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STRESS AND PERMEABILITY HETEROGENEITY WITHIN THE DIXIE VALLEY GEOTHERMAL RESERVOIR: RECENT RESULTS FROM WELL 82-5

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ABSTRACT

To understand causes for localized variations in stress and permeability in a geothermal reservoir associated with the Stillwater Fault Zone (SFZ), we collected borehole televiewer, temperature and flowmeter logs and conducted a hydraulic fracturing test in a well (82-5) that penetrated the SFZ within the known boundaries of the geothermal field but which failed to encounter significant permeability. Although stuck drill pipe prevented direct access to the SFZ, borehole breakouts and cooling cracks indicate a ~90° rotation in the azimuth of the least horizontal principal stress (S_{hmin}) in well 82-5 at about 2.7 km depth; similar rotations were observed in a producing well located ~0.6 km to the northeast. This rotation, together with the low S_{hmin} magnitude measured at 2.5 km depth in well 82-5, is most readily explained through the occurrence of one or more normal faulting earthquakes in the hanging wall of the SFZ in the northern part of the reservoir. The orientation of S_{hmin} below 2.7 km (i.e., ~20 to 50 m above the top of the SFZ) is such that both the overall SFZ and natural fractures directly above the SFZ are optimally oriented for normal faulting failure. If these fracture and stress orientations persist into the SFZ itself, then the existence of a local stress relief zone (i.e., anomalously high S_{hmin} magnitude) is the most likely explanation for the very low fault zone permeability encountered in well 82-5. Furthermore, under this condition a massive hydraulic fracture within the SFZ would propagate parallel to the strike of the SFZ and possibly intersect the highly permeable reservoir to the northeast. Thus, well 82-5 may be a good candidate for reservoir stimulation, although it would most likely require that a new leg be drilled to regain access to the SFZ.

INTRODUCTION

Beginning in 1995, we have been conducting an integrated study of stress and fracture permeability in wells penetrating the Stillwater fault zone (SFZ) at depths of 2 to 3 km (Figure 1). This fault is a major, active, range-bounding normal fault that comprises the main reservoir for a ~62 MW geothermal electric power plant at Dixie Valley, Nevada (Benoit, 1996). Although earthquakes have not ruptured this segment of the Stillwater fault in historic times, large (M = 6.8 to 7.7) earthquakes have occurred within the past 80 years along range bounding faults both to the northeast and southwest of the Dixie Valley Geothermal Field (DVGF). Geologic evidence shows that the Stillwater fault close to the DVGF experienced at least two faulting episodes during the Holocene (Wallace and Whitney, 1984; Caskey and Wesnousky, this volume).

The long-term goal of this study is to determine the nature, distribution and hydraulic properties of fractures associated with the DVGF, and to characterize the manner in which these fractures, and hence the overall reservoir hydrology, are related to the local stress field. This has involved conducting borehole televiewer (BHTV) and temperature/pressure/spinner (TPS) logging and hydraulic fracturing stress measurements in wells within the primary zone of geothermal production (transmissivities ~1 m^2/min) and in wells outside the boundaries of the DVGF that were relatively impermeable (transmissivities ~10^{-4} m^2/min). These previous results (summarized below) indicate that fault zone permeability is high only when individual fractures as well as the overall Stillwater fault zone are favorably oriented and critically stressed for frictional failure.

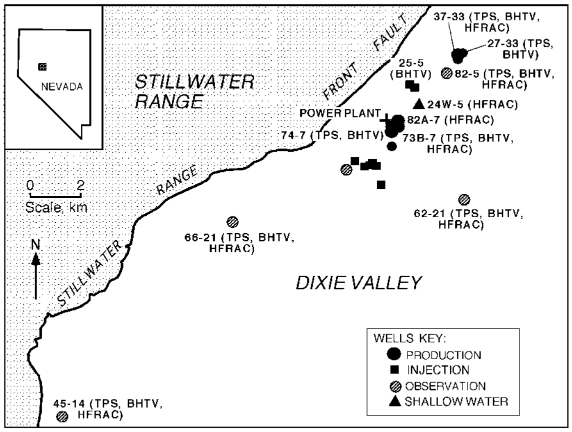

Figure 1. Map showing geothermal wells tested in Dixie Valley, Nevada. Injection and production wells penetrated highly permeable portions of the southeast-dipping Stillwater fault zone, whereas observation wells failed to encounter sufficient permeability to be of commercial value. Measurements conducted in these wells included TPS: Temperature/pressure/spinner logs; BHTV: borehole televiewer logs; HFRAC: Hydraulic fracturing stress measurements.

A number of "dry" legs have been drilled within the known boundaries of the DVGF, where permeability is expected to be high but, in reality, is low to nearly nonexistent. In this paper, we present results from BHTV logging and stress measurements conducted in 1999 in a well (82-5) located within the DVGF but which failed to encounter sufficient permeability to be economically viable (Figure 1). Well 82-5 was drilled and then redrilled three times in 1985 to 1986 in an attempt to encounter reservoir permeabilities. The most recent (open-hole) leg penetrated abundant sealed fractures starting at a depth of about 2740 m – which we infer to be the top of the SFZ – before passing through the main range-front fault at 2833 m. Importantly, this well is located only about 600 m southwest of some of the most permeable production wells in the DVGF. The primary goals of the well 82-5 study are to determine why these pockets of low permeability exist within the DVGF and if and in what manner massive hydraulic fracturing or other reservoir stimulation techniques might be used to turn 82-5 into a viable geothermal production or injection well. TPS and/or BHTV logs recently acquired from wells 25-5 and 27-33 (Figure 1), as well as TPS logs collected in well 82-5, are still undergoing analysis and will not be discussed in detail here.

SUMMARY OF PREVIOUS RESULTS

The results of our prior investigations at Dixie Valley are presented in Hickman et al. (1998), Barton et al. (1998) and Morin et al. (1998). Observations of stress-induced borehole failure in BHTV logs from wells within the permeable main reservoir indicate that the local orientation of the least horizontal principal stress, S_{hmin}, is nearly optimal for normal faulting on the Stillwater fault. Although these BHTV logs revealed pervasive macroscopic natural fractures with a wide range of orientations, TPS logs conducted during fluid injection and withdrawal indicate that the orientations of the most permeable fractures are distinct from the overall fracture population and are subparallel to the Stillwater fault. Hydraulic fracturing tests in these wells indicate that the magnitude of S_{hmin} is low enough to lead to frictional failure on both the main Stillwater fault and these permeable fractures. Crack sealing and permeability reduction would be expected along this segment of the SFZ, given thermal and geochemical evidence for up-dip transport of silica-saturated fluids. However, the observation that highly permeable fractures within the DVGF are favorably aligned and critically stressed for normal faulting suggests that dilatancy due to intermittent fault slip are sufficient to counteract the expected permeability reduction.

Similar measurements were conducted in wells 66-21 and 45-14, which penetrated a relatively impermeable segment of the SFZ approximately 8 and 20 km southwest of the DVGF (Figure 1). The orientation of S_{hmin} in well 66-21 is near optimal for normal faulting on the Stillwater fault, but the magnitude of S_{hmin} is too high to result in incipient frictional failure. In contrast, although the magnitude of S_{hmin} in well 45-14 is low enough to lead to frictional failure on optimally oriented faults, the Stillwater fault itself is locally rotated by ~40° from the optimal orientation for failure. This misorientation, coupled with an apparent increase in the magnitude of the greatest horizontal principal stress in going from the producing to nonproducing wells, acts to inhibit frictional failure on the Stillwater fault near well 45-14. Data from non-productive wells located outside of the DVGF thus indicate that a necessary condition for high reservoir permeability is that the SFZ be critically stressed for frictional failure in the current stress field.

METHOD

The geometry and orientation of drilling-induced tensile fractures, borehole breakouts and natural fractures (see below) were determined using BHTV logs. The BHTV is a wireline logging tool that provides a continuous, oriented, ultrasonic image of a borehole wall (see Zemanek et al., 1970). The high temperatures encountered in these wells (up to ~240° C) required the use of specialized televiewer tools, owned by Stanford University and the U.S. Geological Survey. These tools were repeatedly calibrated at the surface for orientation and ultrasonic travel times in specially designed calibration tanks. Data were digitized from the magnetic field tapes and

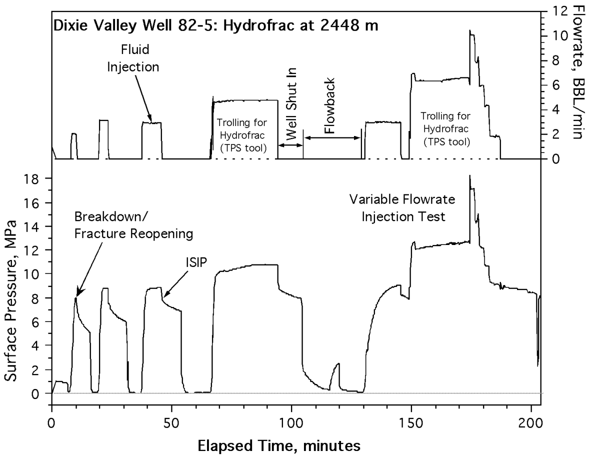

Figure 2. Surface pressure and flow rate records from the hydraulic fracturing test conducted at 2448 m depth in well 82-5. Pressures were also recorded using a downhole temperature/pressure/spinner (TPS) tool suspended just above the casing shoe at 2043 m depth. This TPS tool was also used during high-flow-rate injection on cycles 4 and 6 to identify the exact location of the hydrofrac.

then processed to remove noise, stick-slip effects and other tool-related problems.

Although hydraulic fracturing stress measurements are typically conducted in short intervals of open hole using inflatable rubber packers, high borehole temperatures precluded the use of inflatable packers in this study (see Hickman et al., 1988, for discussion of the hydraulic fracturing technique and the interpretation methods used here). Instead, the hydraulic fracturing test in well 82-5 was conducted by setting a drill-pipe-deployed solid rubber packer in casing and pressuring the bottom of the casing string and the entire open-hole interval to induce a hydraulic fracture in the uncased hole. Repeated pressurization cycles were then employed to extend this fracture away from the borehole. A TPS log was conducted over the open-hole interval of the well and into casing while pumping during the fourth and sixth cycles of the hydraulic fracturing test to identify the depth at which the hydraulic fracture was created (Figure 2).

The magnitude of S_{hmin} was determined from the instantaneous shut-in pressure (ISIP), or the pressure at which the pressure-time curve departs from an initial linear pressure drop immediately after the pump is turned off and the well is shut in (Figure 2). Pressures recorded during a stepwise change in flow rate during the last pumping cycle of the test were used to detect changes in the permeability of the test interval resulting from closure of the hydraulic fracture and provided an additional constraint on S_{hmin} magnitude.

In a hydraulic fracturing test the magnitude of the maximum horizontal principal stress, S_{Hmax}, is typi-

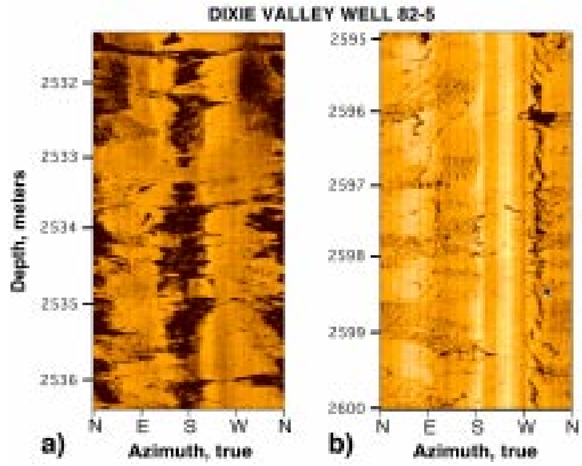

Figure 3. Borehole televiewer log from well 82-5 showing: (a) borehole breakouts (irregular dark patches) and (b) drilling-induced tensile cracks (undulating vertical features) on diametrically opposed sides of the borehole. Several natural fractures can also be seen in (a) as sinusoidal dark lines (e.g., 2531.5 m).

cally determined utilizing a fracture initiation, or breakdown, criteria for pure tensile fractures initiating in intact rock along the S_{Hmax} direction. However, as was the case in other wells tested at Dixie Valley, BHTV logs conducted before the hydraulic fracturing test showed that the open-hole interval in 82-5 contained numerous preexisting fractures (both natural and drilling-induced) at a variety of orientations (see below). Thus, it was not possible to directly measure the magnitude of S_{Hmax}. However, as discussed below, bounds to the magnitude of S_{Hmax} were obtained using estimates of compressive rock strength and the presence of borehole breakouts in well 82-5.

The vertical (overburden) stress, S_V, was calculated for well 82-5 using geophysical density logs conducted in nearby wells, in conjunction with rock densities measured on surface samples obtained from Dixie Valley (Okaya and Thompson, 1985).

RESULTS AND DISCUSSION

Unfortunately, during what should have been a routine work-over to clear a blockage and condition well 82-5 for testing, the drill pipe became inextricably stuck and had to be severed at a depth of 2724 m, preventing further access to the SFZ. Thus, although BHTV and TPS logs and a hydraulic fracturing test were obtained in the open-hole interval from 2071 to 2724 m, these data could not be used to characterize the state of stress, natural fracture population or permeability structure directly within the SFZ. Therefore, in the discussion that follows we of necessity restrict our attention to observations made above the SFZ and their implications for the nature of heterogeneities in stress and fault zone permeability within

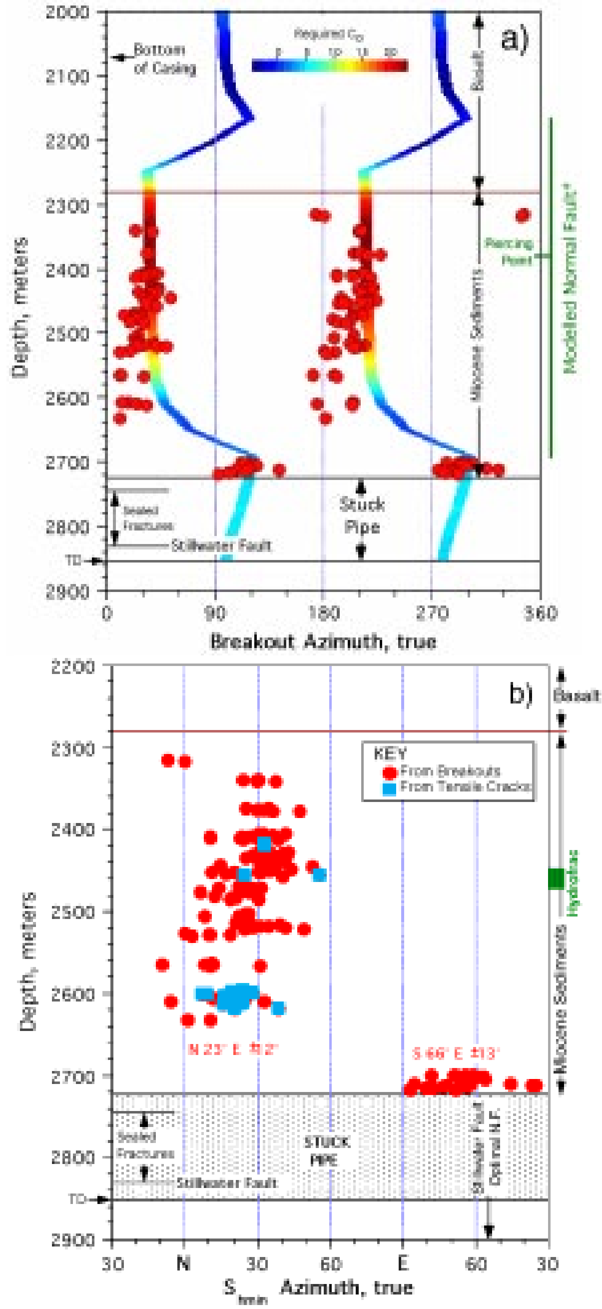

Figure 4. (a) Orientations of borehole breakouts observed in the televiewer logs from well 82-5 (red dots). Calculated changes in breakout orientation with depth that would result from a moderate-sized normal faulting earthquake on a fault passing through the well are shown as multicolored bands (see text). The depth extent of the damage zone for the Stillwater fault (sealed fractures) and drill pipe stuck in the hole are also shown. (b) Azimuth of the least horizontal principal stress, S_{hmin}, determined from breakouts and drilling induced tensile cracks.

the DVGF and the potential for reservoir stimulation in well 82-5.

Stress Orientations

Excellent quality BHTV logs were obtained over the entire open-hole interval in well 82-5 and revealed extensive stress-induced borehole breakouts and, to a lesser extent, drilling-induced tensile (cooling) fractures (Figure 3). As discussed by Moos and Zoback (1990), these tensile cracks result from the superposition of a circumferential thermal tensional stress induced by circulation of relatively cold drilling fluids and the concentration of ambient tectonic stresses at the borehole wall. These tensile cracks – which were also observed in nearby producing wells 73B-7 and 74-7 (Hickman and Zoback, 1997; Hickman, 1998) – should form in a direction perpendicular to the azimuth of S_{hmin}. In contrast, borehole breakouts form via compressive rock failure in response to tectonic stress concentrations at the borehole wall and should be parallel to S_{hmin}.

Borehole breakouts were observed throughout much of the logged interval in 82-5, and extend from the top of the Miocene sediments at 2280 m to the top of the stuck drill pipe at 2724 m, undergoing a sudden ~90° shift in orientation at about 2660 m (Figure 4a). Tensile cracks were observed only between 2420 and 2620 m. The stress orientations indicated by the tensile cracks and breakouts in 82-5 are in very good agreement (Figure 4b), and the azimuth of S_{hmin} above 2660 m is N23°E ± 12° whereas below 2660 m it is S66°E ± 13°. Drilling-induced tensile cracks were also observed in BHTV logs recently obtained in well 25-5, indicating that the azimuth of S_{hmin} in that well is S64°E ± 14°.

The azimuth of S_{hmin} above 2660 m in well 82-5 is anomalous in that it is roughly parallel to the strike of the SFZ, while the orientation of S_{hmin} below 2660 m (i.e., directly above the fault zone) is nearly perpendicular to the strike of the fault (Figure 5). The deeper S_{hmin} direction from well 82-5 is in good agreement with stress directions obtained previously in well 73B-7 and in the producing interval of well 74-7 (Hickman et al., 1998) and in the nearby injection well 25-5 (Figure 5). If this S_{hmin} direction observed just above the SFZ persists to greater depths, then the Stillwater fault where penetrated by well 82-5 would be nearly at the optimal orientation for normal faulting (Figure 4b).

Stress Magnitudes

The well 82-5 hydraulic fracturing test shows that the magnitude of S_{hmin} is 31.1 ± 0.6 MPa at a depth of 2448 m, corresponding to a ratio S_{hmin}/S_V of 0.53 (Figure 6). Hydraulic fracturing tests from nearby geothermal production wells 73B-7, 82A-7 and 37-33 show that S_{hmin}/S_V ranges from 0.45 to 0.51 at depths

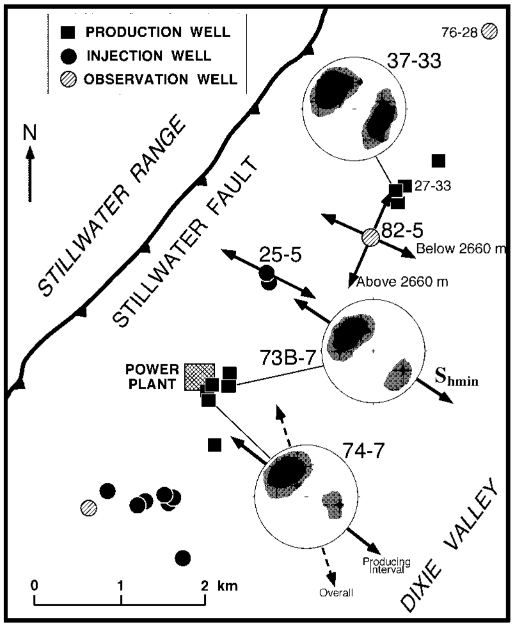

Figure 5. Map of the Dixie Valley Geothermal Field, showing the orientation of S_{hmin} as outward-directed arrows. Also shown are lower hemisphere stereographic projections of poles to permeable fractures in selected production wells, contoured using the Kamb method (see Figure 8), demonstrating that these fractures and the overall Stillwater fault zone are well oriented for normal faulting in the current stress field (see Barton et al., 1998; Hickman et al., 1998).

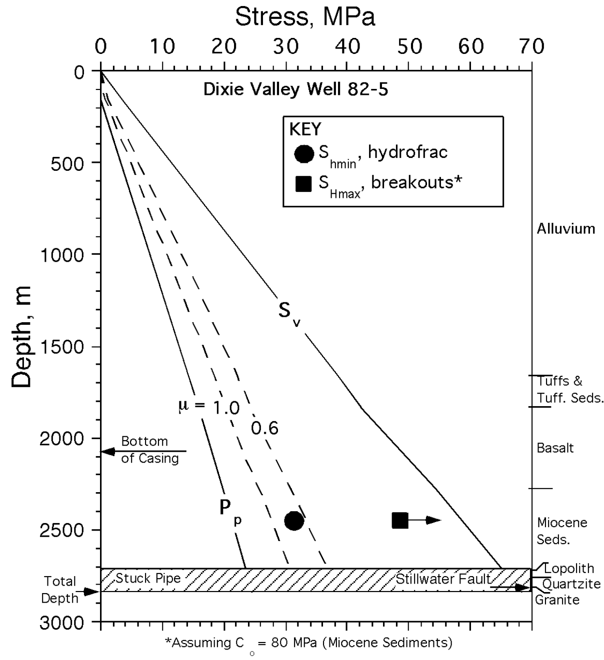

Figure 6. Magnitude of S_{hmin}, from the hydraulic fracturing test in well 82-5. Also shown is a lower bound on the magnitude of the greatest horizontal principal stress, S_{Hmax}, based upon the occurrence of stress-induced borehole breakouts in this well. The vertical stress, S_V, and the formation fluid pressure, P_p, were calculated for the appropriate densities. The dashed lines indicate the range of S_{hmin} at which incipient normal faulting would be expected on optimally oriented faults for coefficients of friction of 0.6 - 1.0.

of 2.4 to 2.6 km, which is within a few hundred meters of the depths at which these wells penetrate highly permeable fractures associated with the SFZ (Hickman et al., 1998). Thus, although the S_{hmin} direction at the hydrofrac depth in 82-5 is highly anomalous (Figure 4b), it is interesting to note that the maximum differential stress (i.e., S_V - S_{hmin}) at near-reservoir depths in this well is comparable to that observed in nearby production wells.

As borehole breakouts were observed in the BHTV log from well 82-5, a lower bound to the magnitude of S_{Hmax} was obtained using the S_{hmin} magnitude from the hydraulic fracturing test together with theoretical models for breakout formation. These models (see Moos and Zoback, 1990) predict that borehole breakouts will initiate along the azimuth of S_{hmin} whenever the maximum effective circumferential stress, $\sigma_{\theta\theta}^{max}$, at the borehole wall exceeds the compressive rock strength, C_o; i.e.:

$$\sigma_{\theta\theta}^{max} = 3S_{Hmax} - S_{hmin} - P_p - P_m \geq C_o \qquad (1)$$

where P_p is the formation pore pressure and P_m is the mud pressure exerted on the borehole wall during drilling. Ideally, laboratory failure tests or geophysical well logs should be used to determine the appropriate value of C_o to use in Equation 1. Although we hope to obtain more refined estimates for C_o in the future, in the meantime we estimated this parameter based upon published compilations of the compressive strength of rocks of similar lithology (Lockner, 1995). This analysis suggests that S_{Hmax} is greater than or equal to 49 MPa at a depth of 2.5 km (Figure 6). In contrast, no breakouts were observed in nearby production well 73B-7, even though it exhibited comparable S_{hmin} magnitudes and penetrated the same rock types as 82-5 (Hickman et al., 1998). This suggests that the magnitude of S_{Hmax} in 82-5 is significantly higher than in 73B-7, regardless of the value of C_o used.

Using the Coulomb failure criterion (e.g., Jaeger and Cook, 1976), one can estimate the critical magnitude of S_{hmin} at which frictional failure (normal faulting) would be expected on optimally oriented faults using:

$$S_{hmin\ crit} = (S_V - P_p) / [(\mu^2 + 1)^{1/2} + \mu]^2 + P_p \qquad (2)$$

and assuming that the coefficient of friction μ ranges

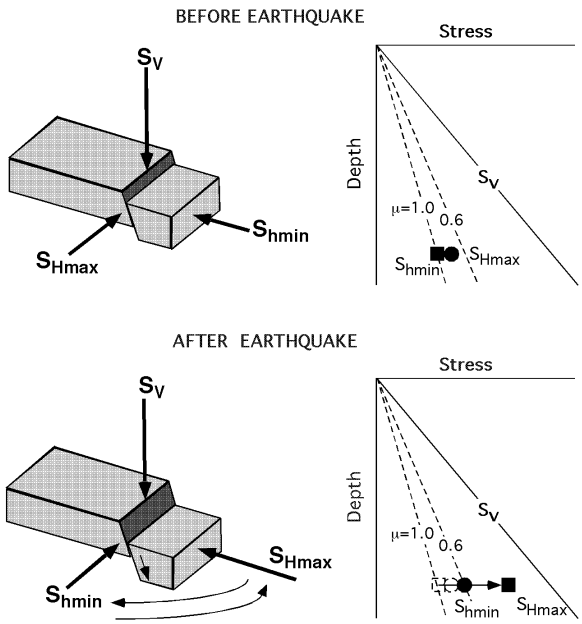

Figure 7. Illustration of the manner in which a normal-faulting earthquake accompanied by a large decrease in shear stress (stress drop) on the causative fault could lead to a 90° flip in the orientation of the two horizontal principal stresses.

from 0.6 to 1.0, in accord with laboratory sliding experiments on a wide variety of rock types (Byerlee, 1978). As done for other nearby wells, we estimated P_p by assuming that it was in hydrostatic equilibrium with the preproduction water table at 152 m depth and integrating water density as a function of pressure and temperature, as appropriate to static temperatures measured in 82-5. This analysis indicates that the S_{hmin} magnitude at 2.5 km in 82-5 is low enough to result in incipient frictional failure on optimally oriented normal faults (Figure 6). However, as the orientation of S_{hmin} at this depth is anomalous and no hydraulic fracturing data are available from greater depths in this well, it is not known if and to what extent this condition of incipient frictional failure persists into the SFZ.

Model for Observed Stress Perturbations

A conceptual model for permutation (or exchange) of the horizontal principal stresses due to a normal faulting earthquake in the hanging wall of the SFZ can explain the current stress state in well 82-5. In this model (Figure 7), the state of stress before the hypothesized earthquake was similar to that observed today in well 73B-7 (Hickman and Zoback, 1997): with S_{hmin} perpendicular to the strike of the SFZ and at the critical magnitude for frictional failure. We further propose, consistent with the upper bound to S_{Hmax} obtained for 73B-7, that S_{Hmax} prior to this earthquake was nearly equal in magnitude to S_{hmin}.

Under these initial stress conditions, a normal faulting earthquake on either the SFZ or a subparallel fault would result in a significant reduction in shear stress on that fault (i.e., a coseismic stress drop). Since S_V is fixed by the weight of the overburden, this stress drop causes an increase in the magnitude of S_{hmin}. Aside from the small elastic (Poisson) coupling of changes in S_{Hmax} to S_{hmin}, the magnitude of S_{Hmax} remains relatively unchanged since it lies in the plane of the fault and contributes nothing to the shear stress driving the earthquake. Given the nearly equal magnitudes of the horizontal principal stresses prior to the earthquake, the effect of the large coseismic increase in S_{hmin} relative to that for S_{Hmax} is for S_{hmin} to transform into S_{Hmax} and S_{Hmax} to transform into S_{hmin}. As can be seen through comparison of Figure 7 with Figures 5 and 6, this model for the permutation of the principal stresses can explain both the anomalous S_{hmin} orientation and the current magnitudes of S_{hmin} and S_{Hmax} above 2660 m in 82-5.

We used the model of Barton and Zoback (1994) to see if we could explain more quantitatively the stress rotation seen in 82-5. This model superposes the elastic stress field induced by slip on a fault of arbitrary orientation on the concentration of ambient tectonic stresses around a borehole. The input stress parameters for this model were chosen to be consistent with the pre-earthquake stress state depicted in Figure 7, tied to the actual stress magnitudes measured at 2448 m (Figure 6). The geometry of the causative fault was prescribed to be parallel to the SFZ, with the extent of the slipped patch (i.e., the earthquake rupture dimensions) treated as free parameters and the coseismic stress drop assumed to be total. The results of this model (Figure 4a) show excellent agreement with the orientation of breakouts observed both above and below 2660 m in well 82-5, for a normal faulting earthquake extending from a depth of about 2160 to 2690 m and piercing the borehole at 2380 m. Although not a unique solution, this model also reproduces some of the important features in the observed distribution of breakouts versus depth. In particular, it predicts that breakouts should be absent in the immediate vicinity of the stress rotation (i.e., from 2620 to 2700 m), where the circumferential compressive stress should be near zero (dark blue line), and most strongly developed adjacent to the midpoint of the rupture, where the circumferential compressive stress should reach its maximum value (dark red line).

Significant local stress rotations, perhaps due to slip on nearby faults, were also observed in some of the nearby production wells (Hickman et al., 1998). Particularly dramatic stress rotations were seen in production well 37-33, located about 0.6 km northeast of well 82-5 (Figure 5), where the direction of S_{hmin} changed by up to 90^o over distances of a few ten

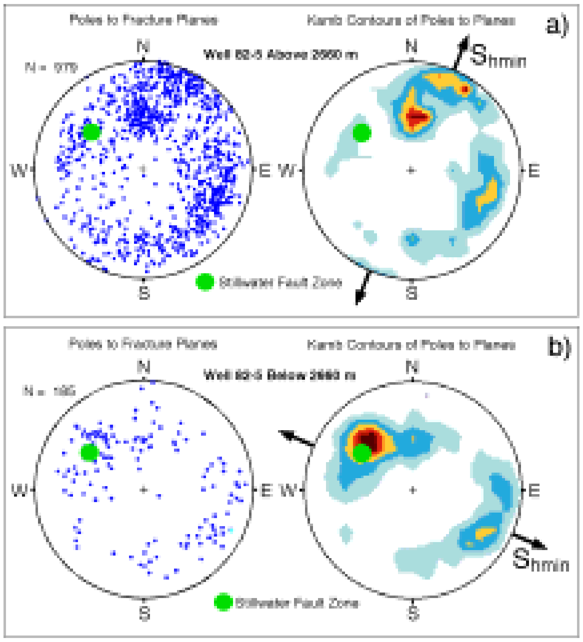

Figure 8. Lower hemisphere, equal area projections of poles to natural fractures observed in the borehole televiewer log from well 82-5: (a) above 2660 m and (b) below 2660 m. In the Kamb contours to these poles (after Kamb, 1959), the density of shading is proportional to the number of poles per unit area on a lower hemisphere projection, normalized to the total fracture count, N. Also shown are the pole representing the local orientation of the Stillwater fault zone along with the azimuth of S_{hmin}, over the corresponding depth interval (see Figure 4b) .

to a few hundred meters. A total of five stress measurements were conducted in well 37-33, indicating relatively high S_{hmin}/S_V values of 0.74 or greater at depths of 1.57 to 1.89 km. These high S_{hmin} magnitudes are most likely due to moderate-sized earthquakes on faults within or adjacent to the SFZ, but in this case S_{Hmax} before the earthquakes would have been closer in magnitude to S_V than inferred for 82-5. It is important to note, however, that the magnitude and orientation of S_{hmin} directly above the SFZ in well 37-33 (i.e., at a depth of 2.65 to 2.75 km) was such that the SFZ and most of the associated permeable fractures were critically stressed for frictional failure, in spite of the dramatic perturbations in stress orientations and magnitudes observed in this well at shallower depths.

Fracture Orientations

As observed in other nearby wells (Barton et al., 1998), BHTV logs from well 82-5 show pervasive macroscopic natural fractures with a wide range of orientations throughout the logged interval (e.g., Figure 3a). To facilitate comparison of these fractures with the in-situ stress data, we have grouped them according to whether they are above or below the stress rotation at 2660 m (Figure 8). Above 2660 m these fractures fall into two distinct populations: one striking between west and northwest with moderate to steep dips (40° to 85°) to the south, the other is more diffuse and strikes between north and east with moderate dips (45° to 75°) to the northwest. Although the west to northwest fracture set strikes nearly perpendicular to the SFZ, it is near-optimally oriented for normal faulting given the local azimuth of S_{hmin} (Figure 8a). Thus, fractures above 2660 m appear to be dominated by normal faulting antithetic to the Stillwater fault (i.e., at high angles to the SFZ). This antithetic fracture set, which has not been observed before at Dixie Valley, presumably reflects a mechanical overprint on the background fracture population formed in response to the earthquake-induced stress perturbation discussed above.

The orientations of natural fractures below 2660 m in well 82-5 (i.e., directly above the SFZ) are markedly different from those observed above 2660 m. In particular, the west to northwest fracture set above 2660 m is notably absent in the deeper fracture population (Figure 8b). Instead, these deeper fractures tend to strike in a northeasterly direction and dip 40° to 75° either to the southeast or the northwest, with the dominant southeast-dipping set being subparallel to the SFZ (green dot in Figure 8b). As the azimuth of S_{hmin} below 2660 m is S66°E, this conjugate fracture set is optimally oriented for normal faulting. The geometry of this conjugate fracture set is remarkably similar to that observed for permeable fractures in production wells to the northeast and southwest of well 82-5 (Barton et al., 1998). As shown in Figure 5, the dominant population of permeable fractures in wells 74-7, 73B-7 and 37-33 are parallel to the Stillwater fault: striking northeast and dipping roughly 50° southeast, with a conjugate set striking in roughly the same direction but dipping to the northwest.

Coulomb failure analysis (see Barton et al., 1998) using the S_{hmin} magnitude and orientation determined in 82-5 above 2660 m shows that many of the natural fractures in this interval are critically stressed for frictional failure. However, as the magnitude of S_{hmin} below 2660 m is unknown, a corresponding analysis could not be performed for the fractures shown in Figure 8b. Thus, it is not known if and to what extent the natural fracture population located immediately above the SFZ is critically stressed for frictional failure.

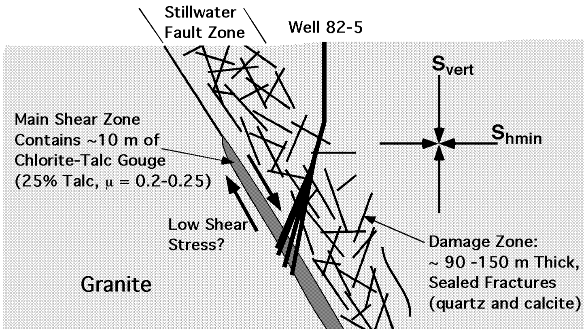

Figure 9. Illustration of the stress shadow model, in which a chlorite-talc gouge with a low coefficient of friction (μ) confined to the main shear zone of the Stillwater fault might lead to anomalously low shear stress on fractures within the adjacent damage zone.

Implications for Low Fault Zone Permeability

The observation that well 82-5 is orders of magnitude less permeable than the nearby production wells suggests that there may be fundamental changes in the fracture population or the stress regime in proximity to the SFZ over distances of less than 600 m that are exerting a profound influence on well productivity. As stuck drill pipe is covering the SFZ in well 82-5, we cannot rule out anomalous fracture or stress orientations within the damage zone of the Stillwater fault as the cause of low fault zone permeability at this location based on our observations. However, we consider this to be an unlikely explanation for this low permeability because both the azimuth of S_{hmin} and the orientation of natural fractures directly above the SFZ are nearly identical to those seen in nearby, highly productive wells (c.f., Figures 5 and 8b).

As illustrated in Figure 9, we consider it more likely that the low productivity of well 82-5 is due to localized increases in the magnitude of S_{hmin} (i.e., a reduction in shear stress) due to the presence of weak talc within the main shear zone of the Stillwater fault at depth. In contrast to other (productive) wells drilled within the DVGF, approximately 10 m of talc-rich fault gouge was encountered on top of the granitic footwall during drilling of 82-5. Laboratory strength measurements show that talc is extremely weak: with a coefficient of friction ranging from 0.2 to 0.25 (Morrow et al., 2000). Thus, the presence of weak talc in the core of the SFZ at reservoir depths could reduce the differential stress (S_V - S_{hmin}) in the immediately adjacent country rock, effectively shielding the potentially permeable (and now sealed) fractures within the overlying damage zone from high tectonic shear stresses. If this "stress shadow" hypothesis is correct, then it suggests that the spatial extent of impermeable patches within the SFZ like that encountered by well 82-5 may be directly determined by the distribution of talc (or other weak minerals) within the main range-front fault

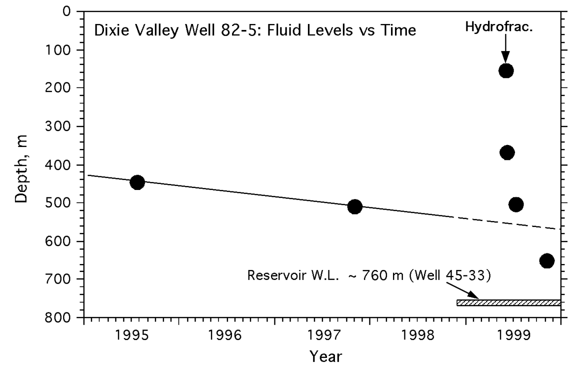

Figure 10. Water level in well 82-5 before and after the hydraulic fracturing test, compared to the static reservoir level in nearby production well 45-33.

Potential for Reservoir Stimulation

There are several factors that suggest that well 82-5 may be a good candidate for reservoir stimulation through massive hydraulic fracturing. First of all, as noted above, it is close to highly productive wells (e.g., 37-33) located ~0.6-0.9 km to the northeast. Secondly, it is in weak pressure communication with the reservoir. Third, the bottomhole temperatures measured in the various legs of 82-5 are similar to those measured in nearby production wells at comparable depths. Thus, one of the goals of this investigation was to evaluate the feasibility of conducting a massive hydraulic fracture in 82-5 to convert it into a viable production or injection well.

Since hydraulic fractures propagate in a plane perpendicular to the least principal stress, it is essential that the azimuth of S_{hmin} and the orientation and spatial distribution of permeable (or potentially permeable) fractures within the SFZ be accurately known in evaluating the feasibility of reservoir stimulation through massive hydraulic fracturing. Although we were precluded from making measurements directly within the SFZ, if the S_{hmin} azimuth observed directly above the fault zone persists to greater depths, then a massive hydraulic fracture within the SFZ would propagate toward the highly permeable wells to the northeast (Figure 5). Thus, well 82-5 may still be a good candidate for massive hydraulic fracturing, although it would probably require that the well be redrilled around the stuck drill pipe so that a massive hydrofrac could be targeted directly within the SFZ. In this regard, it is encouraging that the water level in 82-5 following our hydraulic fracturing test has declined below pre-test levels and is approaching that recorded in nearby production well 45-33 (Figure 10). This suggests that our small-scale hydraulic fracturing test enhanced the hydraulic connectivity of well 82-5 to the overall geothermal reservoir.

CONCLUSIONS

Analysis of borehole televiewer logs and a hydraulic fracturing test in Dixie Valley well 82-5 leads to the following conclusions:

1. There is a ~90° rotation in the azimuth of the least horizontal principal stress, S_{hmin}, in this well at a depth of 2.7 km. This rotation, which is similar to stress rotations seen in producing well 37-33 located about 0.6 km to the northeast, is best explained through a permutation of the horizontal principal stresses in response to a moderate-sized normal faulting earthquake on a fault subparallel to the Stillwater fault zone (SFZ). These stress perturbations suggest that caution be used in extrapolating shallow stress measurements to reservoir depths in seismically active areas.

2. The magnitude of S_{hmin} at 2.5 km depth is about 0.53 of the vertical stress, in accord with Byerlee's law for normal faulting. Since stress-induced borehole breakouts were observed in this well, this suggests that the horizontal differential stress prior to the hypothesized earthquake was quite low (as previously proposed for nearby well 73B-7, located about 2.5 km to the southwest) and that this earthquake was accompanied by near-total stress drop.

3. Although stuck drill pipe prevented us from making measurements directly within the SFZ, fracture and stress orientations immediately above the fault zone are similar to those seen in highly permeable wells (73B-7 and 74-7) located 2-3 km to the southwest. In particular, both the SFZ and the overlying natural fractures are optimally oriented for normal faulting. Thus, a local stress relief zone (i.e., an anomalously high S_{hmin} magnitude) within the SFZ is probably the most likely explanation for the very low permeability encountered in well 82-5.

4. If the S_{hmin} orientation observed in the bottom of this well persists to greater depths, then a massive hydraulic fracture within the SFZ would propagate toward highly permeable wells to the northeast. Thus, 82-5 may still be a good candidate for reservoir stimulation, although it would probably require that a new leg be drilled to regain access to the SFZ.

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