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Shear-wave splitting from local earthquakes at The Geysers geothermal field, California

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Abstract. Shear-wave splitting from local microearthquakes recorded in The Geysers geothermal field shows that seismic anisotropy is distributed in a complex geographic pattern. At stations within about 2 km of northwest-striking regional faults, the fast polarization direction is parallel to those faults. The geothermal field, lying between two such faults, has both northwest and northeast fast polarization directions, often at the same station. This pattern suggests at least two causes of splitting: (1) extensive dilatancy anisotropy (EDA) and (2) fault-produced fractures or rock fabric. The observed anisotropy may derive from the upper 1.5 km of the crust, averaging 4% there, or it may be heterogeneously distributed throughout the upper 5 km. Fast polarization directions coincide with fracture directions inferred from borehole data for one of the youngest rock types in the region, a felsite pluton of about 1 Ma, and with injectate pathways inferred from microseismicity and geochemistry. Including in reservoir models a permeability anisotropy with a pattern similar to seismic anisotropy may help in optimizing fluid injection and steam recovery.

Introduction

The Geysers area is the largest commercially exploited vapor-dominated geothermal field in the world [*McLaughlin*, 1981]. It lies in McLaughlin's "central belt" of the Franciscan assemblage (late Jurassic to late Cretaceous melanges and broken formations of metamorphosed sandstone, argillite, basaltic rocks, chert, and exotic blocks). The area is complexly faulted by Franciscan thrust faults and Quaternary strike-slip and dip-slip faults, with extensive secondary ophiolite and serpentinite along many of these faults. Great Valley sequence rocks are present locally [*McLaughlin*, 1981]. The geothermal field is underlain by a ~1 Ma "felsite" pluton composed of at least three silicic to intermediate rock types [*Hulen and Nielson*, 1993]. The felsite appears to be responsible for atypically high porosity in the overlying rocks through (1) intrusion-induced tensional fracturing, (2) hydrothermal rock fracturing, and (3) mineral dissolution. The reservoir is mostly in Franciscan rocks and the upper 1 km of the felsite, both of which show extensive hydrothermal alteration. The felsite is approximately coeval with the Clear Lake Volcanics (<2.1 Ma), lying within and east of the geothermal field, and appears to be cogenetic with some of them.

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In April, 1991, *Foulger et al.* [1993] operated a portable seismograph network in The Geysers region. Fifteen high-quality digital seismographs recorded continuously at 100 samples per second from 2-Hz three-component L-22™ geophones. Several thousand shallow microearthquakes (0.5 to 4 km below sea level), were recorded. Most were within the boundaries of the geothermal field.

Steam pressure has decreased rapidly since 1987 [*Beall*, 1993]. This decline has been mitigated by injecting water, with the greatest benefit derived at injection sites having high permeability, low steam pressure, and high reservoir superheat.

In this paper, we evaluate upper-crustal seismic anisotropy to infer permeability anisotropy. To the extent that seismic anisotropy reflects fracture orientation or other rock fabric, this information can help in designing optimal programs of injection to augment steam production. Most local earthquakes at The Geysers appear to be induced by production or injection [*Oppenheimer*, 1986; *Stark*, 1992]. Fracture data also will help in understanding earthquake induction and evaluating any hazard the earthquakes may pose.

Data and Method

We measured shear-wave splitting on 173 three-component records from 119 microearthquakes. These records are well within the "shear-wave window", with incidence angles less than the critical angle at the surface.

We inspected horizontal-plane particle-motion plots for linear *S* motion followed by elliptical or more complex motion [e.g., *Zhang and Schwartz*, 1994]. Records were first processed to remove the acausal effects of anti-alias filtering in the IRIS/PASSCAL recorders (J. Fowler, personal communication, 1993) and then resampled to 800 samples per second using the FFT algorithm (IRIS/PASSCAL records are rigorously unaliased). Both proved helpful in identifying and measuring the fast polarization direction, ϕ, and arrival times of the fast shear wave, t_{S1}, and the slow shear wave, t_{S2}.

We analysed all records with the PITSA software system [*Scherbaum and Johnson*, 1993], first using a horizontal-plane particle-motion plot to determine ϕ, then rotating the horizontal seismograms to this direction, and finally timing *S1* and *S2*. Each of these three measurements, ϕ, t_{S1}, t_{S2}, was characterized subjectively as "Excellent", "Good", or "Marginal". Examples of each grade of record are shown in Figure 1. About 69% of the records—an average of one per event—had a pick triple that was entirely at or above "Marginal", while 24% of the records were entirely "Excellent" or "Good". The vertical components of "Good" and "Excellent" records offer little evidence of an *S*-to-*P* converted precursor phase. (The lower example in Figure 1*a* has a noticeable vertical phase, but it lags *S2* by about 0.02 s.) In contrast, "Marginal" records, including those in Figure 1*c*, may be contaminated by precursor phases. We disregard the vertical components of all records, and emphasize "Good" and "Excellent" picks in the discussion that follows.

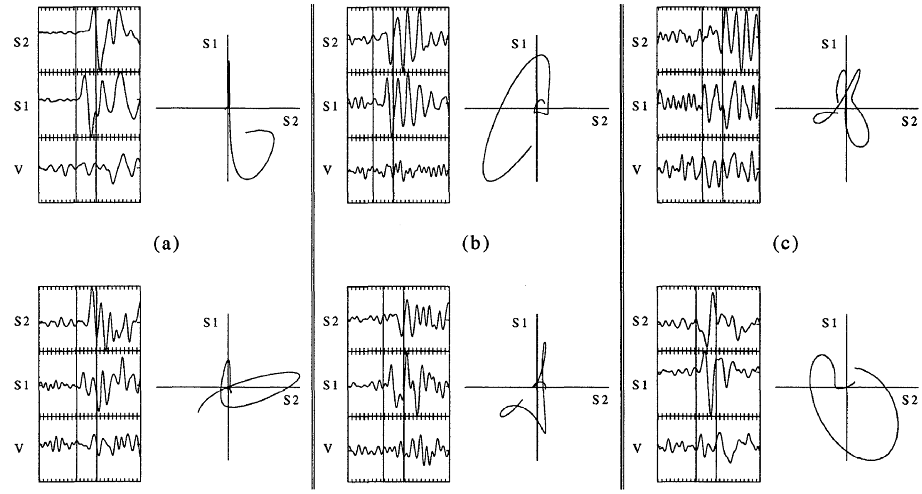

Figure 1. Seismogram examples, with horizontal components rotated to the measured *S1* direction. A 0.5-s window centered near *S1* is shown; relative amplitudes between components are correct. Horizontal particle-motion plots are for the 0.1-s subwindow between the vertical lines. (*a*) Examples of clear splitting (pick triple all "Excellent"). (*b*) Examples of "Good" records. (*c*) Examples of "Marginal" records.

Results

The similarities in Figures 1*a* and 1*b* between *S1* and *S2* waveforms is consistent with anisotropy but not in general with multiple-scattering models. However, systematic scattering effects cannot be ruled out as the source of observed particle motions. High-angle layering due to imbricate thrusts faults and their associated ultramafic rocks might produce multipathing and waveform complexity. A low-velocity surface layer can produce cruciform particle motions that could be misinterpreted as anisotropy [*Booth and Crampin*, 1985]. We proceed upon the assumption that these are anisotropy-induced split shear waves, at least in enough of the "Good" and "Excellent" records to permit meaningful interpretations.

Figure 2 is a map of observed ϕ. We noted no correspondence of ϕ with station-to-epicenter azimuth, so these are not simply measurements of S_V and S_H directions. The pattern of polarizations is complex, but northeast and northwest ϕ are most common (Figure 3). The principal compressive stress, σ_1, in this region lies between northeast [*Mount and Suppe*, 1992] and a more northerly azimuth near 15° (inferred from minimum compressive stress $\sigma_3 \approx 105°$ [*Oppenheimer*, 1986]). Hence, ϕ directions are not in simple agreement with the extensive dilatancy anisotropy (EDA) hypothesis of *Crampin* [1978], which predicts ϕ parallel to σ_1. (The EDA hypothesis is that wave-speed anisotropy in the crust is dominated by subvertical microcracks striking parallel to σ_1. Subvertical rays from local earthquakes are approximately in the plane of the cracks, yielding shear-wave splitting observable in horizontal particle motions.)

On the contrary, ϕ near the Mercuryville fault zone are mostly northwest—fault-parallel. The Mercuryville fault zone is a thrust with at least local Quaternary strike-slip motion

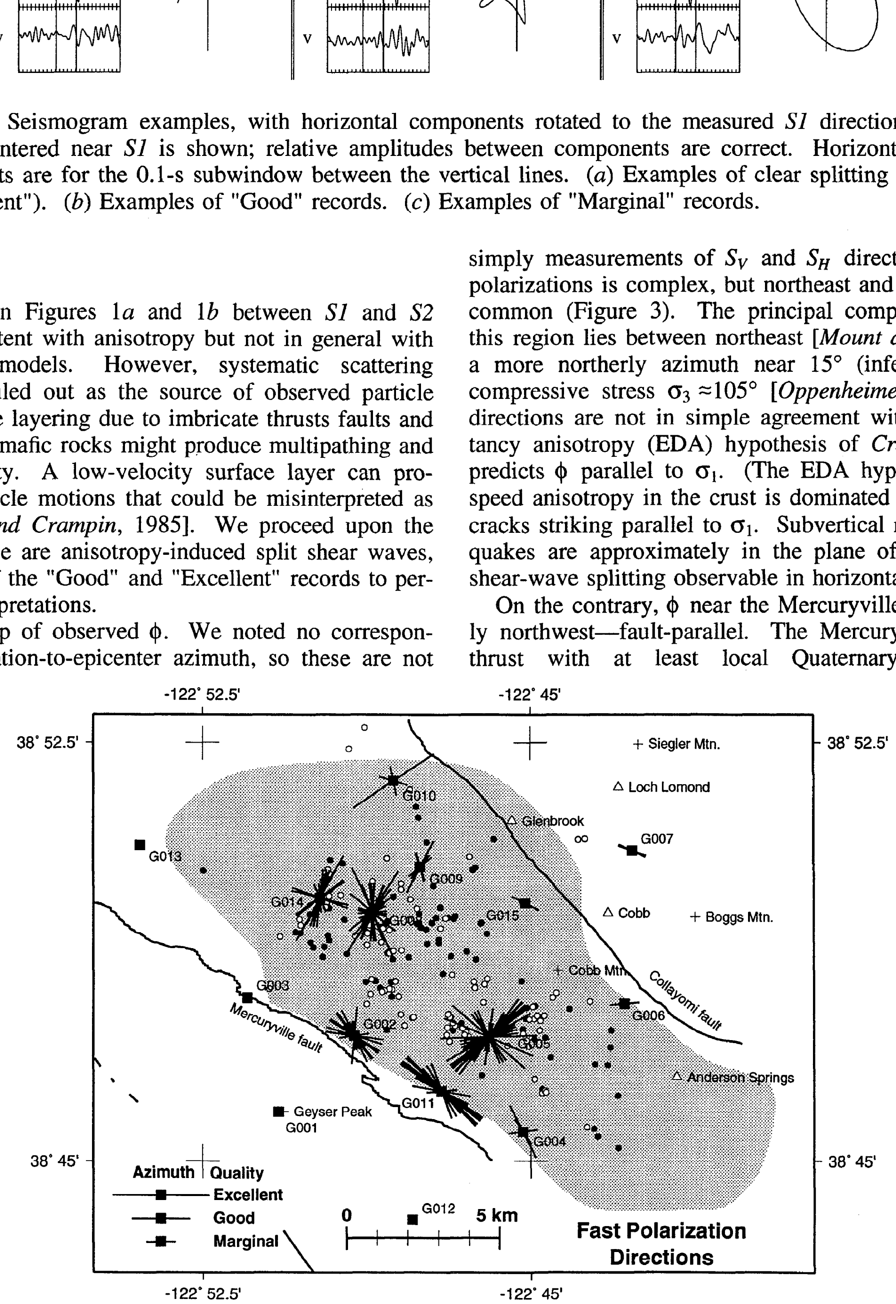

Figure 2. Map of stations used (squares) and observed *S1* polarization directions, ϕ. Shading: geothermal field; triangles: settlements; circles: earthquakes used here; dots: other earthquakes examined. Only data with reasonable estimates of both ϕ and delay time are shown, except at G006, G007, and G015, where either or both t_{S1} and t_{S2} is unreadable. Qualities "Excellent", "Good", and "Marginal" refer to ϕ. Figure made with the "GMT System" [*Wessel and Smith*, 1991].

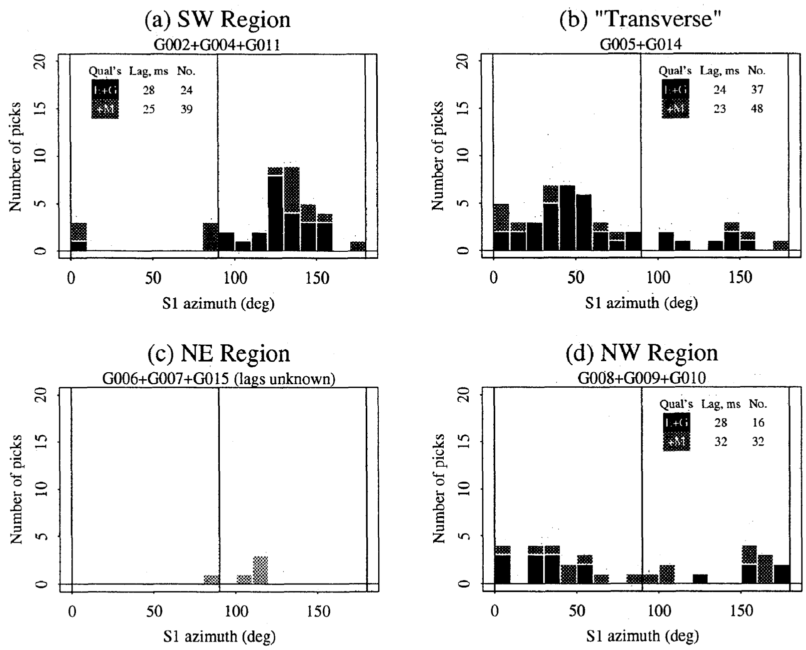

Figure 3. Histograms of ϕ for four groups of stations with similar directions. Groupings determined by examining individual-station histograms of this type. The median $t_{S2} - t_{S1}$ "lag" is given where known, with the number of data contributing. Same data selection as Figure 2. "E", "G", and "M": "Excellent", "Good", and "Marginal" data qualities.

[*McLaughlin*, 1981]. A few data of marginal quality suggest that stations G007 and G015 near the Collayomi fault zone, also have fault-parallel ϕ. The Collayomi fault zone is a regional right-lateral strike-slip fault with some local dip slip [*McLaughlin*, 1981].

In the geothermal field between these faults, two stations are dominated by northeast ϕ (Figure 3*b*) while others have mixed northeast and northwest ϕ (Figure 3*d*). We examined ϕ for different station-to-epicenter azimuths to isolate geographically the sources of these variations. No simple pattern emerged, other than that the few northwest ϕ at station G014 are all from events southeast of that station, near mixed-polarization station G008.

To determine the depths at which *S* traverses the dominant anisotropic medium, we plotted $t_{S2} - t_{S1}$ against event depth (Figure 4). We also plotted data by individual station and also made plots of just the highest quality picks. None of these plots suggested any correlation between lag and depth, with the possible exceptions of (1) events shallower than about 1 km below sea level and (2) the three best picks for G011 (among the asterisks in Figure 4). Both weakly suggest an increase of lag with depth, but there is scatter, even in the "Good" and better data, at least as large as any such signal.

The usual interpretation of this apparent depth independence would be that anisotropy at The Geysers is dominated by the shallowest ~1.5 km of rock. Following that inference, the median delay time of 26 ms (based on the 77 "Good" and better picks) and an average v_S of 2.4 km/s in the shallowest 1.5 km imply that the anisotropy averages 4%. However, the large scatter of lags suggests instead (1) large measurement errors or (2) strong, heterogeneous anisotropy throughout the sampled volume.

Discussion

We observe evidence of seismic wave-speed anisotropy in the splitting of *S* from shallow earthquakes at The Geysers. The measured ϕ make a pattern that is geographically complex but seems to correlate with distance from regional faults. The "Transverse" stations, particularly station G014, suggest an alternate correlation with distance from the center of the steam field or from the felsite. In other words, sites near the periphery of the steam field may be dominated by ϕ parallel to the boundary of the field. Additional stations near the northwest and southeast edges of the field are needed to distinguish between these alternatives.

The observed ϕ group, about in equal numbers, near northwest and northeast. Most stations are dominated by one or the other polarization direction, but several in the central part of the steam field are mixed. There is little correlation between event depth and $t_{S2} - t_{S1}$, and there is a great deal of scatter in these lags, implying shallow anisotropy, measurement inaccuracy, or heterogeneous anisotropy throughout the upper 5 km.

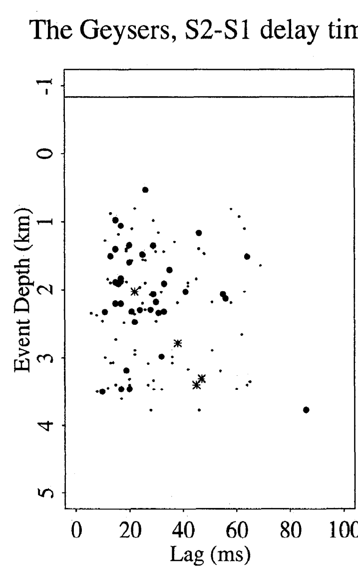

Figure 4. Earthquake depth below sea level *versus* $t_{S2} - t_{S1}$. Larger dots are "Good" or better data; stars: entirely "Excellent". Horizontal line: mean elevation of stations used.

These results are similar to those of *Zhang and Schwartz* [1994] for the Loma Prieta earthquake aftershock region along the San Andreas fault, 200 km south of The Geysers. There, most ϕ are parallel to the fault, while three stations show mixed northwest and northeast ϕ, and one station, the furthest from the fault, shows only northeast ϕ. Zhang and Schwartz interpreted the latter as indicating EDA, and the fault-parallel directions as indicative of fractures or other rock fabric related to the San Andreas fault system. They found no correlation with event characteristics for the mixed-polarization stations, and had no definitive explanation for this phenomenon.

We infer that ϕ near regional fault zones at The Geysers is controlled by fractures or other rock fabric resulting from fault-parallel shear. The other, northeast, group of ϕ is near that expected for EDA, and may be caused by that mechanism. Near the northwest and southeast ends of the steam field, northeast ϕ could also be caused by tangential fracturing at the periphery of an uplifted region formed over the intruded felsite—analogs of cone sheets. Mixed-polarization stations in the center of the steam field may sense both EDA and fault-shear effects.

Our results compare favorably with the borehole "steam-breakout" data of *Thompson and Gunderson* [1992] and with data from an oriented core sample studied by *Nielson et al.* [1991]. The former suggest that fractures in the young (~1 Ma) felsite pluton underlying much of The Geysers field are mostly oriented near northwest and northeast. These fractures presumably reflect Quaternary tectonism, including the San Andreas fault system. The Franciscan metagraywacke overlying most of the felsite and containing much of the geothermal reservoir has no apparent clustering of fracture azimuths in the steam-breakout data. One metagraywacke core examined by *Nielson et al.* [1991] had north-northeast oriented subvertical fractures while the other had low-angle fractures subparallel to bedding. This metagraywacke has been affected by previous stress regimes possibly overprinted only recently by the two modern fracture sets. If the felsite records recent fracturing and/or shearing, then the younger anisotropic features of the metagraywacke may be responsible for much of their seismic signature. Fractures that are open enough to cause seismic anisotropy also may dominate fluid flow patterns, so ϕ may be closely related to permeability anisotropy. To the degree that fault-parallel ϕ reflects rock fabric other than fractures, this fabric may block orthogonal flow and provide pathways for parallel flow. In either case, fluids are likely to flow parallel to ϕ. The strongly fault-parallel ϕ near the Mercuryville and Collayomi fault zones may be related to the bounding of the steam field at those fault zones.

Stark [1992] used microearthquake patterns and geochemical signatures of injectate in produced steam to infer injectate migration in the central part of field. Stark interpreted these patterns as evidence of injectate migration primarily down local steam-pressure gradients, although there is evidence of up-gradient flow in some areas. The microearthquake patterns instead suggest to us a predominance of northwest and northeast striking lineaments—a crosshatch. These are precisely the permeability-anisotropy directions we infer for this area from seismic anisotropy. Fractures or other rock fabric yield two dominant, orthogonal flow directions parallel to observed ϕ. Reservoir modeling may be improved by *a priori* inclusion of northwest and northeast permeability anisotropy in the geographic pattern suggested by Figure 2.

Since a heterogeneous distribution of anisotropy throughout the upper 5 km would explain both the scatter in $t_{S2} - t_{S1}$ and the mixed-polarization stations, we favor that explanation. Detailed mapping of anisotropy in three dimensions should be possible with a larger data set. A three-dimensional anisotropy map would be valuable for reservoir modeling, including the design of a reinjection program to extend the productive life of the reservoir.

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