Modeling seismic anisotropy due to microcracks in granitic rocks from the Utah FORGE geothermal project

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ABSTRACT

We measured the seismic anisotropy of granitic cores from well 58-32 at the Utah FORGE enhanced geothermal site at different confining pressures. We performed mineral analysis using X-ray diffraction (XRD) analysis and imaged microcracks using X-ray CT. Mineral assemblages in the absence of microcracks are not able to explain the observed strong anisotropy. We measured ultrasonic velocities under a range of confining pressures from 5 MPa to 70 MPa. We quantify the contribution of microcracks to the observed anisotropy by applying the excess compliance model of Sayers and Kachanov (1995) and Sayers (2024). These approaches allow us to determine the orientation distribution of microcracks through the inversion of velocities, consistent with the observed anisotropy. Our modeling approach can be used to predict and monitor changes in geothermal reservoirs to guide energy development.

INTRODUCTION

Geothermal energy plays a vital role in the global transition to sustainable energy, offering carbon-free heat and a continuous baseload power supply. In enhanced geothermal systems (EGS), knowing the existence of fractures and cracks (therefore fluid flow pathways) is important for energy production. One of our objectives is to remotely probe the fractures and microcracks and use the obtained information to guide energy development and monitoring of the reservoir. Microcracks may lead to elastic and permeability anisotropy of the rock in a way dependent on the shape, orientation, and content of microcracks. Investigating the relationships between lithology, fractures, and the mechanical properties of rocks contributes to understanding how rocks behave under changing stress states. The mechanical properties of cracked and uncracked granitic rocks can be examined using ultrasonic methods to quantify how microcracks influence seismic wave velocities and anisotropy, both of which can be probed and determined remotely. Such information may be used in the analysis and prediction of the behavior of rock mechanical properties in geothermal reservoirs under various pressure and temperature conditions. This enables the identification and monitoring of production-induced changes in geothermal reservoirs, considering the effects of fluid injection and the opening and closing of natural and hydraulic fractures.

METHODS

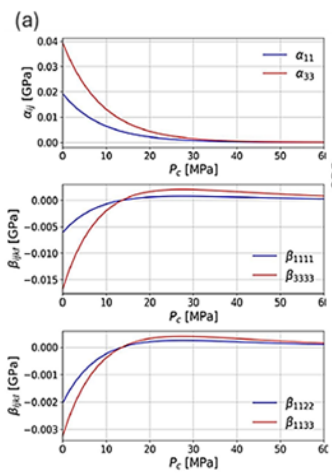
We evaluated two rock samples from well 58-32 at the Utah FORGE site (Moore *et al.*, 2020), from depths of 2074.16 m (6,805 feet) and 2268.01 m (7,441 feet). We analyzed the mineralogy using XRD analysis and classify the shallower rock as quartz monzodiorite and the deeper rock as diorite and tonalite. We imaged the cores using X-ray CT imaging. By processing the X-ray CT images we observed and identified microcracks in both cores. In our rock physics lab, we measured ultrasonic velocities at 1 MHz and under varying confining pressures (5-50 MPa) at ambient temperature conditions using our anisotropy measurement system (Carrasquilla *et al.*, 2023). Assuming transverse isotropy (TI) we measured P-wave velocities in three independent directions and two S-wave velocities and calculated the Thomsen anisotropy parameters (Thomsen, 1986). Using our measured velocities, we calculate the elastic stiffness tensor (C_{ijkl}) at various confining pressures.

We found that mineral assemblages alone cannot satisfactorily explain the observed anisotropy and investigated whether the presence of microcracks can explain the measured anisotropy. For this, we use the excess compliance model of Sayers and Kachanov (1995). In this model, the cracked rock can be viewed as the sum of two parts: the compliance tensor ($S^{(0)}_{\mathrm{ijkl}}$) the rock would have in the absence of microcracks, and the excess compliance tensor (ΔS_{ijkl}) due to the presence of microcracks. The effective compliance tensor (S_{ijkl}) of the cracked rock is expressed as: $S_{\mathrm{ijkl}} = S^{(0)}_{\mathrm{ijkl}} + \Delta S_{\mathrm{ijkl}}$. Inverting the measured stress-dependent elastic stiffnesses of our samples, we obtain $S^{(0)}_{\mathrm{ijkl}}$ and the stress-dependent ΔS_{ijkl} separately.

RESULTS

The input data to our modeling includes the measured increase in seismic velocity for each rock sample with increasing effective pressures, a behavior likely caused by closure of microcracks. We observed that P- and S-wave anisotropy values (ε and γ) decrease with increasing confining pressure. The maximum measured P- and S-wave anisotropy values are ~23% and ~20%, respectively.

Based on the measured elastic stiffnesses of our samples, we determined the second- and fourth-rank microcrack compliance tensors α_{ij} and β_{ijkl} (Figure 1) defined by Sayers and Kachanov (1995) and the microcrack orientation distribution function for each sample as shown in the figure.



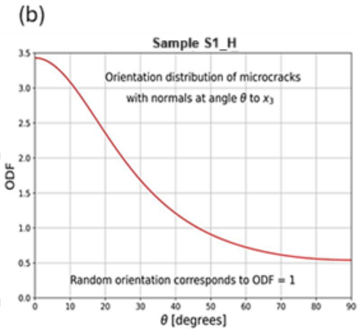


Figure 1. (a) Components of microcrack compliance tensors α_{ij} and β_{ijkl} obtained by inversion for sample S1_H. (b) Microcrack orientation distribution obtained for sample S1_H.

CONCLUSIONS

Our findings suggest that the increase of pore fluid pressure during hydraulic fracturing in EGS (Enhanced Geothermal Systems) could lead to an increase in seismic anisotropy values caused by the nucleation and propagation of microcracks and fractures. Both the presence of fractures and the mineral composition play a role in this anisotropy. Cracks have a significant effect on the Vp/Vs ratio, decreasing it. Our modeling approach provides a framework for monitoring the distribution of subsurface fluids and understanding the evolution of the stress field.