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SHEAR-WAVE SPLITTING: AN EFFICIENT TOOL TO DETECT 3D FRACTURE PATTERNS AT THE GEYSERS, CA

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ABSTRACT

Shear-wave splitting, observed in microearthquake records at The NW and SE Geysers geothermal fields, CA has proved to be effective in the detection of subsurface crack orientations and crack densities. Crust anisotropy due to patterns of stress-aligned fractures causes approaching shear-waves to split into fast and slow arrivals. Within the shear-wave window of a given seismic station, the measured polarization angle of the fast S-wave is in theory parallel to the predominant crack orientation beneath the station. Exceptions, however, caused by complex geometry of the crack system have been discerned. The predominant polarization directions recorded in NW Geysers range between N-S and N60E. In SE Geysers, two major sets of polarization angles are detected. The first set varies from N-S to N80E while the second set strikes generally NW. The time delay between the arrival of the fast and the slow shear-wave is proportional to the crack density (or number of cracks per unit volume) along the ray-path. When normalized to the ray length, time delays at The Geysers range typically between 8 and 40 ms/km. The sizeable collection of high-resolution shear-wave splitting parameters we compiled (polarization direction and time delay pairs) is presented in this paper. In the accompanying paper, the data is used in the inversion for crack geometry and fracture distribution within the reservoir.

INTRODUCTION

The Geysers is the world's largest commercially exploited dry-steam vapor-dominated geothermal field. The Geysers reservoir is located northeast of the San Andreas Fault in the northern Coast Ranges of California about 150 km north of San Francisco. Two major northwest-trending right-lateral strike-slip faults related to the San Andreas fault system, the Collayomi and the local portion of the Mercuryville fault zones, appear to delineate the northeast and the southwest boundaries of the steam field. These faults along with related rock formations may be operating as impermeable walls enclosing the geothermal system (Mclaughlin, 1981; Goff et al., 1977). The Geysers geothermal field is situated within Mesozoic Franciscan assemblage rocks, which have been intruded by Quaternary silicic magmas. The steam reservoir is mainly composed of fractured metagraywacke and intrusive rocks, and is capped by Franciscan greenstone mélanges and unfractured metagraywacke (Thompson, 1992). The felsite intrusion most likely underlies the entire reservoir and has greatly contributed to enhancing its reservoir-rock qualities (Romero et al., 1994). Strike-slip faulting at The Geysers has resulted in a pull-apart block structure with a regional northeast-southwest maximum horizontal compressive stress along whose direction most local fracture systems have developed (e.g., Romero et al., 1995; Thompson, 1992; Majer et al., 1988).

Such stress-aligned fractures produce crustal anisotropy, which causes propagating shear-waves to split into two linearly polarized shear-waves propagating at two different speeds through the medium. The leading (fast) shear-wave becomes polarized parallel to the predominant local fracture orientation while the slow shear-wave is normally polarized perpendicular to it. The time delay between the arrival of the fast and the slow shear-wave (typically a few tens of milliseconds) has been recognized to be proportional to the crack density or number of cracks per unit volume within the rock body traversed by the seismic wave (Hudson, 1981; Crampin 1987; Crampin and Lovell, 1991). These properties can be exploited to detect and image the geometry of subsurface fracture systems as well as to estimate crack intensity and permeability anisotropy within geothermal reservoirs. In geothermal fields, the local seismicity (natural or induced) is the most common source of shear-waves.

SEISMIC DATASETS

The seismic waveforms analyzed for shear-wave splitting were recorded by two seismic arrays deployed in the NW and SE Geysers regions. About two years worth of data (1988 and 1994) from NW Geysers and one month worth of data (March 1999) from SE Geysers have been made available to us by the Lawrence Berkeley National Laboratory (LBNL). The data shows that the NW Geysers area is an active seismic zone with an average of 17 microearthquakes per day. The depth of events is typically less than 5 km with fewer regional events extending below 6 km. Most of the earthquake activity is concentrated in the Coldwater Creek steam field (CCSF), which overlaps the production area (Fig. 1). The data used for the present study was collected by a 16-station (S1 to S16), digital three-component network operated by LBNL. All 16 geophones recorded at 400 samples per second and were buried at about 30 meters below the ground surface. The SE Geysers area is also a seismically active one with an average of 20 microearthquakes per day during March of 1999. Events are generally shallower than 4 km. The data analyzed was recorded by a 12-station (S1 to S14; S7 and S9 being non-functional), three-component, high frequency (480 samples per second) digital network managed by LBNL. All 12 stations had geophones on the ground surface, which did not perceptibly affect the quality of the seismic data in comparison with the NW buried instruments, as noise levels were often relatively low.

SHEAR-WAVE SPLITTING MEASUREMENTS

Ideally, in an anisotropic material, the fast and the slow split shear-waves are polarized perpendicular to each other, with the slow phase arriving a few tens of milliseconds later. Polarization diagrams (also known as particle motion plots) are used to detect the splitting and the marked switch in polarity of the two arrivals, which provides the clearest indication of medium anisotropy.

It is our general assumption that splitting is induced by the presence of oriented fractures in an otherwise isotropic medium. Typically, the angle of the fast S-wave polarization ϕ is measured with relative errors not exceeding 10%.

The time delay δt between the arrivals of the fast and the slow shear-waves is measured directly after the seismogram is rotated to orient the fast and the slow waves along the instrument horizontal components. This operation cleanly decouples the two shear-wave arrivals allowing for direct and accurate measurement of the time delay. Occasionally, rotation of all three components is performed to align the vertical component with the approaching ray. The smallest time intervals or time delays, which can be measured in NW and SE Geysers, are respectively 2.5 ms (sampling rate = 400 samples/sec) and 2.08 ms (sampling rate = 480 samples/sec). Time delays are normalized to the length of the ray-path, which is presumed to be entirely fractured. This assumption is reasonable given that typical event depth does not generally exceed 5 km. Since delay measurements are directly related to the cracking intensity, they can be used to identify regions of high permeability, to monitor changes in fracture density spatially and temporally, as well as to detect localized fluid migration within the geothermal field.

An important constraint in shear-wave splitting analysis is to limit the data to rays traveling within the shear-wave window of various seismic stations. This window represents a cone defined by a critical angle $i_c = \sin^{-1}(\beta/\alpha)$, where α and β are the P-wave and S-wave surface velocities, respectively. For angles of incidence greater than i_c, shear-waves interact strongly with the free surface, distorting the incoming waveform (Booth and Crampin, 1985). For a half-space with a typical Poisson's ratio of 0.25, the calculated critical angle (as measured from the vertical) is equal to 35^o. At The Geysers, however, this angle may be increased to 45^o due to the presence of a shallow low-velocity layer.

At each receiver, polarization and time delay data are collected in rose diagrams and equal-area projection plots. The numerous measurements made per station allow for a statistically robust determination of the preferred polarization direction per station. A complication arises in NW Geysers where seismic stations were installed in wells, about 30 meters downhole. The orientation of the geophone horizontal (North and East) components may have rotated while lowering the instruments into the boreholes. Consequently, the North and East components of the receivers do not necessarily coincide with true geographic North and East. Hence, geophone orientation corrections had to be performed on all 16 stations in NW Geysers by comparing predicted and observed P-wave polarizations from an average of 50 microearthquakes surrounding each station. In SE Geysers, geophones are on the ground surface and fast S-wave polarizations were read directly from horizontal particle motion plots.

In the last few years, we have collected and analyzed shear-wave splitting parameters from thousands of seismograms from The Geysers and Coso geothermal fields in California. As a result, we have accumulated what is arguably the world's most complete set of high quality shear-wave splitting observations. Our experience with the data suggests that automatic picking of polarization directions and time delays without human intervention is unreliable. This is because of the great variability and diversity of the wave patterns, which results from the interaction of shear-waves with complexly cracked rock bodies. The measurement process uses computational GUI's (graphic user interface) that automate measurements through a series of user-friendly interactive devices and multidimensional displays. Human supervision and intervention is however indispensable to carefully investigate ambiguous records, especially while measuring time delays.

SHEAR-WAVE SPLITTING RESULTS

In this paper, we present our final compilation of shear-wave splitting results from NW and SE Geysers in terms of fast shear-wave polarizations and time delays. Initially, the analysis rests on three reasonable a priori assumptions which are summarized as follows: 1) aligned cracks are the sole source of anisotropy, 2) anisotropy producing cracks are wet and vertical, or steeply dipping, and 3) observed polarizations of fast S-waves at a given station reflect the crack orientation in the neighborhood of that station (in our case, a hemisphere with a radius of about 500-600 m, which corresponds to roughly 4 wavelengths). Assumptions 1) and 3) should be true for the method to work. So far, we have not encountered compelling evidence against these two assumptions. Hypothesis 2) is in agreement with the known local tectonics. However, as will be described later (cf. accompanying paper), there is evidence that under some stations cracks may dip at shallower angles.

NW Geysers

Fast shear-wave polarization directions

Microearthquakes from NW Geysers recorded in 1988 and 1994 have been analyzed. For the purpose of this study, we select the best ϕ and δt measurements from NW and SE Geysers, which correspond to high signal-to-noise ratio seismograms displaying a distinct shear-wave split event and a reasonably linear horizontal particle motion. Estimated errors do not generally exceed 3^o and 2.5 ms for the ϕ and δt measurements respectively. Figure 1 shows rose diagrams of fast S-wave polarization directions for each station in NW Geysers. The bin size in the rose diagrams is 10^o and the length of each bin is proportional to the number of polarizations within it. The predominant ϕ directions vary between N-S and N60E, which is reasonably consistent with prevalent NNE crack directions measured in a metagraywacke core (Nielson et al., 1991). There is generally one main polarization orientation particular to each seismic station and fast shear-wave polarization directions are often comparable among all stations, with the exception of stations S1, S9, and S16 displaying mainly N-S and NNW polarizations. Among the stations showing a clear dominant polarization direction and very little scatter, are stations S2 and S6. However, in addition to the prevalent polarization orientation, the two stations show a significant subset of polarizations striking roughly NW almost perpendicularly to the main set. It is interesting to note that in both cases, the smaller polarization subset strikes parallel to an existing adjacent fault. As numerous readings were made for stations S2 and S6 (64 and 120 readings respectively; Fig. 1), the secondary polarization subsets have probably real implications on the local anisotropy patterns and are not artifacts generated by a limited dataset.

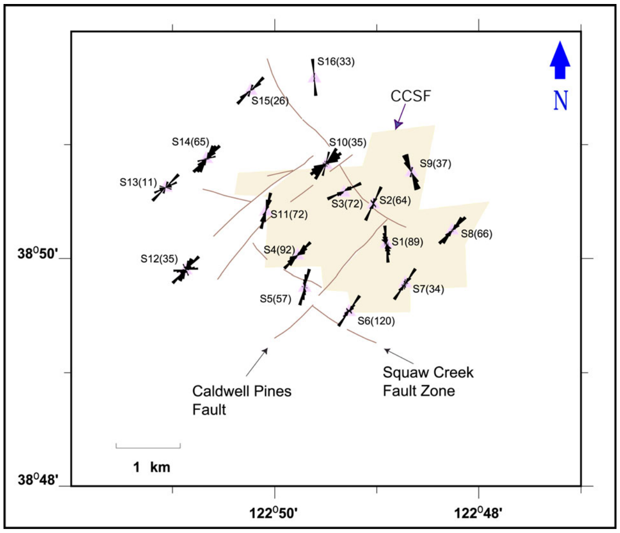

Fig. 1. Rose diagrams showing fast shear-wave polarization directions as recorded by each station in NW Geysers. Most stations display a predominant ϕ direction ranging between N and N60E. The station names along with the number of events (between parentheses) used to generate the rose diagrams are indicated. The extent of the Coldwater Creek Steam Field (CCSF) is delimited by the shaded beige area.

Equal-area projection plots of observed fast S-wave polarizations falling within and at the margins of the shear-wave window are shown in Figure 2. Most stations exhibit generally consistent polarizations within an incident angle of 45^o (especially stations S3, S4, S5, S7, S8, S9, S11, and S16). More complex polarization patterns suggest that the seemingly inconsistent secondary polarization subsets come from specific ranges of azimuths and incident angles. For instance, station S2 recorded two distinct polarization sets striking around N30^{o}E and N30^{o}W respectively. The latter direction corresponds to the minor polarization subset, which forms a northwesterly-trending linear stretch covering a narrow azimuthal range principally within the NW quadrant. On the other hand, station S6 exhibits roughly NE and NW polarization directions. The minor NW-striking set does not define a linear stretch as with station S2, but it appears to be mainly confined to northeastern azimuths of the equal-area projection plot. Station S5 also displays a minor WNW polarization subset parallel to a nearby fault, and in this case, the polarizations are limited to the northern edge of the shear-wave window.

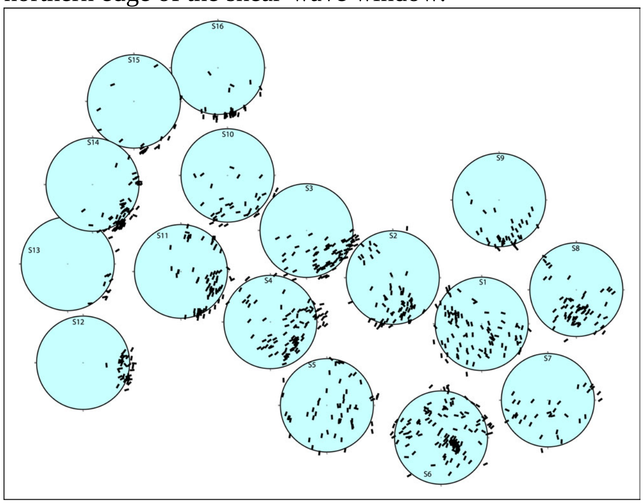

Fig. 2. Equal-area projection plots of polarizations (ϕ) (NW Geysers). The circles correspond to an incident angle of 45 degrees. Ray azimuthal coverage varies from excellent (e.g., S1, S4, S6) to poor (S12 and S13).

Time delays

Normalized delays typically range from 8 to 40 ms/km (Fig. 3) and reflect the overall crack density

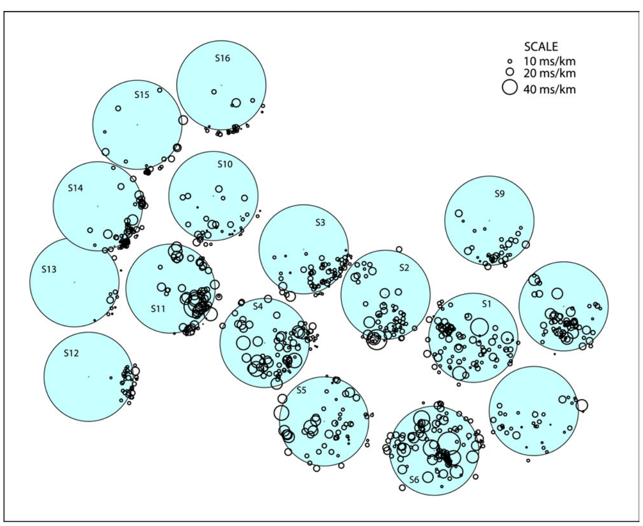

Fig. 3. Equal-area projection plots of normalized δt measurements (NW Geysers). These vary mostly from 8 to 40 ms/km. Circles correspond to an incident angle of 45 degrees.

along the ray-path (crack density e= Na^3/v where N is the number of cracks of radius a in a rock volume v; Crampin, 1993). In comparison, time delays recorded at the Coso geothermal field, CA, cover a narrower range (4 to 17 ms/km; Vlahovic et al., 2002).

In NW Geysers, spatial patterns of time delay variations are rather subtle. However, equal-area projection plots and calculated mean time delays suggest that stations S4, S5, S6, and S11 located along the Squaw Creek Fault Zone may have high mean fracture densities. These four stations cover the southwestern edge of the steam field and show mean δt readings greater than 13.3 ms/km. Stations S1, S2, and S8 also show medium to high average time delays (mean δt greater than 11.7 ms/km). In general, variations in time delays may be related to: 1) an increase/decrease in the number of cracks per unit volume along the ray-path, 2) changes in the magnitude of the local maximum horizontal compressive stress, 3) variations in fracture width, 4) changes in crack aspect-ratio, and/or 5) the filling/emptying of fractures from water or fluids.

<u>SE Geysers</u>

Fast shear-wave polarization directions

Microearthquake epicenters from March of 1999 define scattered clusters within the geothermal field. Locations of clusters are probably indicative of the production/ injection well distribution. Although the data comes from a relatively limited time span, numerous events have been analyzed for shear-wave splitting. Despite the fact that geophones are surface instruments, many good quality seismograms were recorded with high signal-to-noise ratios along with robust and impulsive S-wave arrivals. It should be pointed out that the less uniform the azimuthal distribution of the readings is, the more challenging the detection of a reliable crack orientation becomes. This is especially critical with limited datasets, such as those provided by stations S1, S2, and S3.

Figure 4 shows that in contrast to NW Geysers, the SE Geysers stations have two predominant fast S-wave polarization directions. The first polarization set varies from N-S to N80E while the second set strikes generally NW. These orientations are generally coherent with previous results obtained by Evans et al. (1995). Most stations show one prevalent polarization strike, with the exception of stations S1, S2, S3, S5 and S14. While stations S4, S11, S12, and S13 exhibit a unique clearly principal fast S-wave polarization, other stations (S6, S8, and S10) possess minor polarization subsets in addition to the chief polarization direction. The adjacent stations S10 and S11 show almost perpendicular directions of

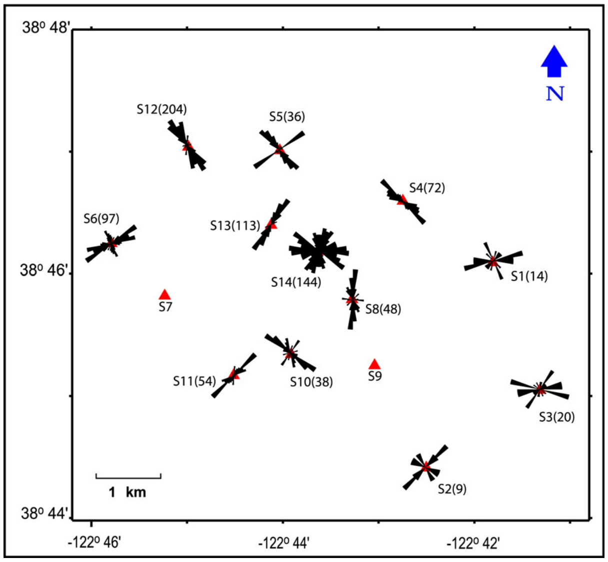

Fig. 4. Rose diagrams showing fast shear-wave polarization directions as recorded by each station in SE Geysers. Two sets of polarizations are identified: one varies from N to N80E, and the other strikes mainly NW. The station names and the number of events (between parentheses) used to generate the rose diagrams are indicated.

polarization, which may indicate that inferred crack orientations in the neighborhood of each station could be different.

Equal-area projection plots (Fig. 5) can be used to spatially separate out apparently conflicting polarization readings. Station S6, for instance, shows that the subset of NNW polarizations do not come from random locations, but are mainly concentrated

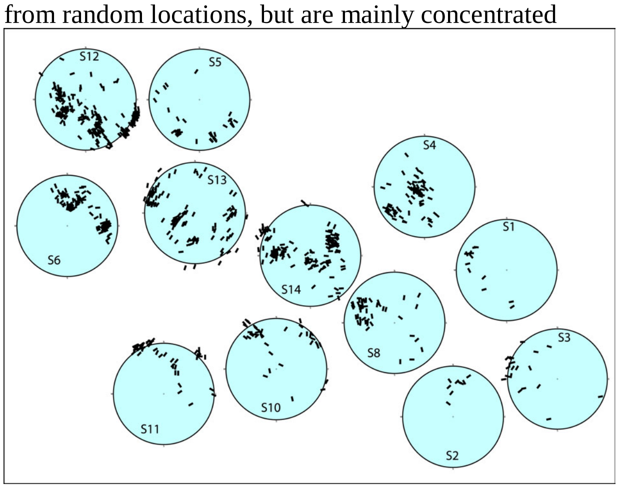

Fig. 5. Equal-area projection plots of polarizations (ϕ) (SE Geysers). The circles correspond to an incident angle of 45 degrees. Ray azimuthal coverage varies from excellent (e.g., stations S12 and S13) to poor (stations S1 and S2).

within most northern azimuths. Station S14, whose rose diagram seems initially intricate, shows a much simpler scenario of systematic polarization distribution in equal-area projection. Two equally predominant polarization directions (one roughly NE, the other WNW) occupy respectively the southwestern and northeastern halves of the equal-area plot, with minor overlap (Fig. 5).

Time delays

Normalized time delays recorded in SE Geysers are comparable to those in NW Geysers and vary between 8 and 40 ms/km essentially (Fig. 6). The highest mean time delays (greater than 13.4 ms/km) are recorded by the stations within the eastern part of the field (S1, S2, S3, S4, and S8). Such high δt measurements suggest that the fracture intensity in this area may on average be higher than beneath western stations.

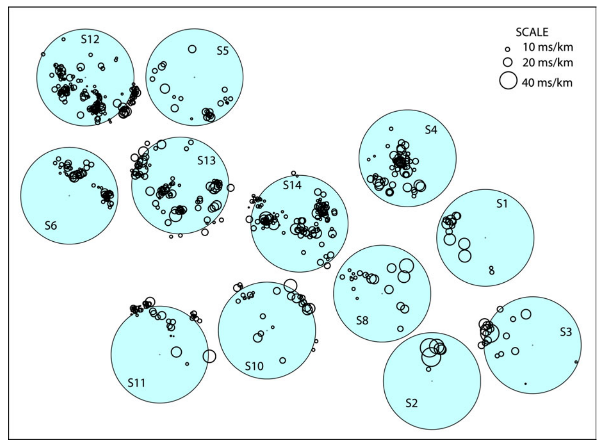

Fig. 6. Equal-area projection plots of normalized time delays δt measurements (SE Geysers). These typically vary from 8 to 40 ms/km. The circles correspond to an incident angle of 45 degrees.

DISCUSSION AND CONCLUSIONS

The most common fast S-wave polarizations in NW Geysers strike generally NE, which is consistent with parallel micro-fractures held open by the regional principal horizontal compressive stress. In fact, the latter ranges from N15E (Oppenheimer, 1986) to NE (Mount and Suppe, 1992; Romero et al., 1995). Evans et al. (1995) propose an additional explanation for common NE polarizations at the NW and SE extremities of the steam field. They suggest that as the felsite was intruded, an uplifted region above it had its margins tangentially fractured in a manner to produce the observed NE polarization directions. The polarization orientations recorded in NW Geysers also match main fracture strikes in geologic core samples (Nielson et al., 1991).

Fast S-wave polarizations recorded in SE Geysers present more variability among stations. Both NE and NW polarizations are equally represented. Recent tracer injection tests showed that pumped fluids in the SE Geysers area flowed along NE-SW and NW-SE paths (Adams et al., 2000). Thus, the inferred fracture patterns from these flow directions appear to be indeed consistent with the two main fast S-wave polarization angles recorded as shown in Figure 4.

Since NE and NW polarizations are concurrent at The Geysers, the extensive dilatancy anisotropy (EDA) hypothesis (Crampin, 1978) cannot alone explain the variety of ϕ readings. The EDA hypothesis states that patterns of aligned vertical micro-fractures parallel to the principal compressive stress control crust anisotropy. The presence of NW polarizations within the field calls for another justification. As mentioned earlier, subsets of NW striking polarizations are frequently parallel to adjacent faults (e.g., the Squaw Creek fault zone, Fig. 1). Hence, recorded shear-waves may have also experienced anisotropy from fractures produced by fault-shear effects and held open by high pore fluid pressure due to injection activities (Crampin and Booth, 1989; Angerer et al., 2000, a, b). Polarization orientations seemingly inconsistent with the regional tectonic setting may also be explained by the presence of dipping cracks, multiple fractures, or even by an anomalous thick low-velocity weathered surface layer. The latter would generate perpendicular particle motion plots (Booth and Crampin, 1985), at times difficult to distinguish from anisotropy-induced shear-wave splitting generated by EDA cracks. Slack et al. (1993) remarked that the near-surface weathering layer may behave like an anisotropic medium. It could imprint propagating S-waves with an anisotropic signature and distort split patterns associated with the underlying actual fractured medium.

The literature suggests that the predominant strike of the last fracture system traversed by the wave essentially controls the fast S-wave polarization, regardless of its polarization at the source (Crampin, 1981). For this to work, the thickness of the last cracked layer needs to be at least 500-600 m, which at the Geysers corresponds to roughly 4 seismic shear wavelengths as was mentioned earlier. In the simple case of vertical wet cracks, all S-wave polarization directions in the shear-wave window are expected to be parallel to the main fracture strike in the environs of the seismic station (Crampin, 1993). This scenario appears to be widely applicable to The Geysers stations exhibiting a single main polarization orientation. Ongoing inversion work for crack strike and dip distribution will validate these findings. On the other hand, an adequate justification for the presence of two or more polarization directions per station is more challenging to obtain. Our next objective is therefore to determine whether different polarization orientations reflect two or multiple sets of cracks beneath the station, or whether they reflect only one set of dipping fractures (Crampin, 1993). Results from forward and inverse modeling are the object of the accompanying paper.

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