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A review of the sensitivity of seismic wave velocity and attenuation to fracturing

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Fractures are ubiquitous throughout the Earth's upper crust, spanning scales from microscopic cracks to large fault systems. Their hydromechanical behavior plays a critical role in controlling fluid migration in hydrocarbon, geothermal, and groundwater reservoirs, which, in turn, makes fracture detection, characterization, and monitoring an important objective in geoscience and engineering applications. Seismic methods, as indirect and non-invasive tools, have become central to this effort due to their ability to probe fractured media with adequate resolution and depth penetration. This work synthesizes our recent experimental and theoretical advances in the study of seismic characterization of fractured rocks, driven by several key observations. First, most fractured reservoirs exhibit effective seismic anisotropy because fractures often develop preferentially aligned with the local principal stress directions, leading to direction-dependent wave propagation. This anisotropy can be estimated using techniques such as shear-wave splitting, azimuthal velocity variations, and amplitude variations with offset and azimuth. Furthermore, we show that incorporating both fracture-induced and intrinsic background anisotropy, a rather common scenario in fractured environments, into inversion workflows is essential for a robust interpretation. Second, when a seismic wave propagates through a fluid-saturated fractured reservoir, it will be significantly attenuated and dispersed as a result of multiple intrinsic (e.g., inelastic effects due to solid and/or fluid friction effects) and extrinsic (e.g., geometrical spreading) mechanisms. In particular, when a seismic wave propagates through a fluid-saturated porous rock containing fractures, it produces fluid pressure gradients between the more compliant fractures and the stiffer embedding rock as well as between hydraulically connected fractures with different orientations and/or properties. Consequently, fluid flows until the pressure equilibrates, a phenomenon commonly referred to as wave-induced fluid flow (WIFF). This mechanism can alter the effective compliance of the fractures. Such compliance changes can significantly influence velocity and attenuation anisotropy across the seismic frequency range. The dependence of this type of mechanism on the petrophysical properties, fracture-geometry, and distribution makes the analysis of frequency-dependent seismic attributes particularly informative with regard to the hydromechanical properties. [NB2] Third, seismic responses in fractured media are highly sensitive to changes in their stress state, fluid saturation, and geometrical properties, thus, facilitating corresponding monitoring efforts through time-lapse seismic surveys. Finally,

highly permeable fractures can often be directly imaged since open fractures with partial surface contacts generally have large mechanical compliance, which, in turn, produces strong scattering of seismic waves. Indeed, there is evidence from full-waveform sonic log data to suggest that the fracture mechanical compliance obtained from P-wave velocity changes and transmission losses correlates with the degree to which fractures are hydraulically open.