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Shear-wave splitting: A diagnostic tool to monitor fluid pressure in geothermal fields

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[1] An experiment on the uses of shear-wave splitting as an imaging tool in fracture-controlled geothermal reservoirs was conducted at Krafla, Iceland. Fifteen days after the beginning of the seismic recording the injection was stopped for eleven days and then restarted, a sequence designed to determine whether shear-wave splitting measurements can detect the transient response of the subsurface crack system to changes in fluid pressure. It was observed that time delays between the fast and slow split shear waves changed significantly and promptly with the stoppage and resumption of injection. Large time delays occurred only during injection, decreased substantially during the stoppage phase, and increased again as injection restarted. Comparisons of these results with similar observations at the Coso geothermal field in California strongly suggest that the time delay of split shear waves can be a useful proxy to monitor fluid pressure in the cracks and changes in crack density. **Citation:** Tang, C., J. A. Rial, and J. M. Lees (2005), Shear-wave splitting: A diagnostic tool to monitor fluid pressure in geothermal fields, *Geophys. Res. Lett.*, *32*, L21317, doi:10.1029/2005GL023551.

1. Introduction

[2] The Krafla volcanic system in northeastern Iceland is made up of the Krafla central volcano and an approximately 100 km long, transecting fissure swarm, with two high-temperature geothermal areas within it. One is located 5 km south of the Krafla caldera and the other, the NW-SE aligned Krafla-Leirhnúkur geothermal field, where this study was performed, is located inside the Krafla caldera. There is a shallow crustal magma reservoir with an upper boundary at a depth of approximately 3 km, near the center of inflation in the caldera [*Einarsson*, 1978].

[3] During the months of July and August 2004, a twenty-station three-component seismic array with L-28 MARK4 4.5-Hz seismic sensors was deployed around the Krafla geothermal field, covering an area approximately 5 km in N-S by 4 km in E-W. Between 5 July and 11 August the array continuously recorded the seismic activity in the region surrounding the injection well K-26. The data were collected at a rate of 500 samples per second.

[4] One objective of the deployment is to use various seismic data processing techniques such as high precision earthquake location, shear-wave splitting, and tomographic inversion to detect the orientation, density and fluid content of the main subsurface fracture systems in Krafla. In addition, an experiment was designed with the collaboration of Landsvirkjun, the power company that runs the Krafla field, to stop and start injection into well K-26 with the objective of determining any change in shear-wave splitting parameters (polarization of the fast wave, time delay between the fast and slow waves) that may accompany a scheduled stopping and resumption of injection. Injection was stopped on 15 July and resumed 11 days later on 26 July. It turns out that the response of the subsurface crack systems to these transient changes in water pressure can in fact be detected with seismic waves, which can potentially provide invaluable information on the preferred directions of fluid migration in the reservoir. The results obtained at Krafla are totally consistent with those of a similar experiment carried out in 2001 in the Coso geothermal field in California. The immediate inference is that the delay time of split shear waves may be a proxy for reservoir fluid pressure, as shall be discussed in what follows.

2. Shear-Wave Splitting Observations at Krafla

[5] Shear-wave splitting is an exploration method of proven reliability and unique imaging power. The method is based on the fact that a shear-wave propagating through rocks with stress-aligned micro-cracks will split into two waves, a fast one polarized parallel to the predominant crack direction, and a slow one polarized perpendicular to it [*Crampin*, 1981, 1984; *Babuska and Cara*, 1991]. The polarization direction of the fast shear wave (φ) parallels the strike of the predominant cracks regardless of its initial polarization at the source in a single fracture set [*Crampin et al.*, 1986; *Peacock et al.*, 1988]. The differential time delay between the arrivals of the fast and slow shear waves (δt) is closely related to crack density, or number of cracks per unit volume within the rock, and crack aspect ratio [*Hudson*, 1981; *Crampin*, 1987; *Crampin and Lovell*, 1991]. Thus measuring the fast-shear wave polarization and time delay from local microearthquakes has become a valuable technique to detect the orientation and intensity of fracturing in the subsurface of fracture-controlled geothermal fields [e.g., *Lou and Rial*, 1997; *Vlahovic et al.*, 2002a, 2002b; *Elkibbi and Rial*, 2003, 2005; *Elkibbi et al.*, 2004, 2005; *Yang et al.*, 2003, 2005; *Rial et al.*, 2005].

[6] Figure 1a shows the epicenters of microearthquakes located during the period 5 July to 11 August, 2004. Figure 1b shows the depth distribution of these events along N-S and E-W cross-sections respectively. The velocity model used is from *Brandsdóttir et al.* [1997]. It can be seen that the epicenters roughly align along the E-W direction, while focal depths are shallow around the injection well, mostly shallower than 4 km. Seismicity at

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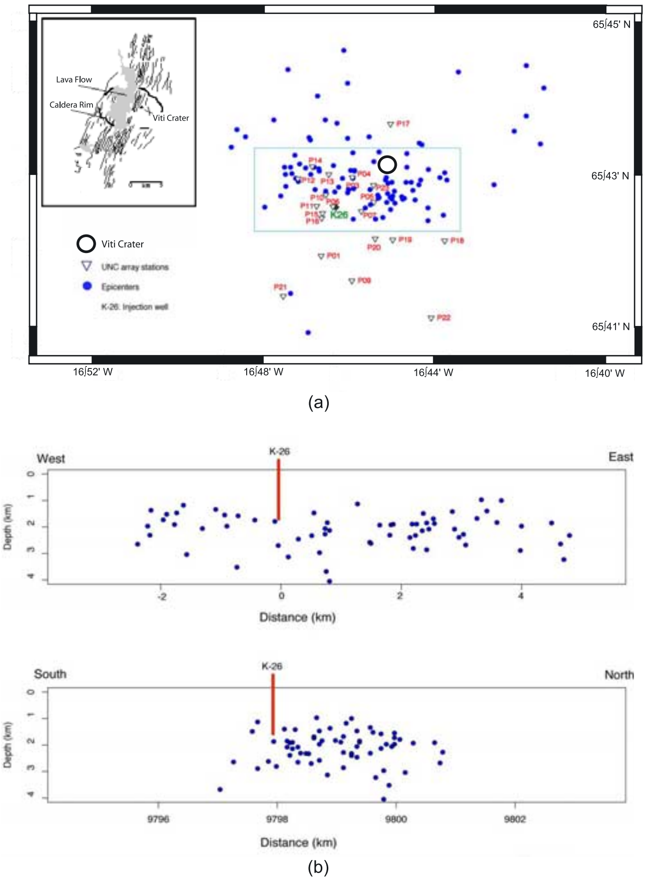

Figure 1. (a) The seismicity recorded by UNC array from 5 July to 11 August. Totally 129 earthquakes are located. (b) The focal depth distribution of the events located around the injection well K-26 (inside the rectangle).

Krafla is not very high, and during the operation the array detected an average of four well-recorded events per day (observed at five or more stations).

[7] Shear-wave splitting is clearly recorded at Krafla at most stations and shows the prevalence of at least two major crack systems oriented approximately N-S and E-W. We have measured the fast shear-wave polarization and time delay of shear-wave splitting events recorded at ten selected stations (P03, P04, P06, P10, P11, P13, P14, P15, P16, and P23). These stations are selected because they either recorded the data of best quality (P13, P14, P23) or had a relatively good coverage of ray paths coming from different azimuths (P03, P04). Stations P06, P10, P11, P15, and P16 are chosen because they are the nearest to the injection well K-26.

[8] Fast shear-wave polarization angle φ is measured by interactive rotation of the seismogram until the horizontal particle motion plot shows that fast and slow shear-waves are oriented along the instrument's horizontal components. Angle of rotation from the original polarization direction determines φ. Meanwhile the two shear-wave arrivals, which are often coupled in the original recording, separate out in time domain and δt can then be directly measured. In this study δt is normalized by dividing it by the length of the ray path in order to correctly compare delays from different paths. Figure 2 shows the rose diagrams (polar histograms) of fast shear-wave polarization directions observed within the shear-wave window of the ten stations. The predominant polarization directions observed at stations P13, P15, P16 and P23 are close to E-W or NW-SE, and those at P04, P10 and P11 are generally close to N-S, while P03, P06 and P14 display two major sets of polarizations nearly perpendicular to each other, striking close to N-S and E-W respectively.

3. Time Delay Variations With Fluid Injection at Krafla and Coso

[9] Normalized time delays observed at Krafla are mostly less than 20 ms/km, whereas there are still some cases with very large normalized δt (>30 ms/km). Our focus is on stations P06, P10, P11, P15 and P16 since they are the closest to the injection well K-26 and are expected to provide additional information about the relationship, if any, between the shear-wave splitting events and the ongoing injection. The normalized time delays observed at these five stations throughout the experiment are shown in Figure 3b. Time delays drop significantly after the injection stops and maintain at a lower level until increasing again right after the injection resumes. The *t*-test results show that the time delays during the first injection period are different from those during the absence of injection at 99% confidence level (*t* value = 3.16), and the time delays before and after the injection resumes are different at 68% confidence level (*t* value = 0.995).

[10] In March 2001 a similar injection experiment was conducted, but in an opposite way, at the Coso geothermal field in central California [*Vlahovic et al.*, 2002c; *Rial et al.*, 2005]. Injection into the well was initiated briefly for one day on 13 March, and was restarted on 20 March and maintained on for one week before being stopped on 27 March. The normalized time delays observed in this experiment are shown in Figure 3a. Compared with the observations from Krafla, it can be seen that in both experiments the crack systems are responding promptly in the same way to the transient changes in fluid pressure, i.e. large time delays occur only during the injection phases and drop to a lower level without the injection.

[11] In addition, it should also be noticed that in both experiments large normalized time delays take place only at depths around and shallower than the injection as shown in

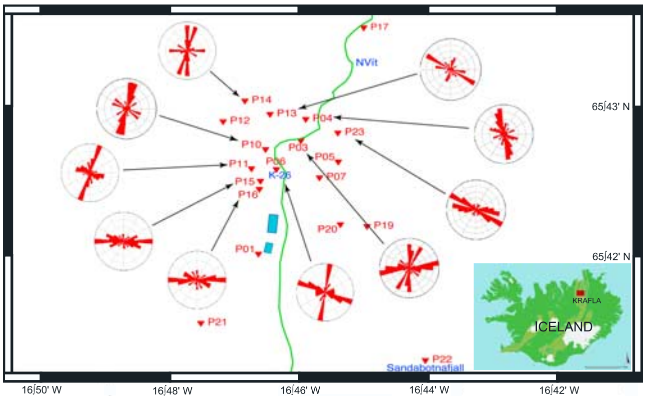

Figure 2. Rose diagrams (polar histograms) of the fast shear-wave polarization directions observed at the ten selected stations. See details in the text.

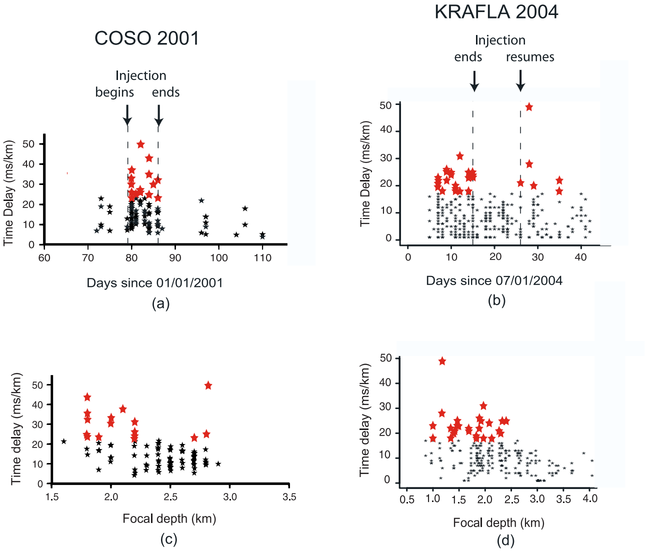

Figure 3. (a) Delay times strongly increase during the injection and drop back to normal values right after injection ends. Time delays greater than or equal to ∼25 ms/km occur only during the injection and are marked in red. (b) Time delays significantly drop after the injection stops and increase again right after the injection resumes. Time delays greater than or equal to ∼18 ms/km occur only during the injection and are marked in red. (c, d) Large normalized time delays appear to occur only at depths shallower than and around the injection. For both cases data selected are those from stations closest to the injection wells. The depth of injection at Coso was 2.6 to 2.9 km, and at Krafla it was between 2.0 and 2.1 km.

the bottom panel in Figure 3, which strongly implies that the observed large normalized time delays are mostly due to the injection. Therefore, all of these observational facts indicate that the injection has either opened new fractures or increased the aspect ratio. In both Coso and Krafla, however, we have not found significant changes in the polarization angles during the experiments. Further study on the time pattern of φ is already underway.

[12] Thus, normalized time delay may be used as a proxy of changes in fluid pressure and possible fluid migrations. Explaining these changes in terms of crack mechanics and the action of fluids in hot rock is not simple, and we are still far from fully understanding what these observations mean. Nevertheless, the significant changes in time delays strongly suggest that detection of time delays of split shear waves can be a useful diagnostic tool for monitoring crack intensities and fluid behaviors in a producing geothermal field.

4. Conclusion

[13] There is clear evidence of shear-wave splitting in Krafla's seismic data. In addition to the observed prevalence of a crack system oriented approximately in N-S which is consistent with the anticipated direction of major fractures in the area, fast shear-wave polarizations along a general E-W direction are also persistent as observed at stations P13, P15, P16 and P23. The influence of fluid injection on fracture systems can be clearly illustrated by the observation of changes in the normalized time delays. Therefore, normalized time delays measured from well recorded shear-wave splitting events can provide a useful tool to closely monitor transient changes in fluid pressure and possible fluid migrations in fractured reservoirs.

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