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When do fractured media become seismically anisotropic? Some implications on quantifying fracture properties

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ABSTRACT

Fractures are pervasive features within the Earth's crust and they have a significant influence on the multi-physical response of the subsurface. The presence of coherent fracture sets often leads to observable seismic anisotropy enabling seismic techniques to remotely locate and characterise fracture systems. In this study, we confirm the general scale-dependence of seismic anisotropy and provide new results specific to shear-wave splitting (SWS). We find that SWS develops under conditions when the ratio of wavelength to fracture size (λ_S/d) is greater than 3, where Rayleigh scattering from coherent fractures leads to an effective anisotropy such that effective medium model (EMM) theory is qualitatively valid. When $1 < \lambda_S/d < 3$ there is a transition from Rayleigh to Mie scattering, where no effective anisotropy develops and hence the SWS measurements are unstable. When $\lambda_S/d < 1$ we observe geometric scattering and begin to see behaviour similar to transverse isotropy. We find that seismic anisotropy is more sensitive to fracture density than fracture compliance ratio. More importantly, we observe that the transition from scattering to an effective anisotropic regime occurs over a propagation distance between 1 and 2 wavelengths depending on the fracture density and compliance ratio. The existence of a transition zone means that inversion of seismic anisotropy parameters based on EMM will be fundamentally biased. More importantly, we observe that linear slip EMM commonly used in inverting fracture properties is inconsistent with our results and leads to errors of approximately 400% in fracture spacing (equivalent to fracture density) and 60% in fracture compliance. Although EMM representations can yield reliable estimates of fracture orientation and spatial location, our results show that EMM representations will systematically fail in providing quantitatively accurate estimates of other physical fracture properties, such as fracture density and compliance. Thus more robust and accurate quantitative estimates of *in situ* fracture properties will require improvements to effective medium models as well as the incorporation of full-waveform inversion techniques.

1. Introduction

The Earth's crust is brittle down to approximately 20 km depth (e.g., Rolandone et al., 2002) and, as such, fractures are expected and observed to be pervasive features within these depths (e.g., Liu and Martinez, 2012). Fractures range in size over several orders of magnitude, from large-scale faults (100 km s) observed on the Earth's surface down to micro-cracks (μm) observed in core samples. Since fractures are ubiquitous features and vary in size over several orders of magnitude (e.g., Narr, 2006), they play a critical role in the multi-physical response of Earth materials. Fractures control the behaviour of geo-mechanical deformation influencing the evolution of the stress and strain fields (e.g., Segall, 2010; Cornet, 2015) and act as conduits for fluid-flow in porous crustal rocks (e.g., Franciss, 2010). For geo-industrial applications, such as hydrocarbon exploration (e.g., Herwanger and Koutsabeloulis, 2011), geothermal energy (e.g., Gaucher et al., 2015), geo-sequestration of CO_2 (e.g., Cook, 2014) and deep geological storage of nuclear waste (e.g., Jaeger et al., 2007), the mechanical and fluid-flow properties of fractures is of critical importance. For instance, fractures have a significant influence on the integrity of boreholes and the sealing capacity of the reservoir overburden and their ability for maintaining barriers between potable water and hydrocarbon, CO_2 or radioactive waste. For non-geo-industrial applications, such as monitoring volcanoes, landslides and earthquakes, fractures have a significant influence on the stability of the rock mass and so have important implications on geo-hazard assessment (e.g., Hamlyn et al., 2014).

Often it is assumed that fractures are critically stressed (e.g., Crampin, 2005; Zoback and Gorelick, 2012) and/or that movement along fractures increases permeability (e.g., Barton, 2007). The as-

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sumption of increased permeability due to fault movement is debatable as some studies have observed that fault movement may occur without significantly increasing permeability when rocks have high porosity and are normally consolidated (e.g., Fisher et al., 2003). Thus, even though we have known for sometime that fractures are prevalent within the crust, it is apparent from such studies that the *in situ* physical properties of fractures still are not well constrained. Hence geophysical imaging of fractures and extracting fracture properties is becoming increasingly important, especially being able to quantify the nature of the fracture infill to assess flow potential for leakage assessment or frictional shear-strength for hazard assessment.

Fractures alter the mechanical and fluid flow properties of rocks and so seismic measurements will be sensitive to the presence of *in situ* fractures (e.g., Liu and Martinez, 2012). Furthermore, since fractures and joints tend to cluster in coherent regions with a directional dependence of reduced stiffness (or increased compliance) associated with stress and strain concentrations within a rock mass, observable seismic anisotropy is often a diagnostic phenomenon (e.g., Crampin, 1981). In other words, the strength of the reduced fracture stiffness is quantified in terms of fracture normal and tangential compliance, where the magnitude of compliance controls the strength of the seismic anisotropy (e.g., an increase in compliance leads to an increase in anisotropy). Seismic anisotropy refers to directional variations in seismic velocities, which in crustal rock can be due to intrinsic anisotropy from preferred orientation of minerals (e.g., Babuska and Cara, 1991), sedimentary layering (e.g., Babuska and Cara, 1991), coherent alignment of sub-seismic scale fractures (e.g., Crampin, 1981; Nakagawa et al., 2003; Baird et al., 2013) and the influence of non-hydrostatic changes in the stress field on micro-cracks and grain boundaries (e.g., Verdon et al., 2008).

There are several seismic methods that can be used to infer fracture properties in the subsurface; the most common being anisotropic velocity model analysis (e.g., Jones, 2010), amplitude versus offset and azimuth (AVOA) analysis (e.g., Liu and Martinez, 2012) and shear-wave splitting (SWS) analysis (e.g., Savage, 1999). These approaches can infer orientation and density of fractures as well as monitor temporal and spatial variations in fracture properties (e.g., Teanby et al., 2004a). For example, SWS analyses applied to teleseismic (Hammond et al., 2010), regional seismicity (e.g., Keir et al., 2011) and microseismicity (e.g., Verdon and Wüstefeld, 2013) data have been used to estimate fracture properties, such as width of fracture (or melt) zones as well as orientation, density and fracture compliance. These methods have shown great promise in qualitatively characterising a range of fracture properties and potentially to quantify the physical properties and distribution of natural and induced fracture systems. Distinguishing between the various sources of seismic anisotropy as well as seismic heterogeneity is often not a simple task, and interpretation can be complicated further by frequency-dependent anisotropy (e.g., Yi et al., 1997; Maultzsch et al., 2003; Baird et al., 2013).

To estimate or invert for the fracture properties a rock physics model is required to map the measured seismic anisotropy attributes (e.g., SWS) to the physical fracture properties. In general there are two approaches to model fractured rock: effective medium models (EMM) and discrete fracture models (DFM). EMM is the most common approach for modelling the seismic behaviour of fractured rock (e.g., Hall, 2000; Baird et al., 2013). EMM is a volumetric approach and models the fractured rock as an effective elastic medium, such that the elastic constants are anisotropic (e.g., O'Connell and Budiansky, 1974; Crampin, 1981; Sayers and Kachanov, 1991). While much has been achieved with these methods, there are limitations such as the applicable frequency range, the types of fracture properties which can be studied, and non-uniform influences for example due to stress-field (e.g. Hildyard, 2007). The main restriction for EMM is that it is valid only when the dominant seismic wavelength of the propagating wave is much greater than the heterogeneity induced by the fractures; this is referred to as the long wavelength approximation (LWA). Furthermore, EMM assumes the rock mass is 'instantaneously' anisotropic and so does not allow for the transition from a scattering regime to an effective anisotropy regime.

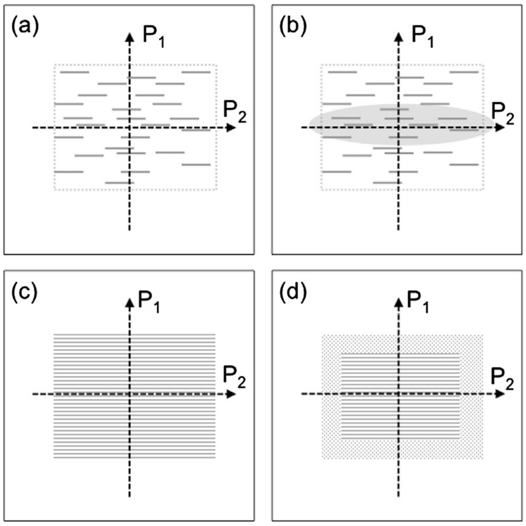

Fig. 1. Schematic diagram of fracture induced seismic anisotropy: (a) two ray paths P_1 and P_2 (dashed arrows) travel through a fracture zone (within the dashed rectangle) with discrete fractures depicted by grey lines; (b) same as (a) but with the inclusion of a velocity anomaly (shaded ellipse); (c) same as (a) but with the discrete fracture zone represented by an effective homogeneous fracture zone; and (d) same as (c) but with the effective homogeneous fracture zone reduced in size and surrounded by a transition region (stippled region).

The alternative approach is to model fracture networks as discrete elements that can encapsulate individual fracture behaviour (e.g. Hildyard, 2007). DFM allows us to reduce many assumptions about the model and enables the solution to simulate the interaction of seismic waves with fractures systems more correctly. DFM models can capture the influence of the stress state, as well as specific fracture properties such as fracture size, fill and compliance. Furthermore, DFM is not restricted by the LWA and allows the dominant seismic wavelength to be greater, less than or equal to the fracture size, allowing the characterisation of low-frequency behaviour (i.e., LWA regime) and high-frequency behaviour (i.e., ray theoretical limit). However, it is generally difficult to determine the spatial geometry of fracture systems deterministically and often the computational costs associated with modelling discrete fractures can be a barrier.

Fig. 1 illustrates some of the uncertainties in inferring fracture properties from seismic anisotropy. Fig. 1(a) shows two ray paths (P_1 and P_2) of equal length propagating through a fracture zone consisting of discrete fractures. The ray path perpendicular to fracture strike (P_1) will experience a longer travel time than the ray path travelling along strike (P_2) due to the presence of the seismic discontinuities (e.g., Babuska and Cara, 1991). This leads to an effective velocity anisotropy with seismic velocity being greater along strike than perpendicular to strike. In Fig. 1(b) we include an elliptical velocity anomaly that can lead to either (i) a perceived greater seismic velocity anisotropy (if the anomaly is a high-velocity ellipse) or (ii) a perceived smaller seismic velocity anomaly or isotropy (if the anomaly is a low-velocity ellipse). This illustrates the inherent ambiguity of traveltime anisotropic velocity analysis. In Fig. 1(c) we apply the standard approach to modelling fractures by introducing a homogeneous representation of the discrete fractures with an elastically anisotropic zone based on an effective rock physics model of the fracture zone (e.g.,