

Dependency of EGS Development on the Alignment between Natural Fracture Set Orientations and Regional Stress State

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ABSTRACT

This work examines how differences in the orientation of two conjugate sets of natural fractures affect the efficacy of hydraulic stimulation to create successful EGS sites in normal, strike-slip and thrust faulting regions. Many potential EGS locations require hydraulic stimulation to create connectivity between injection and production wells and/or increase the number of conductive pathways between the wells. Hydro-shearing natural fractures by increasing their pore pressure sufficient to cause shear failure is one method being actively explored. The injection pumping pressure required to cause hydro-shearing is a function of the stress state of the reservoir and the orientation of the natural fractures. By keeping lithology, thermal gradient, well geometries and both original and stimulated fracture transmissivity constant while varying natural fracture set orientation and regional stress state, this paper explores the significance of these varying factors for EGS impedance and thermal evolution. Performance using vertical vs horizontal well trajectories is also examined.

Natural fracture orientation variation for normal stress conditions shows large contrasts in the percentage of critically stressed fractures for two sets both aligned maximally aligned to the current stress field (87%), one set maximally aligned (45%) and neither set well aligned (4%). Impedance is quite sensitive to natural fracture alignment but not well orientation. Thermal performance is similar for both one and two sets aligned with the stress field. Strike slip stress conditions show less dependence upon natural fracture set orientation for the number of critically stressed fractures during hydro-shearing (16-86%) but greater sensitivity for impedance and well orientation with horizontal wells out-performing vertical wells. Compressional stress conditions show a range for the percentage of critically stressed fractures of 10-89% for having zero, one or two sets being favorably aligned, a strong dependence for impedance and some sensitivity for thermal evolution. Well orientation is important for the compressional stress state with vertical wells out-performing horizontal ones.

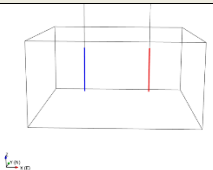
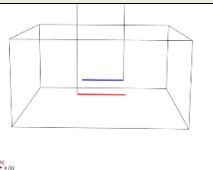
1. INTRODUCTION

There are many potential EGS sites where the regional stress state is not known before substantial investment in exploratory boreholes is undertaken. Even more common is the uncertainty regarding the orientations of existing natural fractures and joint systems given that the target depths for producing electricity are often several kilometers below the surface and outcrop data is often unavailable. How significant is this lack of knowledge for estimating the risks of choosing an EGS site? Also, what are the risks associated with utilizing only vertical wells as opposed to horizontal wells which can be significantly more expensive to drill? This paper illustrates the range in outcomes using numerical experiments for one pair of injection and production wells into a granite reservoir where the regional stress state varies from normal, strike-slip and thrust faulting values for the principal stresses and an existing conjugate set of natural fracture is either completely aligned with the regional stress state (often true for younger formations in active tectonic settings), where only one of the two fracture sets is well-aligned with the regional stress state, or finally where neither of the two sets is well-aligned with the current regional stress state (more likely in very old lithologies with complicated histories). The different models were first hydraulically stimulated in order to increase the transmissivity of critically stressed fractures and then had simulations carried out to determine the impedance of the flow pathways and the thermal decline of production waters over a period of 20 years. Successful systems were expected to have impedance values less than 0.15 MPa/(l/s) and maintain production water temperatures above 180 °C with flow rates of 70 l/s (Finnila et al, 2015).

2. EXPERIMENTAL DESIGN

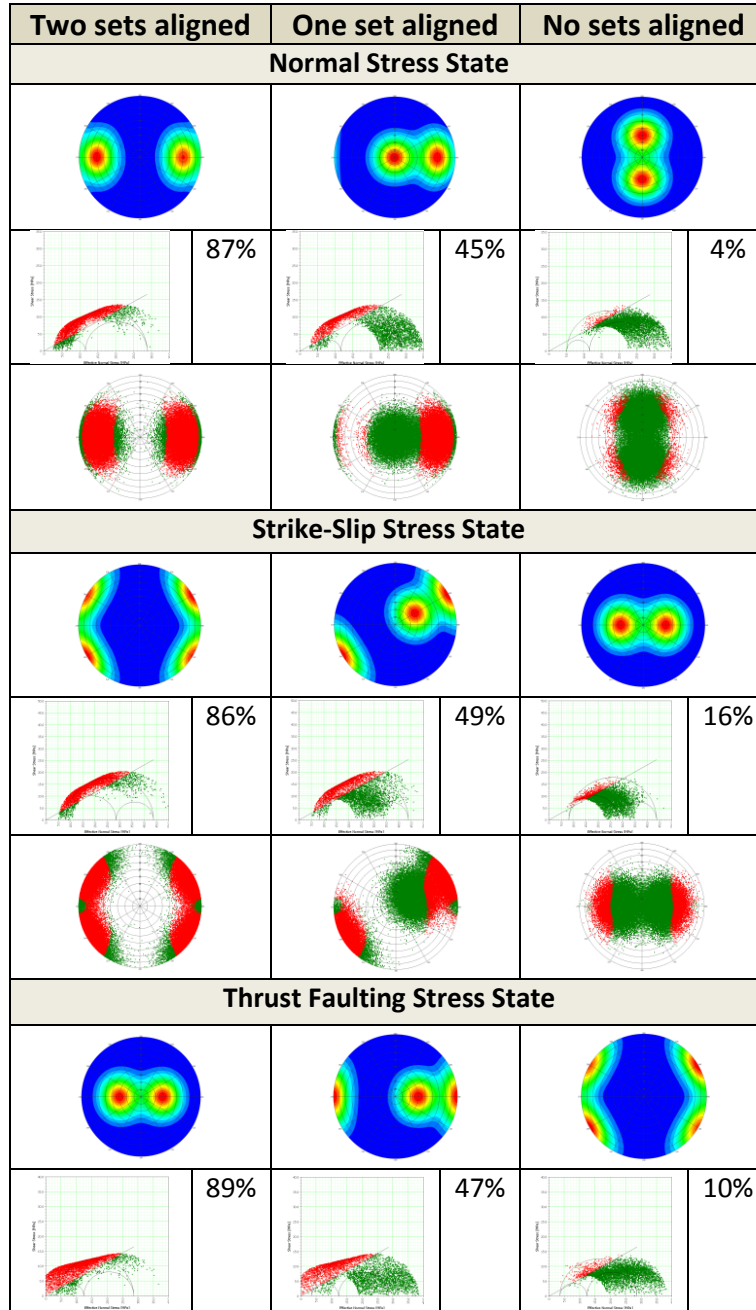
Discrete Fracture Network (DFN) models were constructed using Golder Associates' FracMan software (Golder Associates, 2016). Model properties are shown in Table 1. Once each initial DFN model was created, the effects of hydro-shearing were simulated by increasing the pore pressure to the midpoint between hydrostatic pressure and the minimum principal stress value. Natural fractures were evaluated for Mohr-coulomb failure and those that were critically stressed had their transmissivities increased by a factor of 100. All connected fractures having transmissivities above 1.2×10^{-5} m²/s were then used in finite element and finite volume simulations to determine the impedance and thermal drawdown behavior. Impedance was calculated using the MAFIC capabilities in FracMan while the thermal drawdown was calculated using HydroGeoSphere (Therrien and Sudicky, 1996; Brunner and Simmons, 2012). Both vertical and horizontal well trajectories were evaluated for system impedance while the well orientation producing the lowest impedance values was used for the thermal drawdown calculation. These were horizontal well orientations for the normal and strike-slip stress states and vertical for the thrust faulting stress state.

Table 1. Model parameters. ¹The amount of excess pressure used for hydro-shearing was determined by taking 50% of range between the first hydro-shearing events at the center of the reservoir and the hydraulic fracture limit (equal to the minimum principal stress) and subtracting the hydrostatic pore pressure.

Reservoir Properties		Fracture Properties	
Reservoir Dimensions [km]	2 x 2 x 1	Mean Size (equivalent radius, power law distribution with exponent of 2) [m]	37
Thermal Gradient [°C/km]	60	Initial Mean Transmissivity (correlated to size) [m ² /s]	4.6x10 ⁻⁸
Well Depth [km]	3.5	Initial Mean Aperture (0.3*Transmissivity ^{0.3}) [m]	1.6x10 ⁻³
Rock Properties		Initial Mean Storativity (0.0016* Transmissivity ^{0.17})	8.6x10 ⁻⁵
Type	Granite	Min/Max Radius [m]	20/500
Density [kg/m ³]	2,600	Aspect Ratio	2
Heat Capacity [J/kg°C]	750	Number of Sides	4
Thermal Conductivity [W/m°C]	3.0	Intensity for single set P ₃₂ [m ² /m ³]	0.05
Young's Modulus [GPa]	40	Total Intensity, P ₃₂ [m ² /m ³]	0.01
Poisson's ratio	0.25	Generation model	Fisher
Water Properties		Concentration	15
Density [kg/m ³]	1000	Shear Strength Criterion	Mohr-Coulomb
Thermal Conductivity [W/m°C]	0.68	Cohesion [MPa]	0
Heat Capacity [J/kg°C]	4180	Friction Angle [degree]	30
Injection Water Temperature [°C]	75		
Well Geometry			
Orientation	Vertical and Horizontal		
Perforation interval depths [m]		2950 - 3550	3500 - 4100
Perforation Length [m]	600		
Well spacing [m]	875		
	Normal	Strike-Slip	Thrust
Stress State			
σ ₁ Trend, Plunge [degree]; Magnitude [MPa/km]	0, 90; 22.3	0, 0; 27.0	90, 0; 30.0
σ ₂ Trend, Plunge [degree]; Magnitude [MPa/km]	0, 0; 17.0	0, 90; 22.3	0, 0; 25.0
σ ₃ Trend, Plunge [degree]; Magnitude [MPa/km]	90, 0; 15.0	90, 0; 16.0	0, 90; 22.3
Hydrostatic Pore Pressure [MPa/km]	9.9	9.9	9.9
Excess Pore Pressure ¹ [MPa]	11.5	11.7	36.7
Conjugate Fracture Sets Mean Pole Orientations			
Two Sets Aligned (Trend, Plunge) [degree]	(90, 30), (270, 30)	(60, 0), (120, 0)	(90, 60), (270, 60)
One Set Aligned (Trend, Plunge) [degree]	(90, 30), (90, 90)	(60, 0), (60, 60)	(90, 60), (90, 0)
No Sets Aligned (Trend, Plunge) [degree]	(0, 60), (180, 60)	(90, 60), (270, 60)	(60, 0), (120, 0)

3. CRITICALLY STRESSED FRACTURES

The orientation of critically stressed fractures from hydro-shearing stimulation is determined by the relationship between the natural fracture sets and the stress state. Critically-stressed fractures are oriented in conjugate sets at $(45^\circ \pm \phi/2)$ symmetric about the minimum principal stress direction, σ_3 , where ϕ is the friction angle. The natural fracture orientations and critically stressed fractures for each of the nine models are shown in Figure 1. The percentage of fractures that are critically stressed is shown next to the Mohr diagrams. There is a very large range displayed between the various set alignments with a low of 4% for the normal stress state having neither of fracture sets well-oriented with respect to the stress field and 89% for the thrust faulting stress state having both natural fracture sets well-aligned with the current stress field. These percentages have significant consequences for the efficacy of hydraulic stimulation to create flow pathways between the injection and production wells. With only 4% of fractures having enhanced transmissivity after stimulation, the normal stress model having neither natural fracture set well-aligned with the stress field did not have a connected flow path sufficient to produce the desired production flux of 70 l/s.



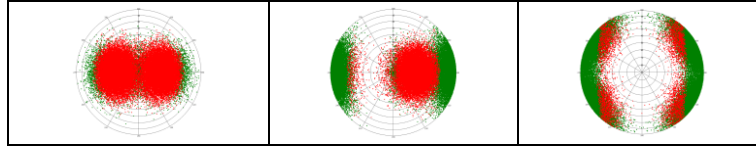


Figure 1. For each of the three regional stress states, the top row of the table shows a contoured stereonet of the natural fracture sets (pole, Schmidt equal angle, lower hemisphere), the middle row shows a Mohr diagram of the hydro-sheared system with percentage of critically stressed fractures (red), the bottom row shows the stereonet with fracture poles shown in red if critically stressed and green if non-critically stressed.

4. IMPEDANCE AND WELL TRAJECTORY

Impedance results for both vertical and horizontal well trajectory orientations are shown in Table 2. Impedance values for geothermal systems are generally desired to be below 0.15 MPa/(l/s). You can see from the results that when neither of the two natural fracture sets was well-aligned with respect to the principal stress directions either no flow paths capable of a 70 l/s flow rate were available or that the impedance value exceeded this limit. This was true for all the stress states. When at least one set was well aligned with the stress field, the impedance values ranged from a low of 0.013 MPa/(l/s) for the thrust faulting model using vertical wells and having both sets well-aligned and a high of 0.142 MPa/(l/s) for the thrust faulting model using horizontal wells and only having one set well-aligned. All the models having at least one set well aligned had acceptable impedance values although there were significant differences between the impedance depending upon the well orientations with the horizontal wells out-performing the vertical wells for the normal and strike-slip stress conditions and the vertical well providing lower impedance for the thrust faulting stress conditions. This is as expected as intersections between wells and critically-stressed fractures in conjugate sets are maximized when the well trajectory aligns with the minimum principal stress direction.

Of note when looking at the results in Table 2 is that the impedance difference comparing the two well trajectories can be quite small as in the case of the normal stress state models (0.006 – 0.026 MPa/(l/s)). This may mean it would be possible to use vertical wells in the normal stress regions without sacrificing too much in terms of system impedance. Where the differences are much larger as in the case for the strike-slip stress models (0.074 -0.083 MPa/(l/s), only looking at the cases where at least one set is aligned), it may mean that it would make more sense to spend the extra money for horizontal wells.

Table 2. Impedance results for all models with a flow rate of 70 l/s. Green shaded boxes show the lower impedance results when comparing the vertical with the horizontal well trajectories. Models having “N/A” did not have connected flow pathways. The Delta column (Δ) shows the difference in impedance between the vertical and horizontal wells.

	Impedance [MPa/(l/s)]								
	2 Sets Aligned			1 Set Aligned			No Sets Aligned		
	Vertical	Horizontal	Δ	Vertical	Horizontal	Δ	Vertical	Horizontal	Δ
Normal	0.025	0.019	0.006	0.108	0.082	0.026	N/A	N/A	N/A
Strike-Slip	0.110	0.027	0.083	0.133	0.059	0.074	0.727	0.356	0.371
Thrust	0.013	0.024	0.010	0.048	0.142	0.094	0.358	N/A	N/A

5. THERMAL DRAWDOWN

The modeled reservoir region is 2km x 2km x 2km and centered at a depth of 3,250 m. With a thermal gradient of 60°C/km, the temperature ranges from 165.6 °C at the top and 224.4 °C at the bottom. The goal was to produce water remaining above 180 °C for at least 20 years maintaining a flow rate of 70 l/s. The injection water temperature was 75 °C. Horizontal wells used for the normal and strike-slip models were placed at a depth of 3,500 m with initial reservoir temperatures of 210 °C. Vertical wells used for the thrust-faulting models were perforated from 2,950 m to 3,550 m, corresponding to initial reservoir temperatures of 177-213 °C. The initial production water temperature of these vertical wells was determined by the depth of the intersecting flowing fractures which varied in the three thrust-faulting models. Results of the thermal simulations are shown in Figure 2.

Results from the two normal stress models having at least one well-oriented natural fracture set are similar with production water temperatures dropping between 4 and 6 °C in 20 years. The two strike-slip stress models having at least one well-oriented natural fracture set show similar behavior with the normal stress models with temperature drops between 4 and 7 °C in 20 years. The strike-slip model having no well-aligned fracture sets loses 24 °C in 20 years which still keeps the production water temperature above 180 °C since the starting temperature was 210 °C. The vertical wells in the thrust faulting models show very different thermal drawdown histories compared with the normal and strike-slip stress models. The initial production water temperatures are much lower, reflecting well-fracture intersections at shallower depths and the temperature declines over time are less. After

20 years the thrust- faulting models having at least one well-aligned fracture set lose less than 1 °C while the model having no well-aligned fracture sets starts with production water temperature at 180°C and loses 8 °C in 20 years.

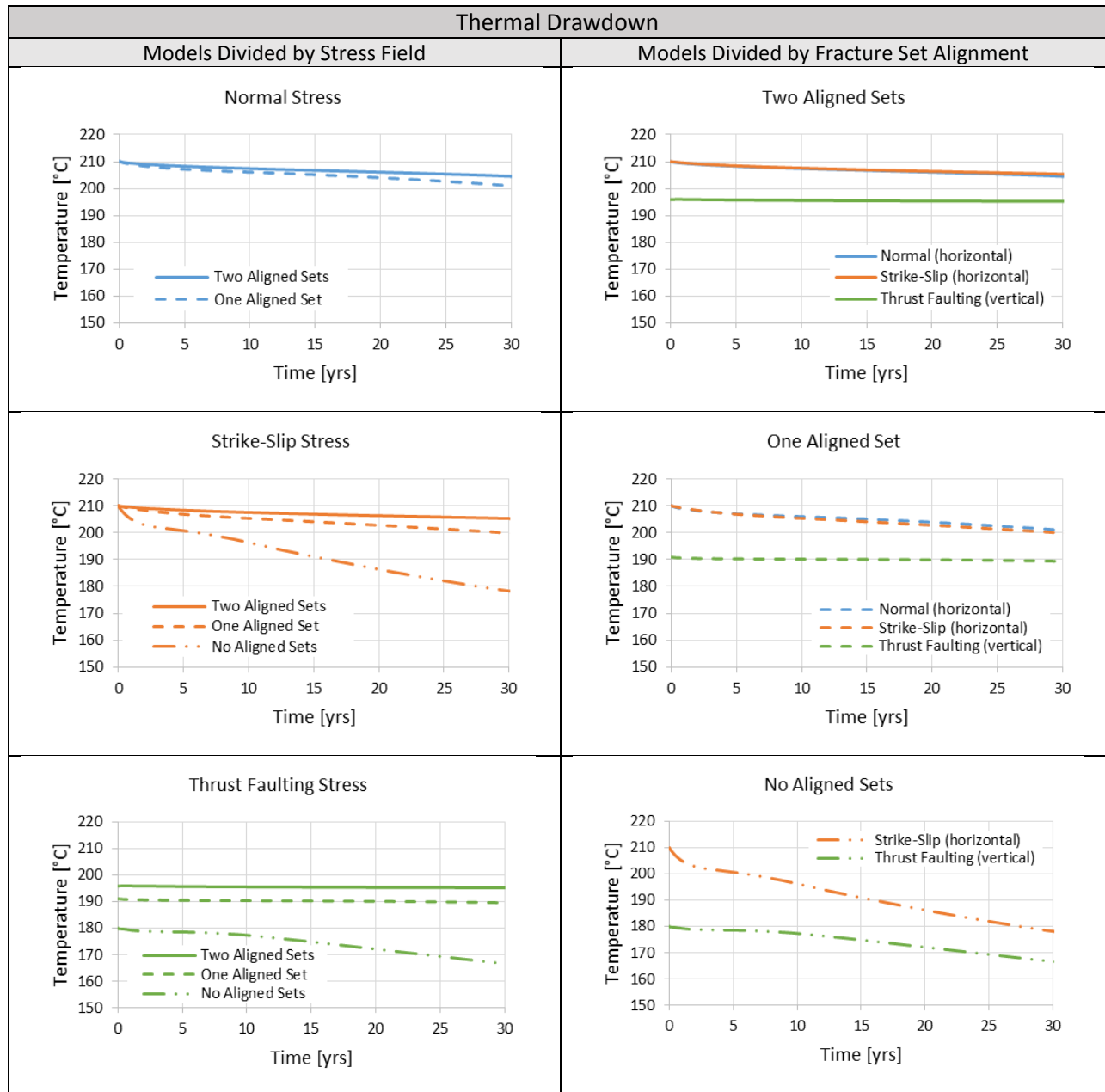


Figure 2. Thermal drawdown over a period of 30 years maintaining a flow rate of 70 l/s. Results for eight models are shown, the first column shows results grouped by regional stress while the second column groups results by how the conjugate sets were oriented with respect to the regional stress. The missing normal stress model (having no sets aligned) did not have a connected flow path available after hydro-shearing.

6. CONCLUSIONS

This work presents numerical experiments using one thermal gradient and a single lithology in a geothermal reservoir having a pair of conjugate natural fracture sets. Regional stress conditions and fracture set orientations are varied in an effort to highlight the risks associated with not knowing either the stress state or fracture set orientation in a potential EGS site. While care must be taken when extending these results to other geological settings, this is at least one example where some of the risks are quantified. In this study, looking at the choices of having two, one or no fracture sets well-aligned with the stress state in order to

maximize the number of fractures experiencing critical stress during hydro-fracturing, it is necessary to have at least one set well-aligned in order to get a low enough impedance in the system to be economical. It appears horizontal wells are necessary to exploit a strike-slip stress region while vertical wells are viable for normal and thrust-faulting stress regions. If well connected flow pathways can be established, thermal drawdown over a 20 year time period is within acceptable limits, however, initial production water temperature is hard to predict in vertical wells with large perforation zones.

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