CHARACTERIZATION OF FRACTURE PATTERNS IN THE GEYSERS AND COSO GEOTHERMAL RESERVOIRS BY SHEAR-WAVE SPLITTING

Principal Investigator **-** J.A. Rial
University of North Carolina at Chapel Hill
Mitchell Hall, Dept of Geological Sciences CB#3315

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Project Objectives

On the basis of shear wave splitting data recorded and processed from the Geysers and Coso geothermal fields this project aims at developing a computer-based methodology to produce 3D maps of crack distribution and crack density in fractured reservoirs. The raw data for the project consists of seismographic recordings of microearthquakes (MEQ) detected over many years by arrays of sensors in both The Geysers and Coso reservoirs. With the experience acquired in the processing and interpretation of these data we are developing a novel computer-based technology for the exploration of fractured geothermal and hydrocarbon reservoirs that, in its completed form, will include the following software packages (written in Matlab-compatible language):

(1) Data anlyzing package.

(2) Forward modeling package

(3) Inversion package.

Approach/Background

A shear-wave propagating through rocks with stress-aligned cracks will split into two waves, a fast one polarized parallel to the predominant crack direction, and a slow one, polarized perpendicular to it. In fact, the polarization direction ϕ of the fast split shear wave parallels the strike of the predominant cracks regardless of its initial polarization at the source, while the time delay δt between the fast and the slow waves is proportional to crack density, or number of cracks per unit volume. The analysis of split shear waves is thus a valuable technique to detect and map the main orientation and intensity of fracturing in the subsurface, which, when fully developed as a computer application, could become a highly desirable technical and industrial resource to explore fracture-controlled geothermal and hydrocarbon reservoirs.

For the last few years we have studied and processed shear-wave splitting data in two seismically active, fracture-controlled environments, The Geysers and Coso geothermal fields in California, using 14- and 16-station seismic arrays of 3-component, mostly down-hole instruments running up to 480 samples/sec (Lou and Rial, 1994; 1995; 1997; Erten and Rial, 1998; Erten et al., 2001). From the careful analyses and processing of over 30,000 local microearthquakes we have to date collected what is arguably the world's largest and most complete set of high resolution, high quality shear-wave splitting observations. This constitutes one of the main contributions of this project to the geothermal community.

Status/Accomplishments

All phases of the proposed research are on schedule. Surface mapping of fast shear-wave polarizations and delay times in The Geysers and Coso has been completed and the results described in the previous peer reviewed report (San Diego, August 2001). Preliminary results have been published (see below).

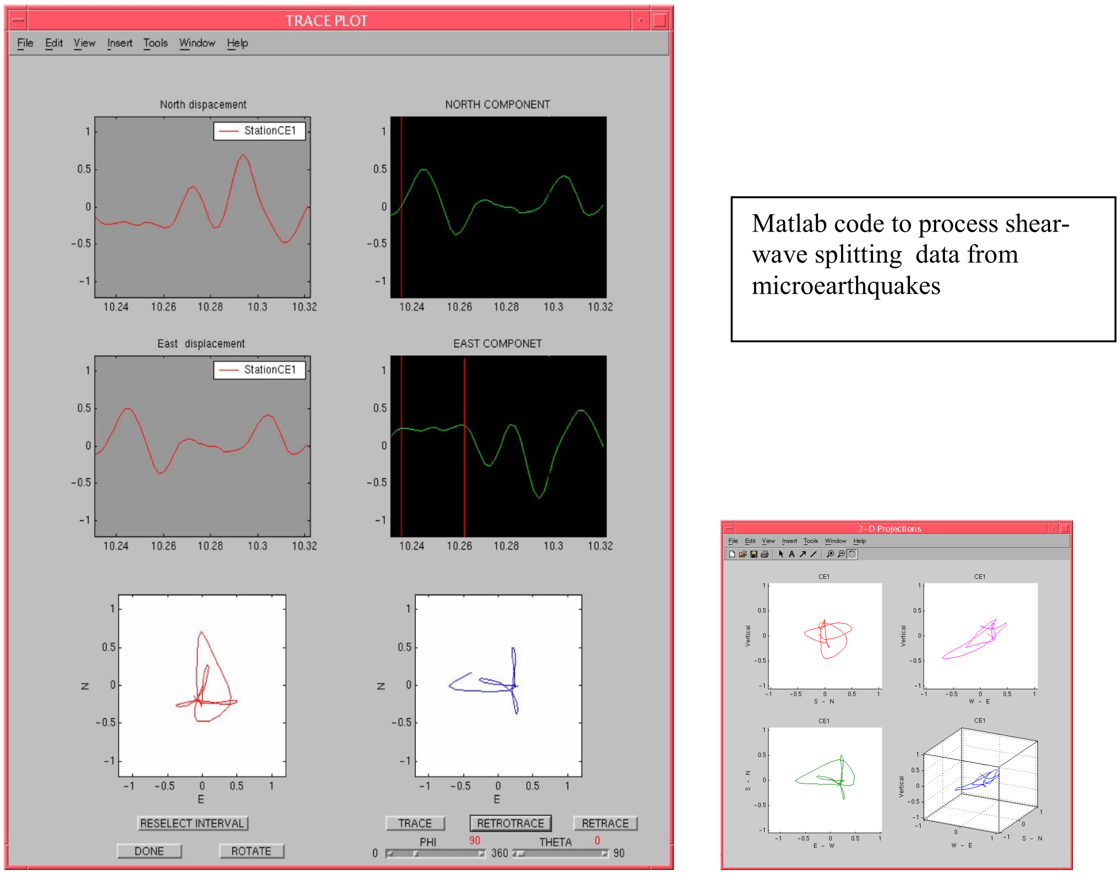

Figure 1. Matlab GUI (Graphic User Interface) from the data analyzing package. The purpose of this package is to provide the user with a complete set of interactive routines to read, display, frequency analyze, filter, window and process shear-wave splitting from seismographic data. The current input format is derived from the UW (University of Washington). The above example shows the part of the code (left) where the operator, after windowing and filtering the data, can determine the fast wave polarization direction ϕ and the time delay between the split shear waves δt. For illustration the figure shows shear wave seismograms (in red, left) from station CE1 (Coso) and the corresponding particle motion diagram (bottom left) for the selected window. When necessary, the instrument components are rotated interactively using the sliders and the tracer/retracer commands on the bottom right of the window. All these operations are automatic and can be restarted at any time. In routine work, the rotation of the seismographic components (right) is done to align the polarization of the fast shear wave with one of the coordinate axis. This gives the polarization angle ϕ in a geographic frame, and makes the seismographic components split, as shown. The time delay δt can then be measured (vertical red lines). Both parameters are automatically archived along with the identification of the station and the event. Vertical plane projections and three-dimensional plots of the particle motions can also be constructed and displayed, as shown in the inset on the lower right.

The data analyzing package (1) is now completed. The program consists in Matlab-based fully interactive GUIs (Graphic user interface) that allow display, windowing, spectral analysis and polarization analyses of three-component seismograms (Figure 1). The code also allows the operator to plot the ground particle motion in 2D and 3D diagrams, rotate the components to determine the polarization ϕ, time delay δt and automatically store them for later use in the modeling and inversion procedures. This code has been successfully tested and used in the analyses and processing of the Geysers and Coso shear-wave splitting database.

Matlab code to compute synthetic shear-wave splitting data

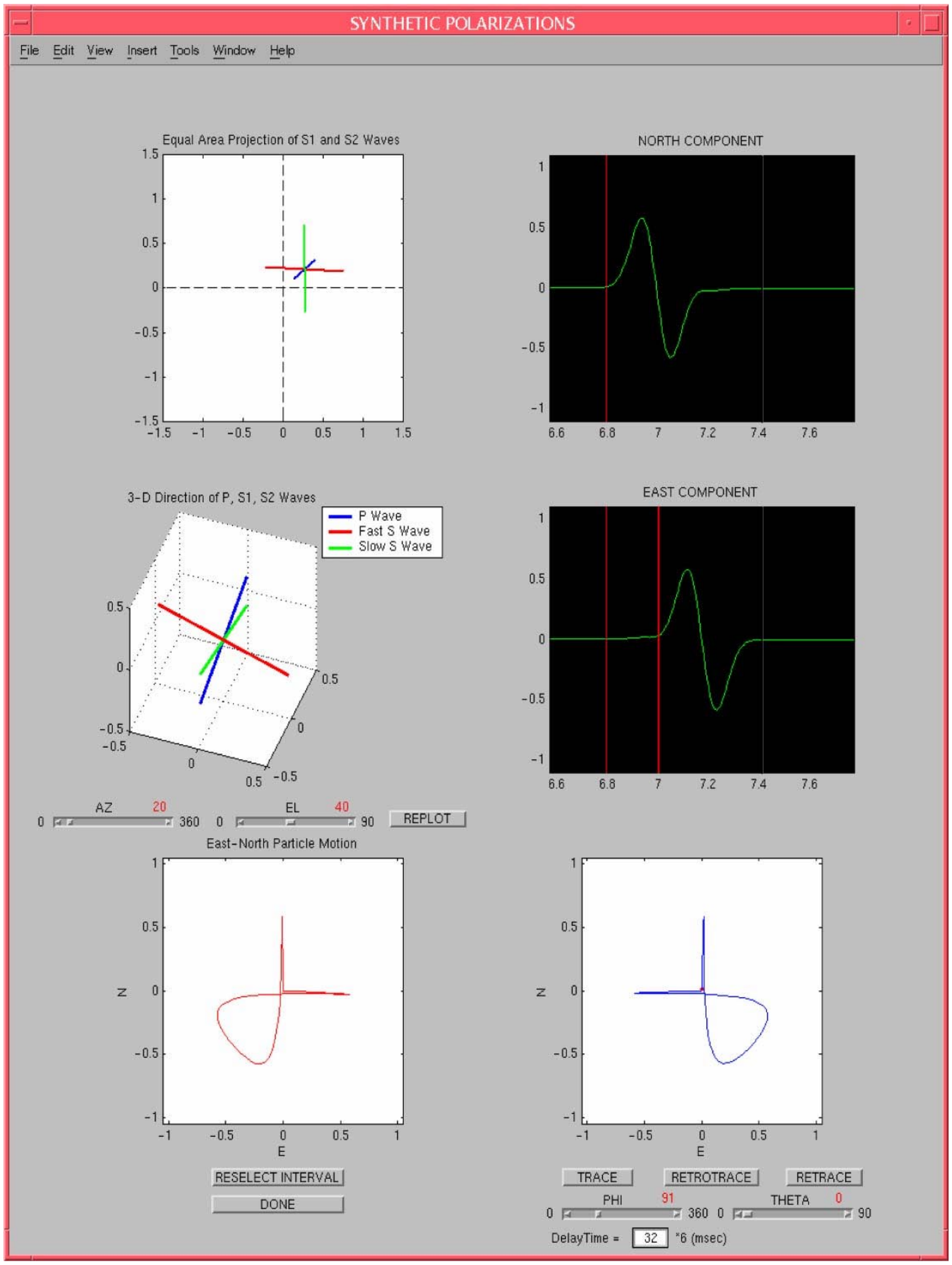

Figure 2. Example of Matlab GUI from the forward modeling package. Here synthetic polarizations and synthetic seismograms are computed for prescribed models of the anisotropy-producing medium. In the example above the medium is modeled using a HTI (hexagonal transverse isotropic) that represents saturated cracks. The operator can change orientation and dip of the cracks by using the sliders (left, middle) and re-plot the result, which shows the map and 3D orientation of the P-wave and the fast and slow shear waves (middle left) in the station's reference frame. The diagrams on the right are similar to those in Figure 1 and are used to simulate the rotation and measuring process of the real data. The results are automatically archived. The computed changes in polarization direction and time delay with azimuth, dip and strike of the cracks are used in the inversion process that follows.

The forward modeling package (2) is now near completion. This package has two important uses: a) it allows the operator to map polarization ϕ and delay δt on the area of interest, which helps determine data consistency, data anomalies and general azimuthal distribution of the data prior to interpretation, and b) the operator can interactively construct synthetic seismograms that reproduce the polarizations of the P, fast S1 and slow S2 split waves traveling through a standard Horizontal Transverse Isotropic (HTI) model that can fully simulate the anisotropy induced by a crack system (Figure 2). The operator can change the dip of the crack system and the crack density, as well as specify whether cracks are empty or fluid-saturated. As shown in Figure 2, the operator can construct two and three-dimensional graphs depicting the predicted synthetic polarizations for the P, S1 and S2 waves. The code computes synthetic seismograms and synthetic particle motions from which the predicted values of ϕ and δt are compared with actual ones in a station-by-station basis. The purpose of this pacakge is to produce a first trial-and-error inversion of the data to use as fundamental constraints in the next step. The synthetic seismogram computations have been successfully tested against published results of ϕ and δt for a number of transversely isotropic (TI) models.

This project has so far fully supported two graduate students and partially supported a post-doctoral associate.

Planned FY 2002 Milestones

A) Completion of the forward modeling package (2). This includes the incorporation of an automatic code to detect and store the differences between synthetic and observed seismograms.
B) Completion of two research papers that describe the results obtained in The Geysers and Coso regarding crack distribution. A research paper with a comprehensive study of the space-time variation of ϕ and δt at Coso and its implications to monitoring local tectonics and production has been submitted to the Journal of Volcanology and Geothermal Research. Completion of the seismographic analysis. The latest results for crack directions in SE Geysers and Coso are shown in Figures 3 and 4.

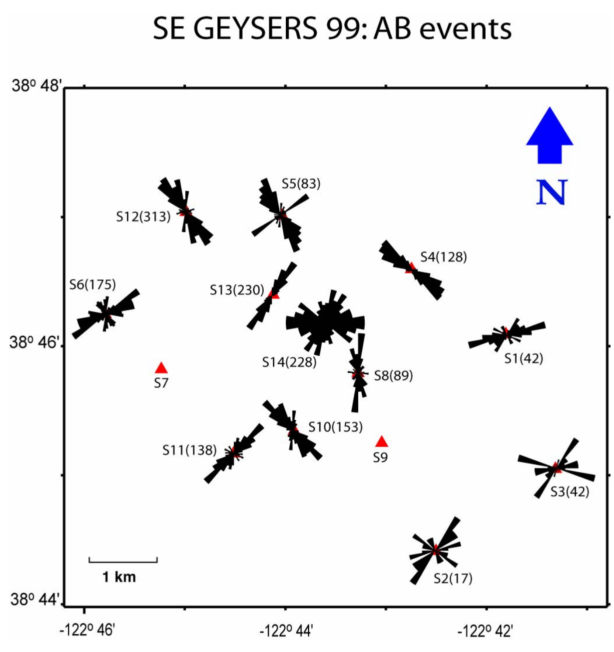

Figure 3. Rose diagrams for the SE Geysers area for events of quality A and B (best quality recordings), recorded in 1999. Numbers in parenthesis are the number of events used in each station. Though most stations show strong consistency in the measurements, stations 14 and 3 require a detail study to determine the source of the strong variability in detected orientations. These could be due to the presence of multiple crack planes, non-vertical dipping or strong scattering porduced by geological structure. The data in stations 14 and 3 present an interesting challenge, and thus will be subject to careful study before tomographic inversion.

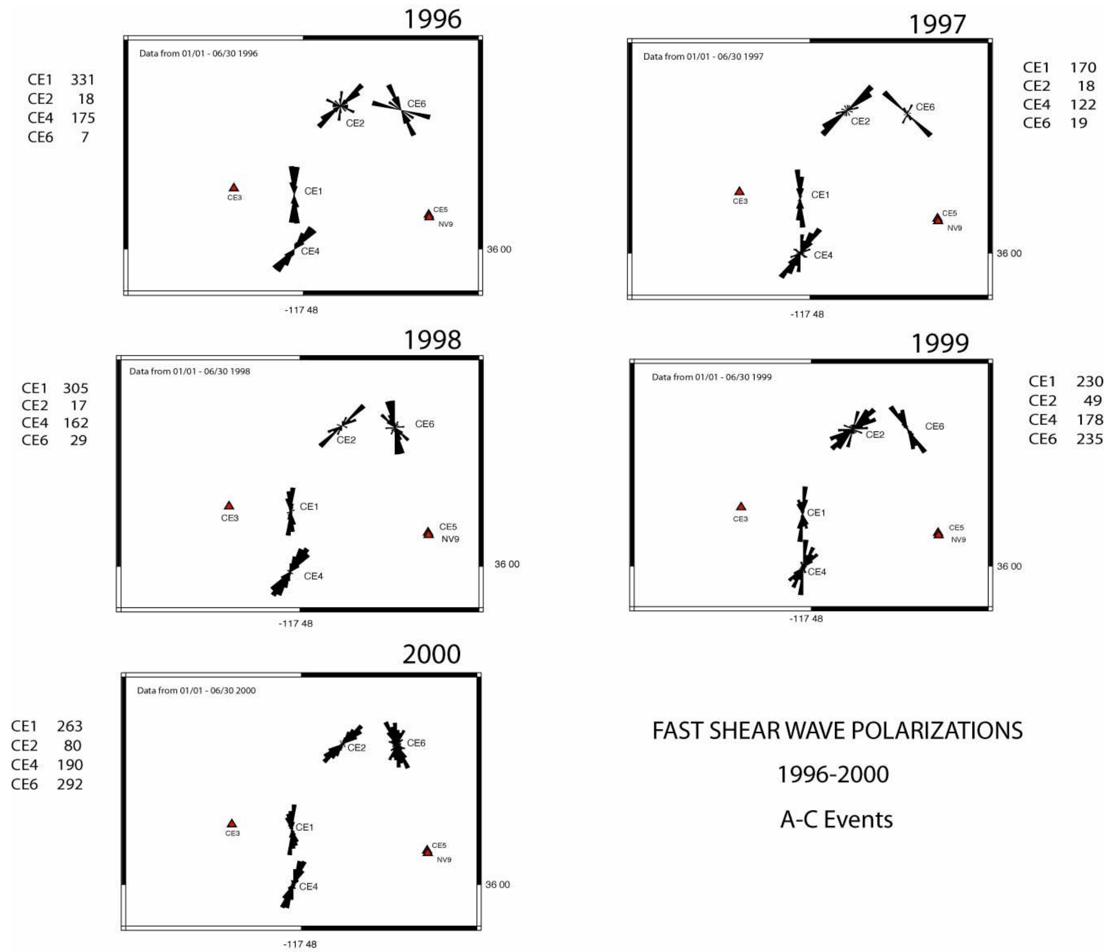

Figure 4. Rose diagrams for over 2,800 (quality A-C) events in the Coso reservoir from 1996-2000. The data are highly consistent and with the exception of the year 1999 (when changes due possibly to nearby production occurred), the rose diagrams are stable and the measurements consistent throughout.

C) Development and validation of the inversion package (3). This package consists of two parts:

a) Station-by-station inversion of the δt data to determine crack dip. The results will reflect local structure because accurate measurements of δt are limited to rays arriving at the station within the 35 degree vertical angle that constitutes the shear-wave window. Since at any given station ϕ and δt vary with azimuth in a predictable manner, the objective of this first inversion approach is to use the observed azimuthal variations of ϕ and δt to refine the crack direction determined before and accurately determine its dip.

b) Inversion of the crack density. The δt measurements corrected for crack dip will then be used to invert for crack density using groups of near stations and, if possible, the entire array. Because of the shear window limitation we anticipate that the density of ray crossings will be optimal only for some groups of nearby stations. The technique is however to be implemented for any distribution of sensors. The data for the inversion is first depicted in the form of maps showing the orientation of the fast shear wave with the corresponding time delay plotted at the epicenter of the event used to determine them (Figure 5).

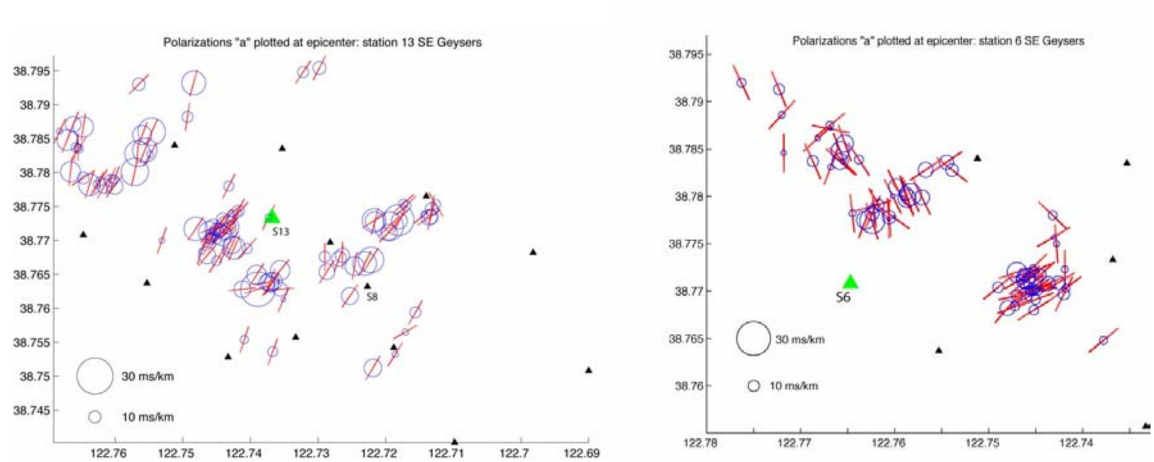

Figure 5. An example of mapping the polarization (short red bars) and delay times (circles) recorded at stations 13 and 6 (large green triangles) in SE Geysers. Any crack direction is plotted on the epicenter of the event from which it was determined, not on its actual location, which is of course, unknown. The small black triangles mark the locations of the rest of the stations in the array. Most data from station 13 are consistent with a fracture orientation N40-45E. To the southeast of the station a few polarizations are inconsistent with that direction. The distribution of time delays is not inconsistent with cracks dipping vertically or nearly so. The data set for station 6 (right) is more complex, showing strong azimuthal variation of polarization angle, which may be an indication of shallow dip of the crack system (60 degrees or less), or the presence of biplanar (more than one dominant direction) vertical cracks. The simulataneous inversion of these data will help resolve among these possibilities, as these maps provide strong constraints and useful hints.

Using both ϕ and delay δt for tomographic inversion of cracked reservoirs is a novel approach. With the high quality of data available we are in a unique position to produce a first-time result that will not only provide a close look at the 3D crack distribution in The Geysers and Coso, but may stimulate new research into seismic imaging of anisotropic/fractured media using observed space and time variations of ϕ and δt.

For instance, if understood correctly, spatial variations in ϕ and δt can be used to detect hidden or buried faults in seismically active zones, while understanding their time variations would make it possible to monitor production in crack-controlled reservoirs, understand the local stress field and monitor fluid migration. It would also be possible to use accurately detected time variations in ϕ and δt to better understand the focal mechanics of impending earthquakes, or even help forecast volcanic eruptions.

Major Reports published in FY 2001

Erten, D., M. Elkibbi and J.A. Rial (2001): Shear wave splitting and fracture patterns at The Geysers (California) geothermal field., Geothermal Res. Eng. Proceedings, 26th Workshop, p139-147.

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Vlahovic, G., Elkibbi, M., and J. A. Rial (2002). Temporal Variations of Fracture Directions and Fracture Densities in the Coso Geothermal Field from Analyses of Shear-wave Splitting, Geothermal Reservoir Engineering Proceedings, Twenty-seventh Workshop, Stanford University. SGP-TR-171 (In press).

Major Articles Published in FY 2001

Finished in 2001, to be published in 2002: Vlahovic, G., Elkibbi, M., and J. A. Rial (2002). Shear Wave Splitting and Reservoir Crack Characterization: Coso Geothermal Field. Submitted to *Jour. of Volcanology and Geothermal Research*.

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