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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.

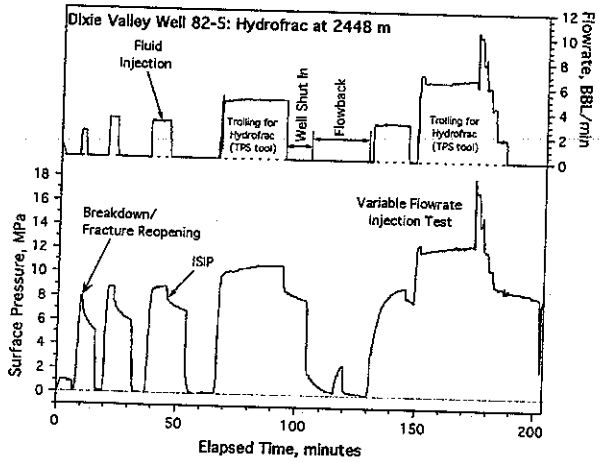

Figure 2. Surface pressure and flow rate records from the hydraulic fracturing test conducted at 2448 m depth in well 82-5. Pressures were also recorded using a downhole temperature/pressure/spinner (TPS) tool suspended just above the casing shoe at 2043 m depth. This TPS tool was also used during high-flow-rate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

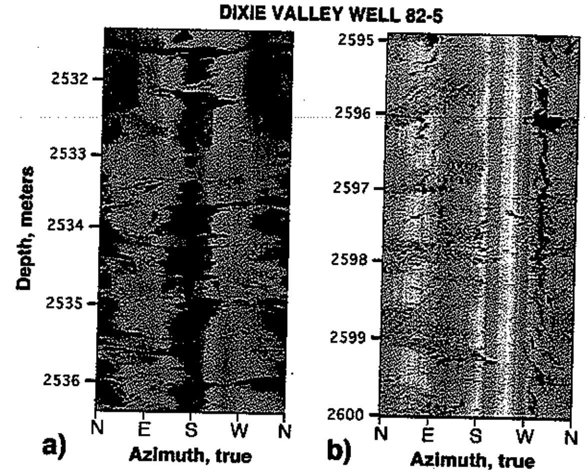

Figure 3. Borehole televiewer log from well 82-5 showing: (a) borehole breakouts (irregular dark patches) and (b) drilling-induced tensile cracks (undulating vertical features) on diametrically opposed sides of the borehole. Several natural fractures can also be seen in (a) as sinusoidal dark lines (e.g.,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

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 typically determined utilizing a fracture initiation, or breakdown, criterion 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

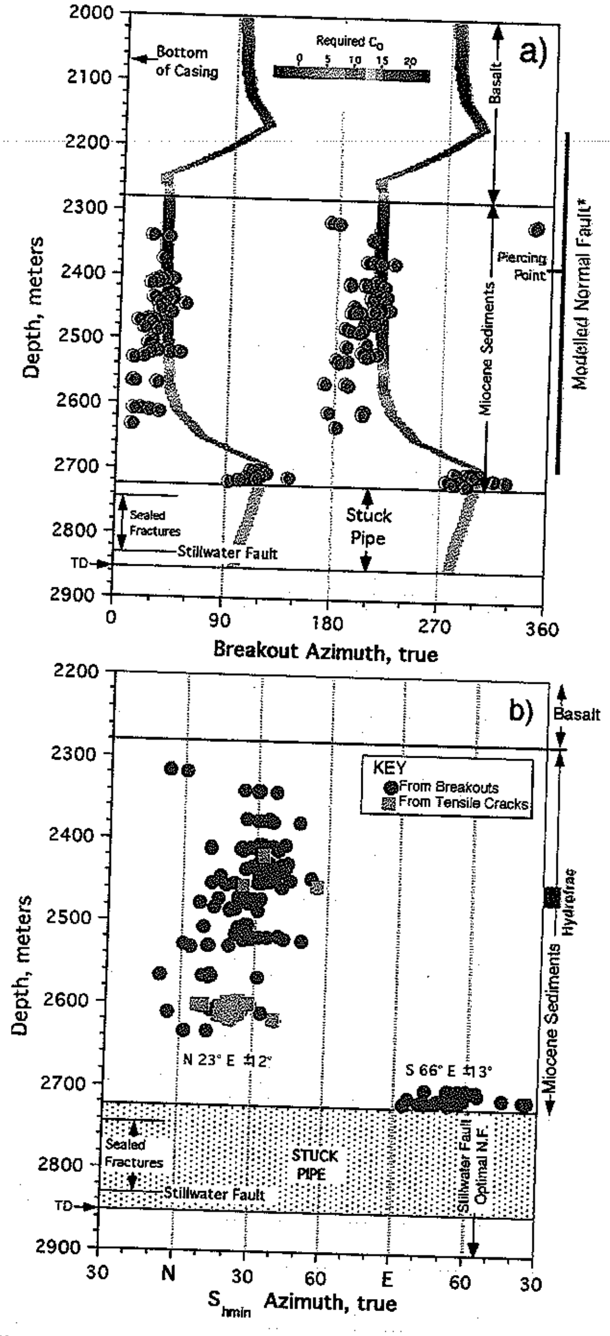

Figure 4. (a) Orientations of borehole breakouts observed in the televiewer logs from well 82-5 (red dots). Calculated changes in breakout orientation with depth that would result from a moderate-sized normal faulting earthquake on a fault passing through the well are shown as multicolored bands (see 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. They 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. They 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 thus in good agreement with stress directions obtained in well 73B-7, 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

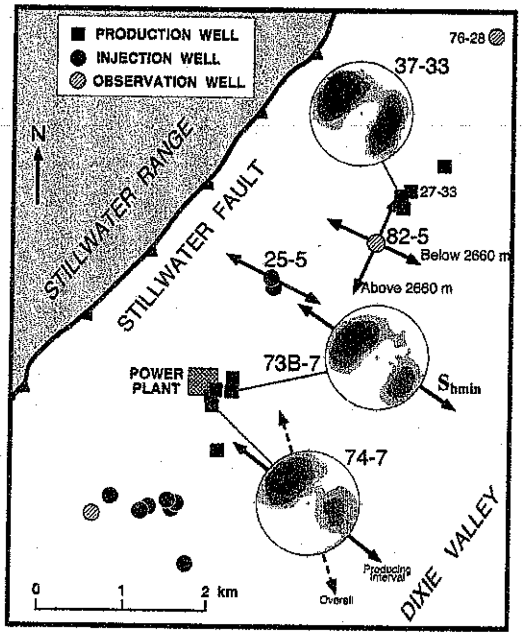

Figure 5. Map of the Dixie Valley Geothermal Field, showing the orientation of S_{hmin} as outward-directed arrows. Also shown are lower hemisphere stereographic projections of poles to permeable fractures in selected production wells, contoured using the Kamb method (see Figure 8), demonstrating that 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).

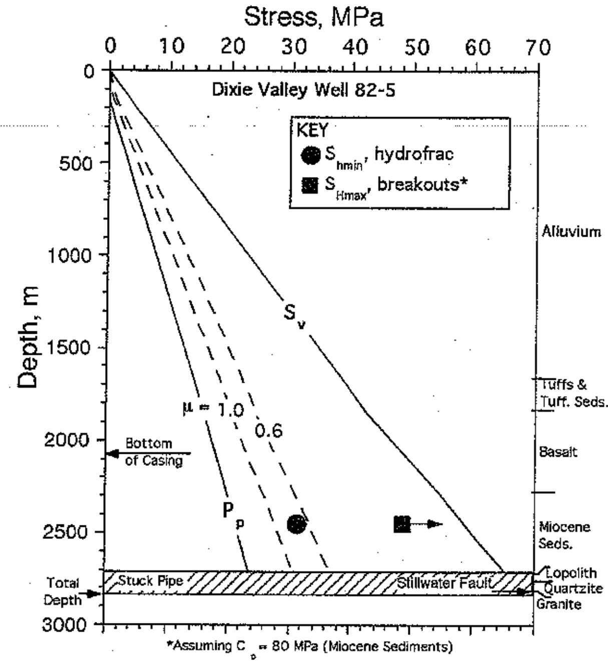

Figure 6. Magnitude of S_{hmin}, from the hydraulic fracturing test in well 82-5. Also shown is a lower bound on the magnitude of the greatest horizontal principal stress, S_{Hmax}, based upon the occurrence of stress-induced borehole breakouts in this well. The vertical stress, S_V, and the formation 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

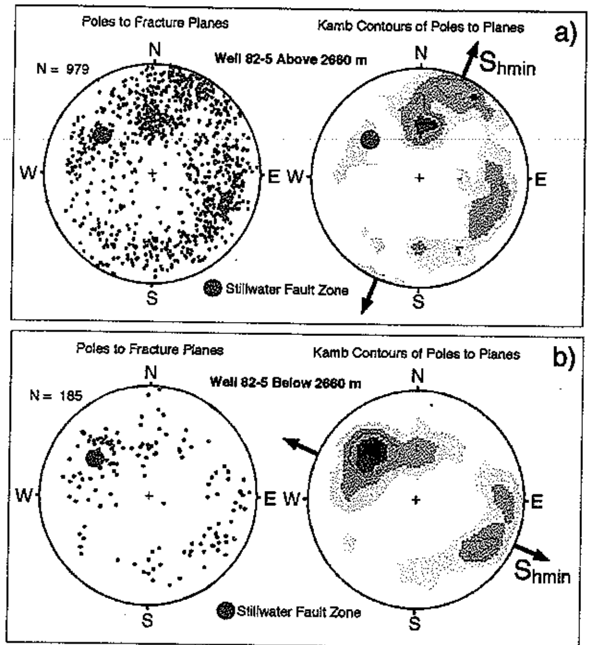

Figure 8. Lower hemisphere, equal area projections of poles to natural fractures observed in the borehole televiewer log from well 82-5: (a) above 2660 m and (b) below 2660 m. In the Kamb contours to these poles (after Kamb, 1959), the density of shading is proportional to the number of poles per unit 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.

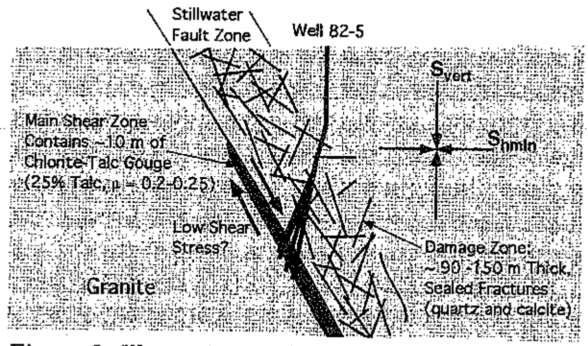

Figure 9. Illustration of the stress shadow model, in which a chlorite-talc gouge with a low coefficient of friction (μ) confined to the main shear zone of the Stillwater fault might lead to anomalously low shear stress on fractures within the adjacent damage zone.

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.

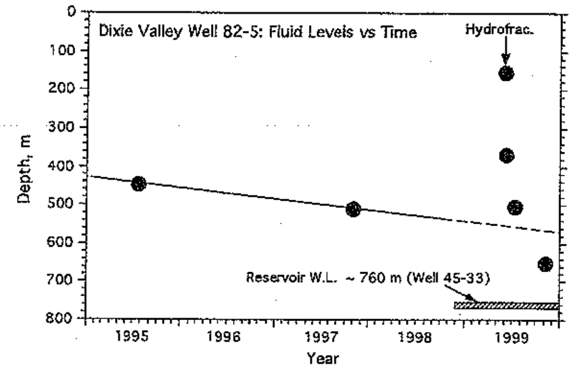

Figure 10. Water level in well 82-5 before and after the hydraulic fracturing test, compared to the static reservoir level in nearby production well 45-33.

Potential for Reservoir Stimulation

Several factors 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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