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Shear-wave splitting as a tool for the characterization of geothermal fractured reservoirs: lessons learned

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Abstract

We review our experience with the construction of models of subsurface fracturing in geothermal fields by the inversion of shear-wave splitting (SWS) observations from natural and induced seismic events recorded by local arrays of three-component digital seismometers. SWS is a phenomenon whereby shear seismic waves split into two as a result of the mechanical anisotropy created in an otherwise isotropic rock by aligned micro-fractures. The two split waves travel at different speeds, and the polarization of the faster wave is usually parallel to crack orientation. The time delay between the two split S-waves is proportional to the number of cracks per unit volume.

Success in the inversion of SWS data hinges on the assumption that the observed SWS is due *solely* to the mechanical anisotropy induced by aligned cracks and micro-cracks in an otherwise isotropic matrix. The presence of lithologic anisotropy and/or strong heterogeneity in the reservoir rock limits the resolvability of the method. However, despite the large amount of data and diversity of geologic settings we have studied so far, the above assumption has been found to be reliable. In practice, stability and resolution in the inversion of SWS data are the issues of utmost importance since both are critically dependent on the distribution of the two SWS measured parameters (polarization and time delay) around each seismic sensor.

In this paper we discuss a few lessons we have learned as to the value of SWS for geothermal exploration, its limitations and potential extensions, from nearly a decade of practice.
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Keywords: Shear-wave splitting; Geothermal fields; Coso; The Geysers; Krafla

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Nomenclature

B	back azimuth (°)
$\overline{\overline{C}}$	stiffness matrix (Pa)
e	crack density (dimensionless)
I	incident angle (°)
α	aspect ratio (dimensionless)
Δt	delay time ($\mathrm{s\,m^{-1}}$)
θ	crack dip (°)
λ	Lame constant, isotropic elastic medium (Pa)
μ	Lame constant, rigidity of isotropic elastic medium (Pa)
φ	crack strike (°)
ϕ	polarization (°)
χ_c	porosity (dimensionless)

1. Introduction

Elastodynamic theory and observational evidence support the idea that a seismic shear wave propagating through isotropic rocks containing stress-aligned cracks behaves as if the rocks were anisotropic (Crampin, 1981; Hudson, 1981). This means that, regardless of its polarization at the source, a shear wave propagating through a cracked rock splits into two: a fast shear wave polarized parallel to the strike of the predominant cracks, and a slow one polarized perpendicular to it, which is time-delayed by an amount proportional to the number of cracks per unit volume (crack density or fracture intensity) along the path between source and receiver (Fig. 1).

Hence, if the SWS parameters (polarization of fast wave and time delay) are readily observable and self-consistent as the theory suggests, their measurement can be profitably used to determine the geometry, distribution and density of subsurface cracks, and possibly other parameters of importance to the exploration and exploitation of fracture-controlled geothermal reservoirs. An important part of the project we report here was in fact designed to test the scope, reliability and limitations of SWS using the exceptionally rich seismographic database available from The Geysers and Coso geothermal fields in California (USA), where we readily had found clear evidence of SWS. The results to date are highly encouraging: Within mildly restrictive conditions regarding the spatial distribution of seismic sources, standard inversion methods reliably detect 3D crack distribution, crack geometry, zones of highly fractured rock, and regions of potentially productive reservoir rock. SWS is a useful technology with the potential of becoming the standard approach to selecting geothermal drilling sites and to monitoring fluid flow at depth. Over the last decade our research group at UNC-Chapel Hill has accumulated substantial expertise and developed techniques for the seismic imaging and characterization of subsurface fracture systems from the analyses and interpretation of seismic waves from natural and induced micro-earthquakes in active geothermal fields (Lou and Rial, 1997; Erten et al., 2001; Vlahovic et al., 2002a, 2002b;

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