

## SHEAR-WAVE SPLITTING CRACK DENSITY MAPS FOR THE GEYSERS AND MAMMOTH

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### ABSTRACT

We have developed a method for mapping subsurface fracture density using the time differences of split shear waves from microearthquakes. In regions where a consistent direction of fracturing exists, shear waves from different source and receiver locations are systematically split into fast and slow components. The greater the fracture density, the greater the time differences between the fast and slow components for a given path length. Also, the greater the path length in the fractured rock, the greater the time difference. With a large number of spatially distributed sources and receivers, tomographic backprojection of the time differences can be used to map the distribution of fracture density.

We have applied this method to 3 geothermal fields, the Geysers, Mammoth, and Coso. Our best example to date comes from Mammoth, where we recorded over 1/4 million source-receiver pairs, from which we extracted 1480 splitting times. Inversion of these times suggests the presence of zone of higher fracture density at depths of 1.5 to 2.5 km north and east of the Casa Diablo geothermal field.

### CRACK DENSITY MAPS

We have been able to map crack density in 3 established US geothermal energy reservoirs using the travel time differences produced by anisotropic (direction dependent) S-wave propagation. The S-wave sources we used were small earthquakes. Using S-wave polarization diagrams, we first established that the time differences resulted from the splitting (birefringence) of S-waves by crack induced anisotropy. The average azimuthal orientation of the cracks was determined from the polarization of the first S-wave. We then identified and measured a large number of split S-wave time differences for different parts of the reservoir volume. These measurements are then inverted using back-projection tomography to locate the spatial distribution of crack density. Standard tomographic display methods were then used to create maps of crack density for characterization and development of

the reservoir. The full theory and methods behind crack-density mapping using shear-wave splitting tomography are given in Malin, 1993; Lou and Rial, 1994; Shalev and Lou, 1995, Lou et al., 1997; Shalev et al., 1998; and in a forthcoming publication that we are currently preparing (Malin and Shalev, in prep.).

In this short note, we present our crack orientation and density maps and cross sections for the Geysers and Mammoth areas, with the later being our best example to date. The crack orientations are displayed as rose diagrams superimposed on the maps of the seismic recording stations (Figs. 1 and 2). The crack-density maps (Figs 3 and 4) and cross sections (Figs 5 and 6) are displayed as level and profile dependent tomographic slices through the reservoirs. Each tomogram is plotted on a relative crack density scale.

### MAMMOTH: PRELIMINARY INTERPRETATION

Our maps and cross sections of the Mammoth area suggest that there are 2 major zones of high crack density: one north and east of the Casa Diablo area, near the junction of Highway 395 and 205, and one near the Mammoth airport. Both zones lie at depths of about 1.5 to 2.5 km.

### REFERENCES

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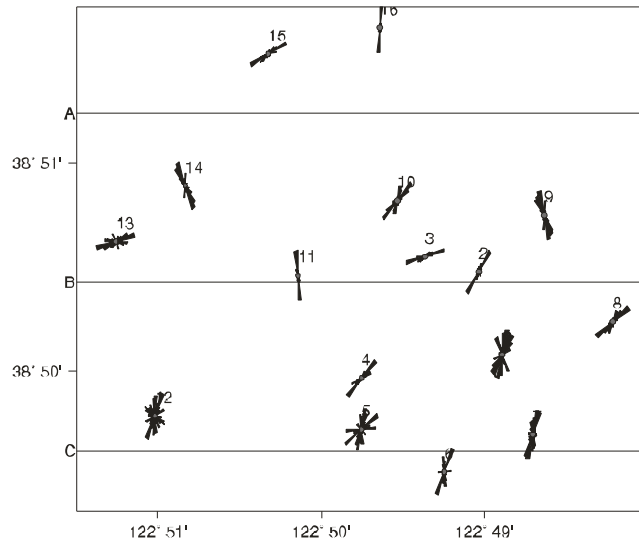


Figure 1. Crack azimuths for the Geysers area. The numbers refer to seismic stations and the length of lines in the rose diagrams refer to the number of S-wave splitting observations within a given azimuth bin.

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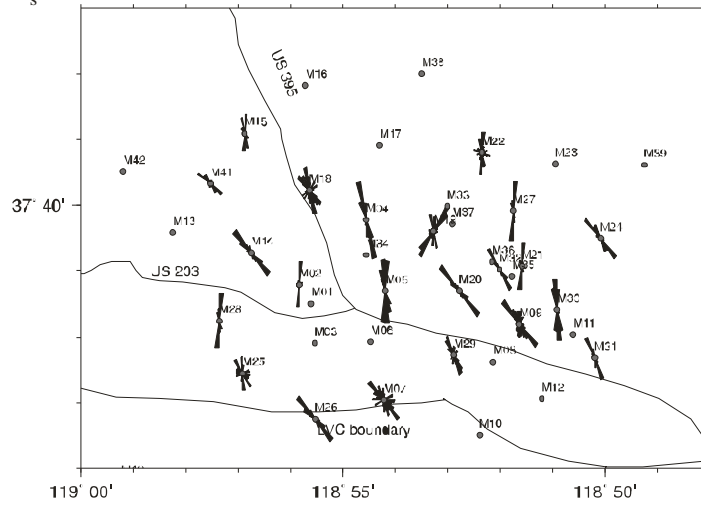


Figure 2. Crack azimuths for the Mammoth area. The numbers refer to seismic stations and the length of lines in the rose diagrams refer to the number of S-wave splitting observations within a given azimuth bin.

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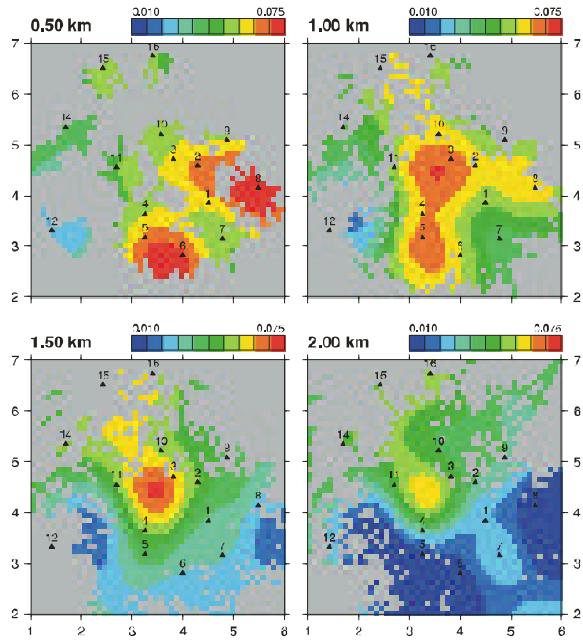


Figure 3. Crack density maps for the Geysers area. The numbers refer to seismic stations and the colors relative density of cracks, with high densities in red.

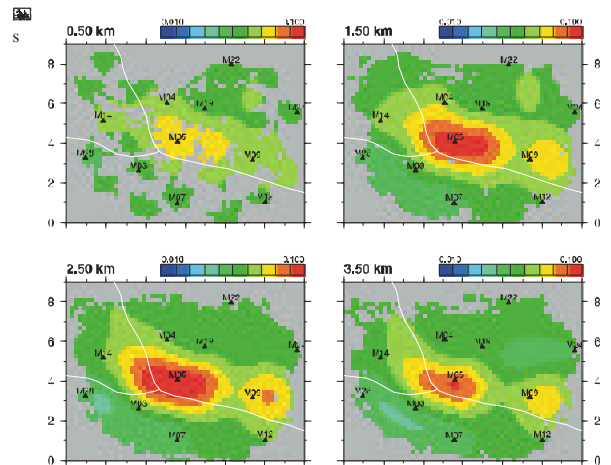


Figure 4. Crack density maps for the Mammoth area. The numbers refer to seismic stations and the colors relative density of cracks, with high densities in red.

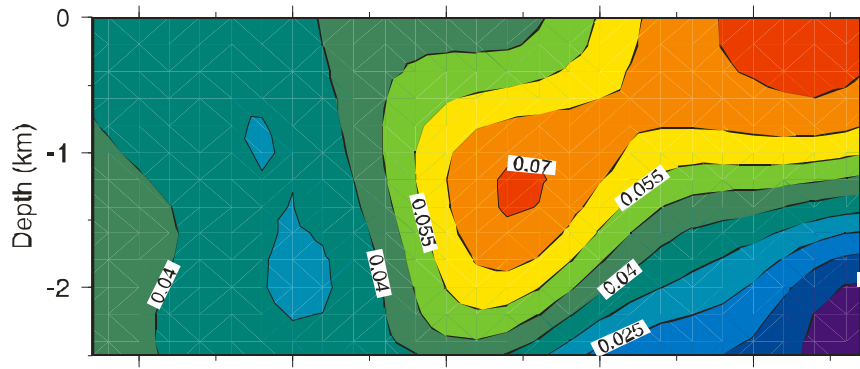


Figure 5. East-west crack density cross section for the Geysers area. The numbers refer to relative crack densities on the same scale as in Figure 3. The vertical and horizontal axes are in kilometers.

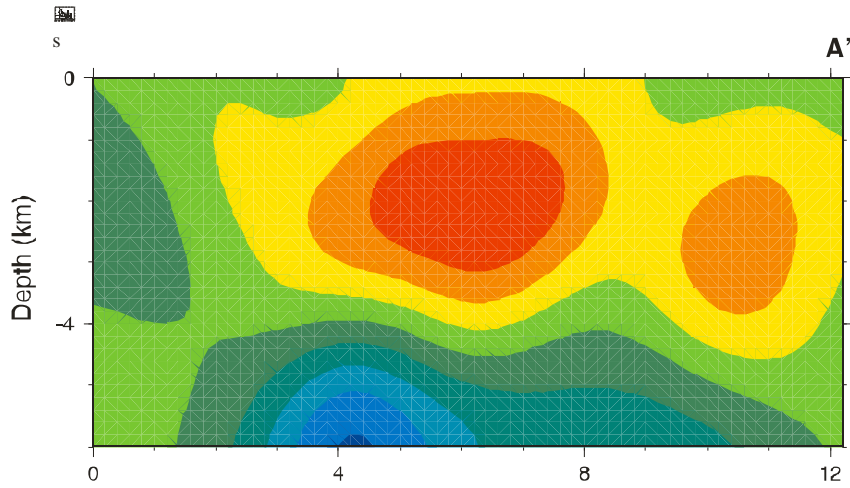


Figure 6. East-west crack density cross section for the Mammoth area. The numbers refer to relative crack densities on the same scale as in Figure 3. The vertical and horizontal axes are in kilometers.

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