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MODELING OF 3D CRACK ATTRIBUTES AND CRACK DENSITIES IN GEOTHERMAL RESERVOIRS

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ABSTRACT

We describe a Matlab-based, interactive, self-contained, graphics-oriented code to process shear-wave splitting data from microearthquakes in order to image the fractured subsurface in geothermal reservoirs. The code consists of three main modules: 1) data processing, 2) forward modeling, and 3) inverse modeling. The first module allows for rapid and precise measurement of fast S-wave polarizations and split delay times through the display of seismic waveforms, corresponding power spectra, and particle motion plots. The second module uses the basic horizontal transverse isotropy (HTI) model to simulate crack-induced anisotropy and computes S-wave polarizations, time delays, and synthetic seismograms. One or two crack sets can be simulated. Equal-area projection diagrams of polarizations and time delays, as well as rose diagrams for specific crack models are interactively generated. The third module permits inversion for crack geometries through interactive trial-and-error comparison of real and synthetic data. The operator optimizes the fit while observing the sequence of previous trial-and-error events. A fully automated complementary inversion program is being incorporated. It discretizes the medium into blocks each having its own HTI model.

INTRODUCTION

Seismic waveforms from microearthquakes recorded at The Geysers, CA show recurrent evidence of shear-wave splitting (cf. accompanying paper for an extensive description of the seismic data). The splitting phenomenon occurs when a shear-wave propagates through an anisotropic medium (e.g., an inherently isotropic body of rock which is fractured) and splits into a fast and a slow shear-wave. The polarization of the fast S-wave is shown to correlate with the strike and the dip of the main crack system traversed by the wave. The delay time between the arrivals of the fast and the slow shear-waves is proportional to the crack density (or the number of cracks per unit volume). These two properties are exceptionally appealing since they provide direct means of describing fracture characteristics in a methodical way and thus they help delineate major subsurface fluid flow directions through stress-aligned cracks. The information gathered on crack density also offers good prospects of depicting areas of increased permeability within the reservoir rock.

In order to efficiently process a large number of seismograms, we use a three-module Matlab-code for high-resolution measurement and analysis of the split parameters, namely: a) the polarization of the fast shear-wave and b) the time delay between the arrivals of the split shear-waves.

Three-component seismograms from many microearthquakes have been analyzed in the present study. These cover seismic events recorded in the NW and the SE Geysers geothermal fields in 1988, 1994, and 1999. Only events falling within the shear-wave window of each seismic station (i.e., within a calculated solid angle of 34.8^{o} from the vertical) are selected for analysis and subsurface crack modeling. Microearthquakes whose hypocenters are located outside the shear-wave window are better avoided since complex and undesirable wave interaction with the free surface are likely to occur.

At The Geysers, seismic stations recording only one chief polarization direction are common. Generally, the prevalent polarization reflects the strike of the main crack system in the neighborhood of the station. Some stations, however, display two or more equally important sets of polarizations, which require more careful handling of the data in order to satisfactorily model the crack system(s) involved (e.g., stations S5 and S14 in SE Geysers). We have also identified cases where minor polarization subsets are superimposed on the predominant polarization orientation (e.g., stations S2 and S6 in NW Geysers and stations S6, S8, and S10 in SE Geysers). As will be shown in this paper, these secondary polarizations may provide important clues on the geometry of subsurface fractures and should not be directly regarded as noise or outliers, especially if their distribution fits particular patterns discussed below.

The recording of a single polarization direction at a given seismic station can, in general, be accounted for by the presence of parallel vertical cracks. On the other hand, bimodal polarizations may reflect parallel dipping cracks or may indicate biplanar intersecting fractures, which are either vertical or dipping. Based on the configuration, azimuthal coverage, and distribution of shear-wave split parameters in equal-area projection plots, we propose to model the subsurface fracture geometry and crack density. Tomographic inversion for fracture strike, dip, and density is achieved through successive guided trial-and-error comparisons of real and synthetic fast S-wave polarizations and associated time delays.

SEISMIC DATA PROCESSING

The first module of the Matlab-code is mainly used for data processing. It permits the reading of seismic waveform data (three-component seismograms) as time series of normalized amplitudes. Corresponding power spectra are automatically computed and displayed through fully interactive GUI's (Graphic User Interface). The program also allows for windowing of the seismic records. Once the fast shear-wave arrival is identified, the associated ground particle motion can be traced over a selected interval of time in 2D and in 3D. The seismogram components may be rotated, which helps identifying the polarization of the fast S-wave in the horizontal plane, as well as depicting the timing of the split (cf. previous accompanying paper). The measured polarizations and time delays are automatically stored by the program in a file for subsequent use in the modeling and inversion process. The user can classify the split parameters according to measurement quality and add supplementary comments if need be.

FORWARD MODELING

The purpose of the second module is to permit the modeling of an anisotropic body as a medium with hexagonal symmetry. The horizontal transverse isotropy (HTI) model is used to simulate fracture patterns in an inherently isotropic material. Based on the stiffness matrix proposed by MacBeth (1999), which describes the 3D elastic properties of the fractured solid, the code simulates the effects of crack-induced anisotropy on wave propagation.

By evaluating the eigenvectors and eigenvalues of the Christoffel matrix, which depends on the medium stiffness and direction of wave propagation, the synthetic fast S-wave polarizations and associated synthetic time delays can be calculated for various HTI models (Babuska and Cara, 1991; Tsvankin, 2001). To allow for greater modeling capacity, the program was extended to simulate dipping crack sets as well as double (biplanar) fracture sets. There are no restrictions on the relationship between the fracture systems and one may choose to input any pair of crack attributes.

The user is initially prompted to input the matrix parameters of the undisturbed rock body (the mass density and the two lame constants mu and lambda), as well as the crack parameters defined as: crack strike, dip, density, aspect ratio, and percentage of fluid saturation. Synthetic seismograms, particle motion plots, polarization rose diagrams, and equal-area projections of polarizations and time delays may be generated once the frequency, back-azimuth, and angle of incidence of the rays have been selected. Abundant and diverse synthetic data for different crack models may be produced efficiently. The numerous synthetic examples enable us to better comprehend the relationship between the split parameter distribution and the corresponding anisotropy model, and consequently obtain beforehand a decent initial crack model guess during the inversion procedure.

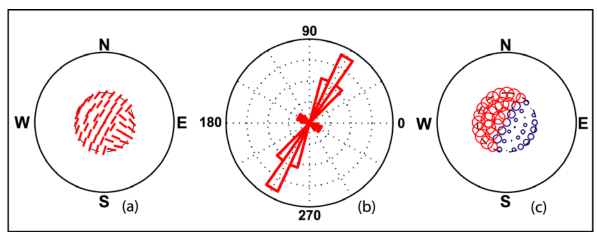

Fig.1. Forward synthetic modeling. The code calculates equal-area projections of theoretical polarizations (a), delay times (c),and the polarization rose diagram (b) for a selected model of cracks.The equal area projections depict the entire lower hemisphere underneath the station. The interior circle is the shear-wave window. The circle size in (c) is proportional to the predicted delay time at that point. Blue and red circles represent below and above average delays respectively. This model is of one crack system striking N30E and dipping to the SE at 70 deg. Crack density is 0.05 and crack aspect ratio is 0.01. Fracture saturation is 1.

A reasonably simple crack system to model is one characterized by a single set of vertical fractures. In this case, all fast S-wave polarizations, computed for vertical to nearly vertical rays, are uniform and parallel to the fracture strike regardless of back-azimuth and angle of incidence. On the other hand, when cracks are dipping, the distribution of polarization directions in equal-area plots becomes asymmetrical in a fashion that depends on fracture strike and amount of crack dip. Since NE polarizations are commonly recorded at The Geysers (cf. previous paper), we decide to model a fracture system striking N30E. The cracks however are not chosen to be exactly vertical; instead they are rather steeply dipping to the SE with an angle of 70^o from the horizontal. As shown in Figure 1a, not all synthetic polarizations in the shear-wave window are uniform and striking N30E, as would the case be for vertical fractures. In fact, a non-insignificant fraction of the calculated polarizations appears to be perpendicular to the remaining synthetic NE polarizations and the known fracture model. Hence, introducing crack dip creates clear irregularity and asymmetry within polarization and time delay distributions. As a result, the polarization shift is well-discerned in the rose diagram (Fig. 1b), which displays two sets of polarization directions even though the fracture model contains only a single crack system. It is therefore crucial not to analyze rose diagrams separately but rather in conjunction with equal-area plots, since the latter provide better indication as to whether dipping cracks or biplanar fractures are responsible for the occurrence of multiple polarization directions. As an example, **Figure 2** illustrates the forward modeling of biplanar

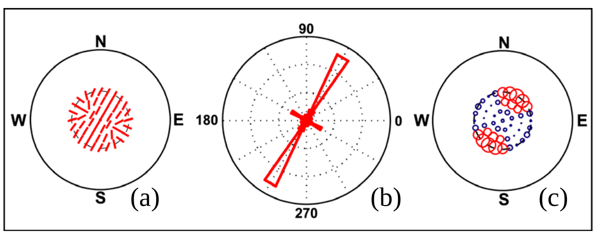

Fig. 2. Forward synthetic modeling. General description same as in Fig. 1. Diagram 2a shows the theoretical polarizations of the fast split shear-wave in an equal-area projection. Diagram 2b is a rose diagram of polarization orientations and diagram 2c is an equal-area plot of synthetic time delays. This model represents two orthogonal vertical crack systems. The first fracture set is oriented N30E, with a crack density of 0.05, and an aspect ratio of 0.1, while the second fracture set strikes N60W, with a crack density of 0.04 and an aspect ratio of 0.01. Fracture saturation is 1 for both systems.

fracture systems. The two crack sets are chosen to strike N30E and N60W respectively. Both have vertical dips for simplicity. As expected, the rose diagram shows two main polarization directions, which are parallel to the fracture strikes. However, it is interesting to note that although the rose diagrams in Figures 1b and 2b look almost identical, the associated equal-area plots show completely distinct distributions of polarizations, and therefore differente the effect of biplanar fractures from that of single dipping cracks on shear-wave behavior.

INVERSE MODELING

When fast S-wave polarizations are collected in rose diagrams, a common roughly N-to-NE main polarization orientation is observed in most stations at NW Geysers and in several stations at SE Geysers (e.g., stations S8, S11, and S13). The frequently encountered nearly NE polarizations are well-correlated with the state of stress in The Geysers area, which can be summarized as follows:

Based on earthquake first motion analysis, Bufe et al. (1981) showed that the vectors of maximum regional compression vary from approximately N30E to N at The Geysers. On the whole, the majority of the existing main Quaternary faults display offsets which are compatible with a generally N-S direction of maximum compression. The additional 30^o of eastward spread among the vectors of maximum compression may be accounted for by the local aspects of the terrain such as reservoir subsidence, differential strain buildup, and strain release along diverse faults and fault branches (McLaughlin, 1981). Hence, vertical faults and fractures in the area are expected to be open when striking parallel to the principal vectors of horizontal compression (i.e., N to N30E). The resulting open fracture and microfracture network produces theoretically a medium which is transversely isotropic and whose axis of symmetry is horizontal. Since the splitting theory suggests that fast S-waves are polarized parallel to the main fracture system they travel through, it is then only natural (and encouraging) for us to observe a wealth of polarization directions broadly falling within the N-NE range.

On the other hand, our abundant collection of split measurements show that fast S-wave polarizations do not exclusively strike N-to-NE at The Geysers. Polarizations are revealed to cover a larger range of orientations and vary from station to station. As a matter of fact, some stations show primarily NW polarizations, or secondary polarization subsets striking at about 90^o from the anticipated polarization orientation (e.g., stations S2 and S6 in NW Geysers and stations S4, S5, S6, S10, S12 and S14 in SE Geysers). Such findings do not necessarily always imply the presence of NW-striking fractures (cf. Fig. 1 on the effect of dipping cracks). However, it is necessary to clarify the reasons behind such counter-intuitive polarizations and explain the implications they convey on fracture geometry and density.

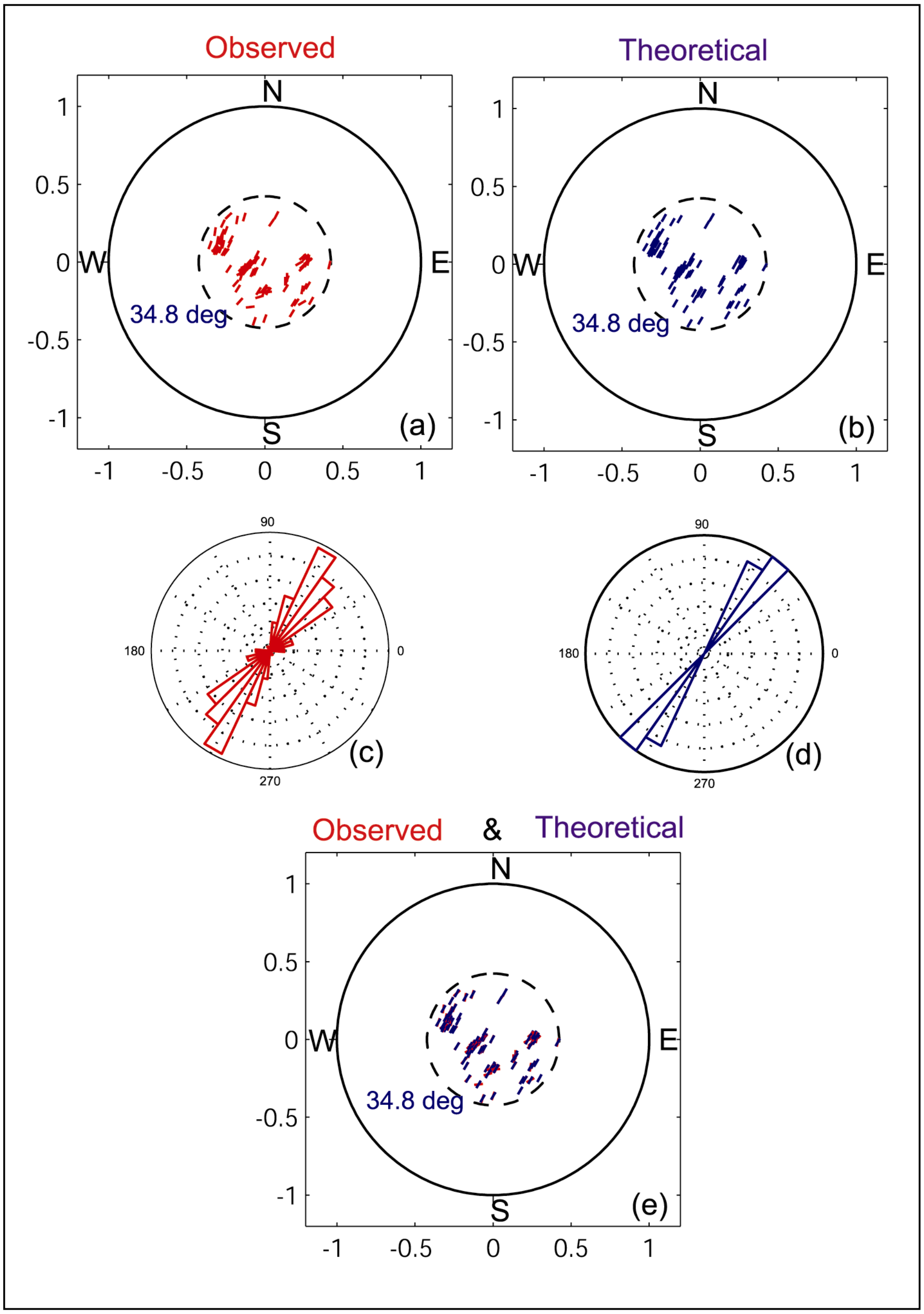

Fig. 3. *Inverse modeling. Example of polarization and delay time inversion using a one-crack set model (station S13 in SE Geysers). By trial-and-error, the user chooses a first crack model and refines it by tracking changes in the misfit history provided by the code. The best model obtained corresponds to a fracture system with a crack density of 0.037 and an aspect ratio of 0.1. The modeled fractures are vertical and strike N30E. (a) and (b) are equal-area plots of observed and predicted polarizations respectively while (e) shows the superposition of both. The limit of the shear-wave window corresponds to a calculated angle of 34.8^o. (c) and (d) are observed and theoretical polarization rose diagrams respectively. (f) and (g) are equal-area plots of observed and predicted time delays respectively while(h) shows the difference between observed and predicted delays. Green and purple circles indicate that observed time delays are respectively smaller and greater than synthetic delays. When the difference is less than ±2.1ms (smaller than the sampling interval), a little cross appears.*

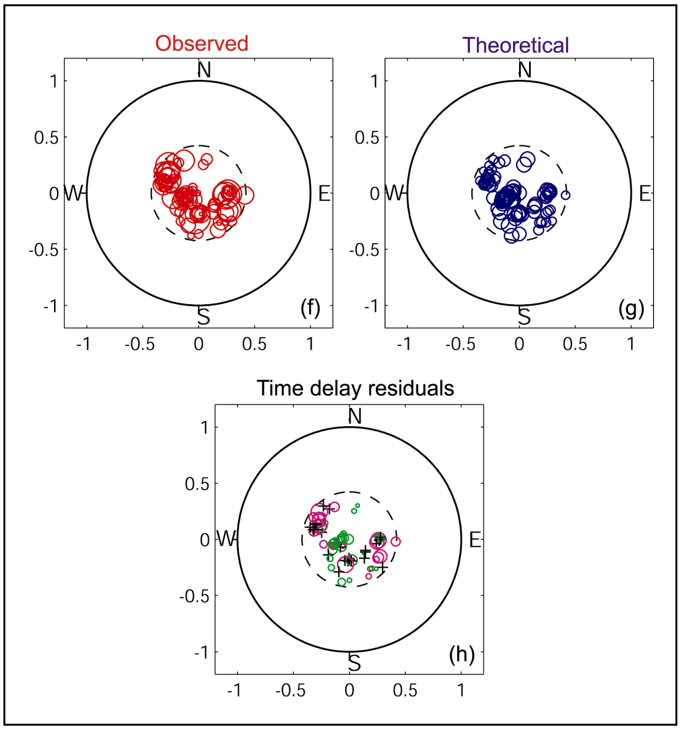

Fig. 3. (continued).

For that purpose, we make use of the already processed and stored shear-wave split parameters (module 1) and our previous results from forward modeling (module 2) in order to start inverting for various fracture models on a station-by-station basis (module 3). The program begins by comparing actual pairs of fast S-wave polarization and time delay distributions with theoretical values corresponding to a particular crack model selected as our first guess. Then, we try to refine the starting model with the aid of efficient and interactive GUI's. The initial modeling attempts make use of the trial-and-error technique but are soon guided by computations of the goodness of model fit, which indicate whether the best possible solution is being approached or not. The goal of this double inversion is to maximize the fit between the theoretical and observed polarizations and time delays, using a combination of visual and quantitative measures. Two examples of inversion are discussed in detail. The first example is illustrated in Figure 3. Station S13 from SE Geysers is one of the stations with the best azimuthal ray coverage. Almost all polarizations recorded are parallel to each other and strike uniformly to the NE. The simplest best-fitting anisotropy model, in this case, is one characterized by a single set of vertical cracks striking N30E with a crack density of 0.037. The fracture system modeled is thus parallel to the maximum compressive stress and in complete agreement with the regional tectonic setting as discussed earlier.

The second example (Fig. 4) shows more complex

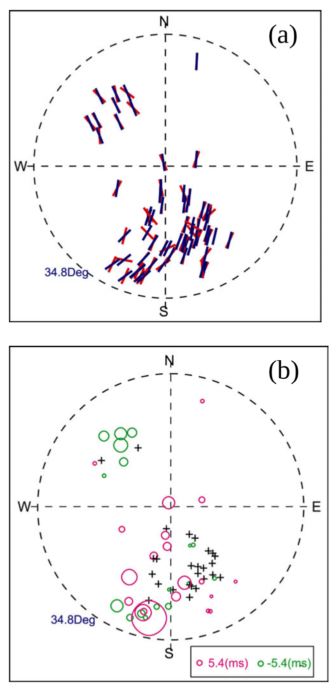

Figure. 4. Inverse modeling. Example of polarization and delay time inversion using a two-crack set model (Station S2 in NW Geysers). The equal-area projection (a) shows the superposition of observed (red)

and theoretical (blue) polarizations. Diagram (b) shows the difference between observed and predicted delays in equal-area projection. The best model obtained corresponds to a system of two cracks of equal densities of 0.068. The first crack set is vertical and strikes N30W with an aspect ratio of 0.01while the second crack set strikes N52E and is steeply dipping at 70^o NW with an aspect ratio of 0.1. (Cf. Fig.3h for a description of common details).

patterns in polarization orientations. Station S2 displays two distinct polarization sets, one is striking N30E while the other one is oriented N30W. The best fit was obtained with a model characterized by two steeply dipping fracture sets.

CONCLUSION

Using a fully-interactive three-module Matlab-based program, subsurface fracture patterns and fracture densities can be inverted for using shear-wave splitting parameters: the fast S-wave polarization and the time delay between the arrivals of the fast and slow shear-waves.

As demonstrated above, good ray azimuthal coverage is crucial to properly constrain proposed anisotropic models. This is due to the fact that polarization orientations and time delay distributions are sensitive to the details of fracture geometry and crack density. Thus, the better the data coverage is, the more unique and supported the fracture model becomes. Figure 5 represents our current 3D interpretation of subsurface crack geometry and distribution at the NW and SE Geysers. We are now working on refining it and complementing the Matlab-code with a fully automated inversion program by Weidlinger Associates. The latter discretizes the medium into blocks each having its own HTI model.

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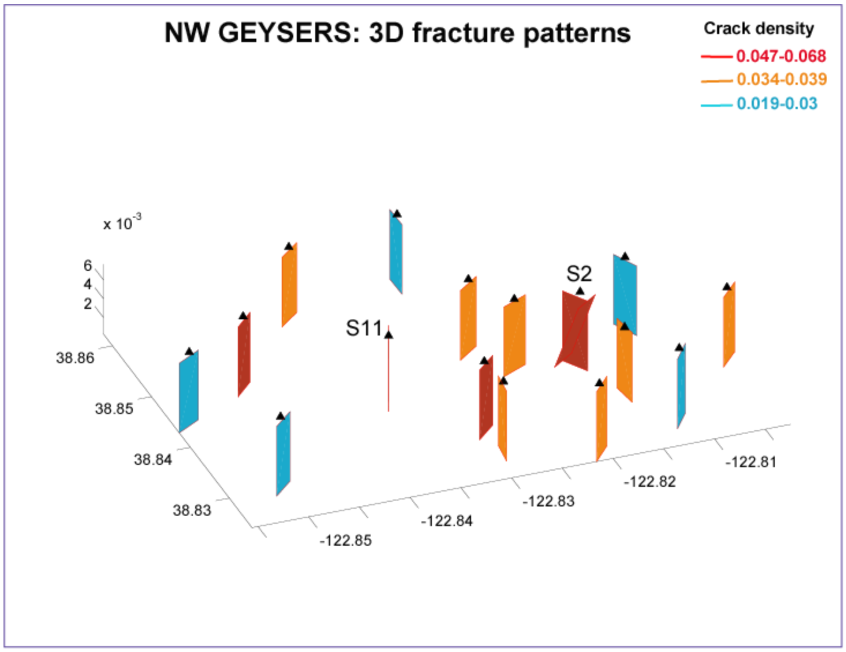

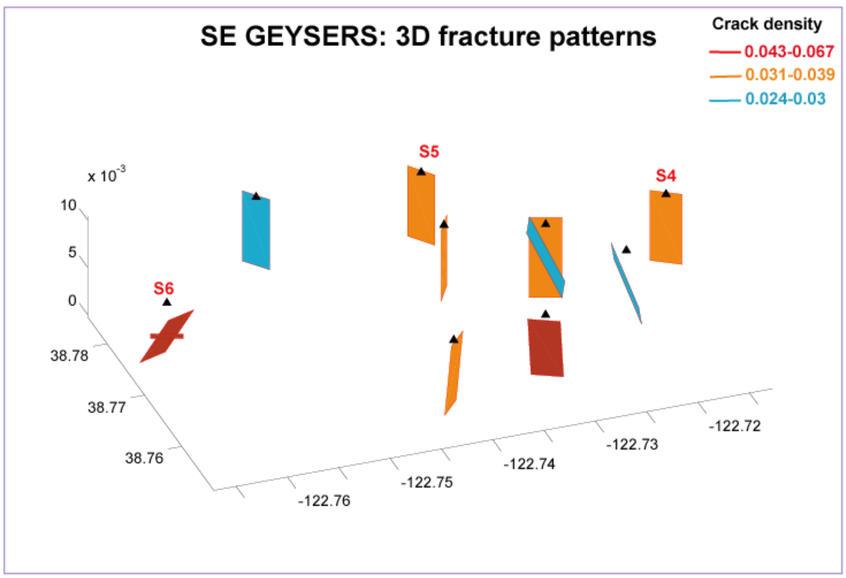

Fig. 5. A representation of our current 3D interpretation (based on the Matlab-code) of subsurface crack geometry and spatial distribution beneath each station at the NW and SE Geysers. Crack colors denote different crack densities. The shown width of individual cracks is a conservative one and extends for about 4 wavelengths (approximately 500m). Black triangles represent seismic stations.