a collection of spherical pores, an isotropic collection of randomly oriented micro-cracks and an aligned set of fractures. An important feature of the model is that the fractures can be of a different size to the pores and micro-cracks. This leads to a coupled problem where the fluid motion occurs on two different scales, the grain scale and the fracture length scale. The behaviour predicted by this model is significantly different to that of the earlier models where only single scale behaviour was considered.

Description of the model

Chapman (2001) derived a poroelastic model based on a network description of the grain scale fluid dynamics. The isotropic case was considered, with pore space consisting of a collection of spherical pores and randomly oriented micro-cracks. Pair-wise exchange of fluid took place between adjacent elements of pore space, with the exchange of mass being proportional to the pressure difference between the elements.

The assumption that the cracks and pores were of the same size was critical for the argument, since it permitted the assumption that all cracks and pores should interact with the same number of other elements. We refer to the number of other interactions an element participates in as its coordination number. Clearly in the case where we have fractures which are very much larger than the pores they must have a higher coordination number. A schematic diagram of a large fracture interacting with pore space is shown in Figure 1.
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We solve this problem with an argument based on conditional probability. We assume that there are many more micro-cracks and pores than there are fractures, and that the fractures do not intersect one another. A fracture is assigned a coordination number proportional to its surface area, and it only interacts with pores and micro-cracks. Following Chapman (2001), the micro-structural elements have coordination number proportional to the square of the grain size, but they can interact either with other microstructural elements alone or with a combination of a fracture and microstructural elements. The expected mass flow out of any given crack or pore is consequently an average weighted by the probabilities of these two possibilities. An appealing feature of the model is that these probabilities can be given in terms of macroscopic quantities (see Chapman, 2002 for details).

The resulting dynamical system can be solved by a generalization of the techniques employed by Chapman (2001). We find a frequency dependent, anisotropic elastic tensor which is explicitly a function of the fracture sizes. Two "characteristic squirt flow frequencies" emerge from the analysis. One is the typical squirt flow frequency that has been inferred from laboratory measurements. The other is a lower characteristic frequency associated with the fractures.

Numerical Results

We choose a parameterization in an attempt to simulate a canonical water saturated sandstone. Thomsen (1995) assumed that the squirt flow frequency for such rocks was between the sonic and ultrasonic bands, and we repeat this assumption, taking a value of 50 kHz. This value and the other parameters chosen are consistent with those deduced by Chapman (2001).

We now introduce a fracture set of density 0.06 and radius 10cm into the analysis. Figure 2 shows the resulting qP-wave velocities for propagation at 0 and 90 degrees to the fracture normals as a function of frequency. Note the existence of two characteristic frequencies, one associated with the isotropic microstructure, the other with the anisotropic fractures. It must be emphasized that this analysis neglects scattering, so that the results are not strictly valid at high frequency.

Figure 3 shows the shear wave anisotropy for propagation at 70 degrees as a function of frequency for various fracture sizes and 10% porosity (spherical pores). We see again that anisotropy tends to decrease with frequency, with the position of the maximum decrease depending on the fracture size. Note that a similar relationship between shear wave anisotropy and frequency in field data has been reported by Chesnokov et. al. (2001).

The ideas discussed above have implications for time-lapse anisotropy. According to the theory, increasing the viscosity of the saturating fluid acts in the same way as increasing the frequency. In Figure 4 we plot the difference in the percentage of shear-wave splitting between gas and brine saturation as a function of the fracture length for frequencies of 40 Hz and 0 Hz. For fractures 1m in length, there is a substantial difference between the two saturations for a frequency of 40 Hz. If one assumes the low-frequency limit, this behaviour is not predicted. This is consistent with the observations of Guest et al. (1998) who noted the sensitivity of shear-wave splitting to the saturating fluid.

Conclusions

This study underlines the importance of the equant porosity effect for the interpretation of seismic anisotropy. Nevertheless, in the presence of meso-scale fractures it may not be safe to assume, as did Thomsen (1995), that seismic frequencies represent the zero-frequency limit, even when the squirt flow frequency lies above the sonic band.

The scale length of the fractures plays a key role in the analysis. This presents a potential method for discriminating between micro-crack and fault induced anisotropy. More ambitiously, with sufficient local calibration it may be possible to measure a characteristic fracture scale from seismic data.
The existence of fractures of different scales enhances not only the magnitude of dispersion and attenuation, but also the frequency band over which they are important. This gives scope for the fluid viscosity to play an important role, and this is important for fluid substitution calculations.

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**References**


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Figure 1: Schematic diagram showing a fracture interacting with pore space.

Figure 2: qP velocity as a function of frequency for propagation parallel and perpendicular to the fracture normals.

Figure 3: Shear wave anisotropy for propagation at 70 degrees to the fracture normal as a function of frequency for a variety of fracture sizes.

Figure 4: Difference in shear-wave splitting between brine and gas saturation for propagation at 70 degrees to the fracture normal as a function of fracture radius.