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# Seismic imaging of the geothermal field at Krafla, Iceland using shear-wave splitting

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ABSTRACT

Shear-wave splitting is emerging as a useful exploration method for geothermal reservoirs as it can detect the geometry of the fracture system, the intensity of cracking and possibly, changes in fluid pressure within the reservoir. The method is based on the analyses of polarizations and time delays of shear-waves that have been distorted by the anisotropy of the medium through which the seismic waves have propagated. Observations of shear-wave splitting within the Krafla–Leirhnúkur geothermal field, Iceland, using a 20-station 3-component portable seismic array have provided evidence for at least two major crack systems of microfractures, oriented approximately N–S and E–W. Located microearthquakes align roughly along the E–W direction of the geothermal field, with shallow focal depths mostly around the injection well, probably related to the ongoing injection. This unexpected direction is however consistent with results from a simultaneous MT (magnetotelluric) survey.



## 1. Introduction

The Krafla volcanic system, located within the Northern Volcanic Zone of Iceland, is made up of the Krafla central volcano and an approximately 100 km long, transecting fissure swarm. The central volcano is a major eruptive center less than 500,000 years old, approximately 21 km long by 17 km wide and enclosing a 10 km by 7 km caldera formed 100,000 years ago during the last interglacial period. Two high-temperature geothermal areas occur within the Krafla volcanic system. The NW–SE aligned Krafla–Leirhnúkur geothermal field, where this study was performed, is located inside the Krafla caldera. The other is located within the fissure swarm, 5 km south of the Krafla caldera. The eastern part of the Krafla–Leirhnúkur geothermal field is utilized by the Krafla power plant which started operation in 1978. There is a shallow crustal magma reservoir with an upper boundary at a depth of approximately 3 km, near the center of the caldera (Einarsson, 1978). This magma chamber is smaller than the caldera, about 2–3 km in N–S and 8–10 km in E–W, with a thickness of 0.75–1.8 km (Brandsdóttir et al., 1997). Geodetic measurements support the existence of a shallow magma chamber at a depth of 3 km within the caldera and have been used to argue for the existence of multiple magma reservoirs at depth (Tryggvason, 1986).

During the months of July and August 2004, a twenty-station, three-component seismic array was deployed around the Krafla geothermal field, covering an area approximately 5 km N–S by 4 km E–W. Between July 5th and August 11th the array continuously recorded the seismic activity in the region surrounding the injection well K-26 located 1 km north of the Krafla power plant. Each station in the seismic array consisted of a three-component short-period MARK4 L-28 (4.5 Hz) seismic sensor, a data-logger or DAS (Data Acquisition System), a GPS antenna, and a 12 V car battery. The data were collected continuously at a rate of 500 samples per second.

The main objective of this experiment was to use shear-wave splitting (SWS) as a tool to detect the orientation, density and fluid content of the main subsurface fracture systems within the Krafla–Leirhnúkur geothermal field. Besides the passive seismic survey an experiment was conducted whereby injection in well K-26 was stopped on July 15th and subsequently resumed on July 26th. We hoped that the response of the subsurface crack system to these transient changes in water pressure could be detected with seismic waves and provide useful information about the preferred directions of fluid migration in the reservoir.

Fig. 1(a) shows the epicenters of seismic events located from July 5th to August 11th along with the distribution of the stations in the array, and Fig. 1(b) shows the depth distribution of the events along N–S and E–W cross-sections respectively. The locating program ("lquake") employs a standard non-linear inverting algorithm based on Geiger's Method (e.g. Lee and Stewart, 1981) to determine the origin time and hypocenter of earthquakes using a 1-D velocity model. The velocity model used in this study is from Brandsdóttir et al. (1997). It is apparent that the epicenters are roughly aligned along the E–W direction of the Krafla–Leirhnúkur geothermal field. Hypocenters are shallow around the injection well with most focal depths being shallower than 2 km.

Seismicity at Krafla was low during the experiment. During its operation the array detected an average of four well-recorded events

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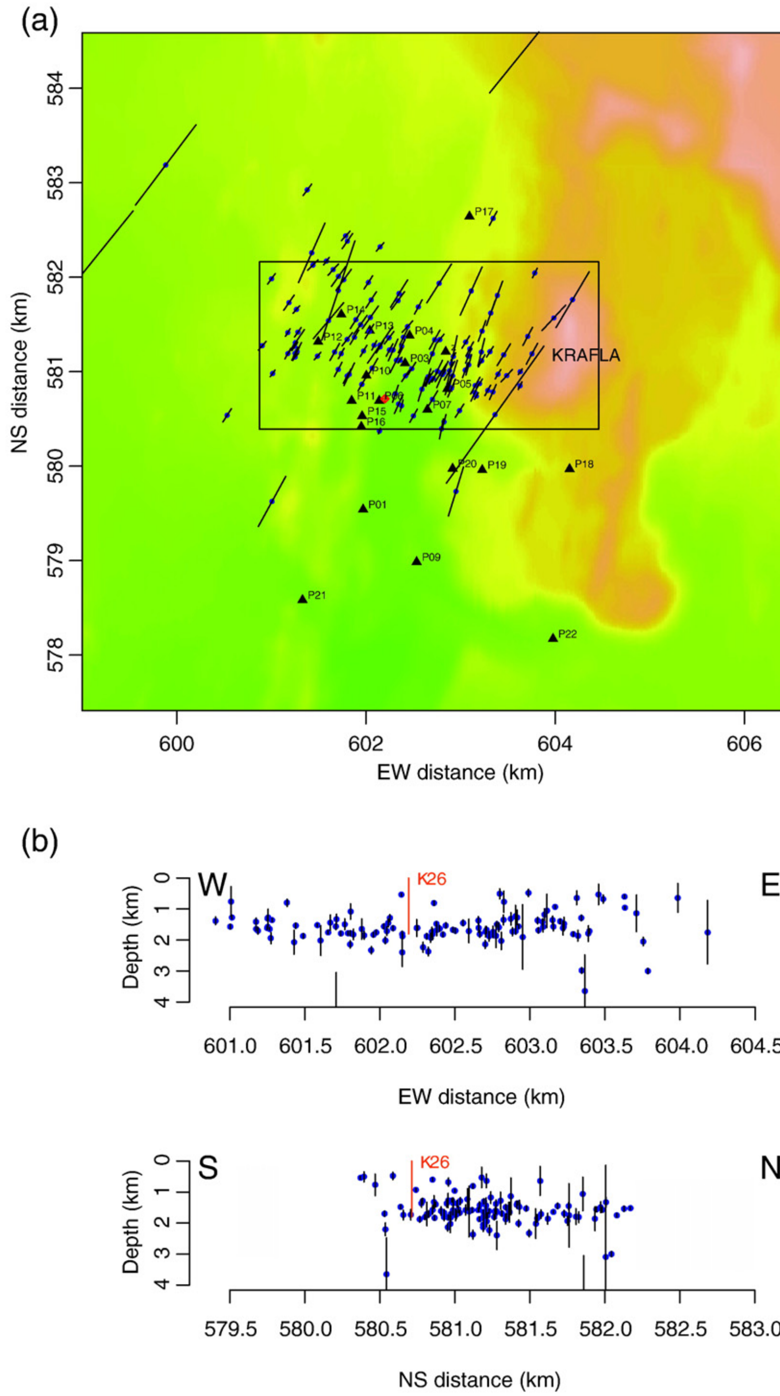


**Fig. 1.** Microseismicity recorded by the UNC array at Krafla. A total of 129 earthquakes were located during the period from July 5th to August 11th. The seismic stations are represented by solid triangles and the red diamond shows the location of injection well K-26. The solid line segments indicate the location error associated with each epicenter in NS and EW directions respectively. The error in the E–W direction is generally smaller than the NS direction. The focal depth distribution of the earthquakes located around the injection well K-26 (inside the rectangle in (a)) is shown in (b). Vertical line segments indicate calculated error in focal depth.

per day recorded at five or more stations. These are very small earthquakes with magnitudes mostly no greater than 2. Microseismicity within the Krafla region is somewhat obscured by the high level of seismic noise from vibrations of the steam pipes, routine plant operations, tourists, local traffic, etc. To avoid strong sources of noise, several stations were relocated to quieter sites. Some stations deployed in abandoned well cellars had a mixed performance, some noisy and some not. In spite of occasional and instrumental interruptions the array performed well, recording over 300 GB of data.

## 2. Shear-wave splitting analysis of Krafla seismic data

### 2.1. Shear-wave splitting

Shear-wave splitting (SWS) is a valuable technique of exploration. The method is based on the observation that a shear-wave propagating through rocks with stress-aligned microcracks (also known as extensive dilatancy anisotropy or EDA-cracks) will split into two waves, a fast one polarized parallel to the predominant crack