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STATE OF THE ART OF GEOTHERMAL ENERGY SYSTEM ENHANCEMENT: A LITERATURE REVIEW

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Abstract: The application of hydraulic fracturing in geothermal reservoirs requires the consideration of aspects related to temperature, geology, and in-situ stresses. This research compares the application of hydraulic fracturing for geothermal purposes in Rotliegend sandstones of sedimentary origin in the North German Basin with that of a Granodiorite reservoir in the Pohang site in South Korea. Furthermore, some recommendations are proposed for the application of hydraulic fracturing in Ecuadorian plays for thegeneration of geothermal energy. The basement reservoirs have a hard structure and are prone to pre-existing natural fractures, especially in reservoirs for geothermal purposes, because they normally have active tectonism due to their location. In contrast, sedimentary reservoirs are not necessarily in areas with active tectonism and their more ductile structure does not make them prone to natural fractures, but their temperature gradient should be analyzed to verify their feasibility. The stress analysis, the coefficient of fracture conductivity (FCD), the Folds of Increase (FOI) and the temperature gradient are complementary factors for determining the economic viability of geothermal reservoirs. Consequently, the application of hydraulic fracturing in geothermal reservoirs requires the analysis of S_v (overburden) stress, S_{h1} (horizontal 1) stress, S_{h2} (horizontal 2) stress, temperature, FCD, and FOI. This is particularly true for the Chachimbiro Ecuadorian geothermal reservoir, where there is high temperature and active tectonism.

Keywords: *Coefficient of fracture, Conductivity FCD, Folds of Increase FOI, geothermal reservoir, Hydraulic Fracturing, overburden stress*

1. INTRODUCTION

This research compares the application of hydraulic fracturing for geothermal energy purposes in sedimentary-hosted geothermal reservoirs to that of a granodiorite reservoir. In particular, the comparison will focus on the hydraulic fracturing applied in Rotliegend sandstones in the North German Basin reservoirs and in a granodiorite reservoir in basement in the Pohang site in South Korea. In addition, some recommendations are made for the application of hydraulic fracturing for geothermal energy generation in Ecuadorian plays.

Hydraulic fracturing is the process of injecting fluid into a well to create tensile stresses in a formation, so that these stresses exceed the tensile strength of the rock and fracture it [1]. The main reason for creating these fractures is to create conductivity in the reservoir, for different purposes. One of these purposes is to produce geothermal energy from the earth's crust, which is defined as extending from the surface to a depth of ten kilometers or more, with a volume of several hundred cubic kilometers. The heat stored in this zone can be used for the generation of energy, also known as geothermal energy [2, 3].

The process of designing a fracture requires analyzing the stresses and pressure of the reservoirs (upper and lower layers), measuring the temperature of the reservoir, determining fracture conductivity (FCD) and folds of increase (FOI), estimating the fracture geometry, and calculating Fluid Loss C, spurt loss, and fluid selection-apparent viscosity (cp) for fracturing. The process also requires calibrating the model (Stresses-DFIT and Fluid loss, and efficiency-minifrac), matching the pressure history, and carrying out an economic analysis [4, 5]. Each of these steps will be analyzed in order to determine the advantages and disadvantages of applied hydraulic fracturing in sedimentary and basement reservoirs for geothermal purposes.

2. METHODOLOGY

The methodology for comparing the basement and sedimentary reservoirs follows the process of *Figure 1*. The methodology is taken from Smith et al. [5], adapted to geothermal reservoirs. The main difference between conventional-oil and geothermal reservoirs is that the active tectonic areas where geothermal reservoirs – and even some sedimentary reservoirs – are normally located can be a source of geothermal energy. Also, the temperature of geothermal reservoirs is normally higher than that of petroleum reservoirs. In this context, the fracturing will be affected by stresses and temperature when it is applied in geothermal reservoirs.

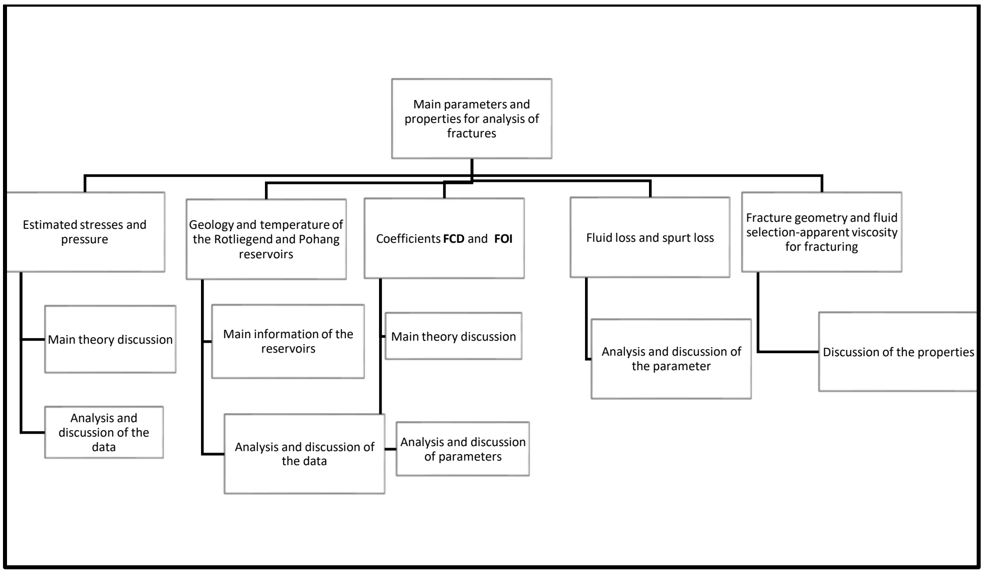

Figure 1. *Methodology flow chart for analysis of the fracturing applied to the geothermal reservoirs* [5]

2.1 Estimating Stresses and Pressures

The fractures propagate in a perpendicular direction to the minimum in situ stress; thus, the injection pressure must be greater than the minimum in situ stress. Hence, the stresses determine the orientation of the fractures. There are three main principle stresses: S_v (overburden), Sh_1 (maximum horizontal), and Sh_2 (minimum horizontal). The orientation of the fracture may be either horizontal or vertical in the majority of the cases. Moreover, Sh_2 is normally the minimum horizontal stress (the pressure where a fracture is mechanically closed) and thus the fractures in the majority of the cases are vertical. Sometimes it is possible to have inclined fractures in active tectonic areas [5, 6].

The vertical stress S_v (also called overburden stress) varies between 1 to 1.05 psi/ft, based on Smith et al. [5] and is the pressure generated for the layers over the reservoir. Then, if the reservoir is shallow the overburden is small. The horizontal stress is a reaction to the overburden stress and a reaction to geologic forces of the local structure. Consequently, if the rock is isotropic H = h1 = h2 then the horizontal stress is X * S_v. And X is defined for Poisson's ratio, lithology, pore pressure, porosity and cofining stress. However, it is important to note that because of the geological structure, the type of fault and the type of rock define the success or failure of fracturing. Of the three kind of faults, the most convenient for fracturing are the normal faults, because in this case the fractures will be vertical and there is less loss of natural fracture fluid [6]. With reverse faults, the horizontal stress is larger than vertical stress and thus the fractures are horizontal. In this case a lot of fluids can be lost. On the other hand, if there are strike-slip faults, one of the horizontal stresses is greater than the vertical stress, and the fractures should be vertical, following the fault orientation [6].

In the earth's crust, the situation of natural fractures is more complex because in the relevant geological age the directions of the main stress could change orientation according to tectonic plate movement. There are some cases, for instance, where a transpressional stress regime which began with reverse faults later changed to a strike-slip fault orientation. A specific explanation can be found in Zoback [6].

Analysis and Discussion

The estimation and analysis of the stresses and natural fracture direction are descrobed in *Table 1*.

The analysis of the stress regime is important because the natural fractures can define the conductivity of the fracture and of course the loss of fluid. In the case of the basement in the Pohang site in South Korea, there is a transpressional stress regime. That means that natural fractures in the reservoir start at the inclination of the fault slip for the compressional stresses, but then the natural faults change direction, becoming vertical in accordance with strike-slip faults. Thus, there is a disordered fracture system in the reservoir.

Table 1

Analysis and comparison of stress and pressures between Rotliegend sandstones in the North German Basin reservoirs and in a granodiorite reservoir in basement of the Pohang site in South Korea [7, 8, 9, 10, 11]

Reservoir		**magnitude of stress**	**stress regime**	**observations**
Basement in Pohang site in South of Korea [7, 8, 9]	S_v[MPa]	107	strike-slip/reverse (Transpressional)	Reverse natural fractures are expected to dip and strike normal to the direction of S_{h1} which is N100°E
	S_{h1}[MPa]	133-153		
	S_{h2}[MPa]	98-119		
Rotliegend sandstones in the North German Basin reservoirs [10, 11]	S_v[MPa]	100	Normal faulting/strike-slip	strike-slip natural fractures are expected to be vertical and strike 40.36° from the S_{h1}
	S_{h1}[MPa]	78–100		
	S_{h2}[MPa]	53		
	S_v[MPa]	100	Normal faulting/strike-slip	
	S_{h1}[MPa]	78–100		
	S_{h2}[MPa]	58.6		

If a well reaches the reservoir basement, the development of artificial fractures can produce a disordered flow of fluids, as depicted in *Figure 2.*

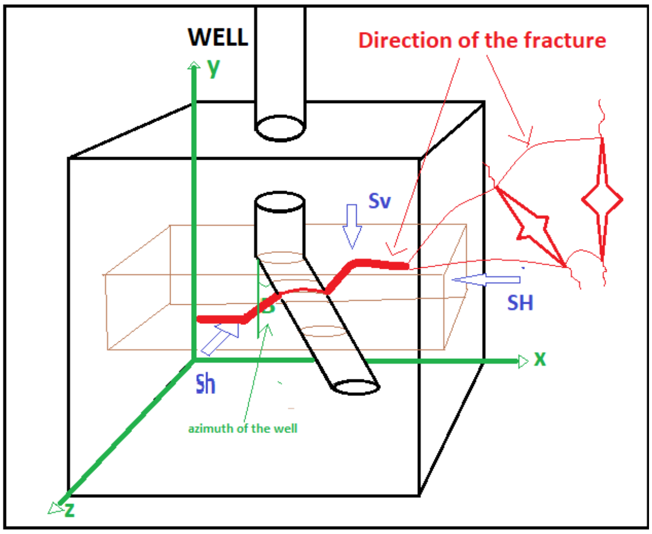

Figure 2

Change in the orientation of the fractures for transpressional regime [7]

Whereas the basement in Pohang site in South Korea has a transpressional regime with strike-slip/reverse regime, the Rotliegend sandstones in the North German Basin reservoirs have a Normal faulting/strike-slip. There, the natural fractures are expected to be vertical. However, like the sandstones it is not common to find natural fractures. Furthermore, if fractures are developed, these are vertical in the offset angle of the direction of the fault. In this case the angle is 40.36° from the direction of S_{h1}, the value calculated by Moeck and Schandelmeier [11] and Legarth, Huenges and Zimmermann [10].

2.2 Geology and Temperature of the Reservoirs

In addition to the stress analysis, the geology and the temperature also are important because they define the hardness and ductility of the reservoir. The main reservoir's characteristics are described here.

Sedimentary Geothermal Reservoir in Rotliegend: Temperature of at least 120 °C. Upper Rotliegend: reservoir compound of silt, sandstones and conglomerate. Lower Rotliegend: reservoir compound comprised of volcanic rocks (Mg-andesites, pyroclastites with interlayered sediments). In the middle, there is a layer of clay with low permeability with higher anisotropy. Permeability over 200 md, Pay zone: 4130–4190 m, 4078–4118 m. Clastic sediments without carbonate cements [10, 11].

Closure stress: lower interval 8.4 MPa of effective closure stress. Identified stress gradients are dpc/dz = 12.7 and 14.3 MPa/km respectively [11].

A granodiorite reservoir in basement in Pohang site in South Korea: The temperature here is at least 160 °C [8]. Granodiorite is an intrusive igneous rock with a phaneritic texture and crystals of medium size (2 mm–5 mm). It is normally made out of quartz, sodium plagioclase and amphibole. The basement rock in Pohang is covered by Cretaceous sedimentary rock (sandstones and mudstones) mixed with sequences of tuff andesite layers. Permeability 0.00018 D, 0.5% porosity [7, 9].

Analysis and Discussion

The temperature for the basement reservoir is higher than for the sedimentary reservoir. Normally, the temperature depends on the reservoir's location. Many geothermal reservoirs are close to places with volcanic activity, at hot spots, rifts, or the union of tectonic plates [12]. The deeper the reservoir, the higher the temperature, so the basement has higher temperatures than those of sedimentary reservoirs [12]. When applying hydraulic fracturing, it is important to have the right temperature when choosing the fluid, especially when using proppant. The proppant must be able to withstand high temperatures in the reservoir conditions, i.e., the proppant's properties should not change at high temperatures. The equipment used for hydraulic fracturing must also support higher temperatures (160 °C to +300 °C) than is common for equipment used in petroleum reservoirs [13].

2.3 Coefficient of Fracture conductivity (FCD) and Folds of increase (FOI)

The coefficient of fracture conductivity (FCD) is defined as the product of high fracture permeability and width in the reservoir over the reservoir permeability and penetration.

$$FCD = \frac{Kf * w}{K * Xf}, \tag{1}$$

where Kf is fracture permeability (a term used for permeability in mD); W is width in m; K is reservoir permeability in mD ; Xf is fracture half-length in m. The FCD indicates the transport capacity of the fluid fed into the fracture. According to Smith and Montgomery [5] the FCD value must be 2 or greater for higher permeabilities, and 10 for lower permeabilities.

The folds of increase (FOI) is the ratio between initial reservoir productivity and reservoir productivity after stimulation (evaluated with various proppants and frac lengths) [5].

$$FOI = \frac{IP_{BEFORE}}{IP_{AFTER}}, \tag{2}$$

where IP_{Before} is the index of productivity before the fracturing in BFPD/psia, and IP_{After} is the index of productivity after fracturing in BFPD/psia. The stimulation ratios or indices of productivity are individual values and have to be determined for each reservoir or fracture setting [10].

Stimulation ratios increase with increasing FCD, reaching a half-length dependent maximum. High values of FCD can be caused by low matrix permeabilities and increases in stimulation ratio can only be achieved by increasing fracture length. A good FOI with a bad FCD means that even with a bad fracture design, the results are good with an effective wellbore radius, which is the apparent wellbore radius:

$$r_{wa} = r_w * e^s, \tag{3}$$

where r_{wa} is effective wellbore radius in feet, r_w is wellbore radius in feet, and s is skin factor.

Analysis and Discussion

The values of FCD and FOI for the Rotliegend sedimentary reservoir and Pohang basement reservoir are given in *Tables 2–4.*

Table 2

Coefficient of fracture conductivity of Pohang reservoir

	Pohang	units	**source**
K_f (fracture permeability)	7599.38 to 50662.51	mD	[7]
K (matrix permeability)	1.82385E-6	mD	[7]
w (width)	0.00006–0.00012	m	[7]
x_f (half fracture length)	15	m	[9]
FCD	16666.67–222222.22		**calculated**

Table 3
Coefficient of fracture conductivity of Rotliegend reservoir

	Rotliegend	**units**	**source**
conductivity (K_f*w)	0.003 to 0.005	mD.m	[10]
k matrix permeability	1.99995E-5	mD	
X_f (half fracture length)	3236	m	
FCD	1.6–1.8 (4.41–7.35 designed)		**calculated**

Table 4
Folds of increase of Pohang and Rotliegend reservoirs

RESERVOIR	FOI	Source
Pohang	7.5	calculated with process of Smith and Montgomery [5]
Rotliegend	1.6–1.8	[10]

According to the theory, the FCD must be a value close to 2. The Pohang reservoir has extremely high FCD values *(Table 2)*, meaning that the reservoir has good conductivity, which might be a product of the natural fractures in the transpressional stress regime and that fracturing is unnecessary. For the case of the Rotliegend reservoir, the FCD was designed to get a value between 4 and 7, but the results give a value between 1.6 and 1.8 *(Table 3)*. This means that the fracture has an acceptable value for the petroleum industry, although it was designed for better results. For the purposes of petroleum engineering the fracture was successful, but for geothermal purposes it was not, as the flow rate was not high enough for optimum geothermal energy production.

The FOI for Pohang reservoir is high *(Table 4)*, and without any other parameter it means that the fracture was successful. However, combined with the results of the FCD, that no longer applies. Additionally, in the Rotliegend reservoir the FOI value means that the conductivity of the reservoir improves, but production results would not necessary be economically profitable *(Table 4)*.

2.4 Fluid Loss and Spurt Loss

Fluid loss is calculated by two parameters, the C fluid loss coefficient and the V spurt. The C fluid loss coefficient is a function of formation permeability, reservoir pressure, reservoir temperature, formation fluid properties, fracturing fluid viscosity, and the wall building characteristics of the fracturing fluid. Typical values of C are from 0.0005 to 0.01 ft/min$^{1/2}$. The fluid loss coefficient is affected by the permeability of the formation. If the formation permeability is bigger there will be more loss of fluids, because a filter cake will not form. The fluid loss coefficient is formed by three more coefficients Cv also known as CI, CII and Cw: Cv is the filtrate viscosity effect, CII the reservoir fluid compressibility effect and Cw the wall building effect coefficient, which is related to the V spurt. Specific explanations can be found in Smith and Montgomery [5].

Analysis and Discussion:
There is no practical way to calculate the C fluid loss coefficient for the Rotliegend sedimentary and the Pohang basement reservoirs. However, the low permeability improves the possibility of a filter cake forming in the fracture, so in this case that parameter is better for basement reservoirs. For the other side, the kind of fluid used is important because it directly affects the calculus of Cv and CII partial coefficients of the fluid loss coefficient. The Cw is calculated only if there is no filter cake [5].
The fluid loss coefficient is normally calculated for petroleum reservoirs but it could be important for the design of fractures in geothermal reservoirs. Besides, the Cv will be affected by relative permeability of the kind of fluid used (for geothermal, usually water) and by the temperature of the reservoirs, especially as geothermal reservoirs require higher temperatures.

The spurt loss is big when there is no wall cake . The geothermal reservoirs in this case have small permeabilities, so filter cake is formed. The Cw wall building coefficient typically is 0 for permeabilities between 0.1–0.5 mD [5].

2.5 Fracture Geometry and Fluid selection-apparent viscosity for fracturing

When selecting the fluid, the viscosity is extremely important, not only for volume considerations but also for the geometry of the fracture. Furthermore, a bad viscosity design can cause the fracture fluid to extend fractures too far, mis-apply the proppant, increase costs, and raise reservoir pressures too high.

The geometry of a fracture relates the permeability with the length and width of a fracture. The petroleum industry uses the FCD coefficient of fracture conductivity for economically profitable designs of fractures. *Table 5* shows the ranges of permeability, length of fractures and width for petroleum designs of fractures.

Table 5

Range of X_f with K and FCD, designed for a petroleum well's fracture geometry [5]

K reservoir permeability[mD]	Xf Desirable[m]	FCD	K_fW [m^2-m]
0.0001	1,066.8	250	2.63E-14
0.0005	1,005.84	125	6.20E-14
0.001	853.44	50	4.21E-14
0.005	609.6	25	7.52E-14
0.01	548.64	10	5.41E-14
0.1	274.32	5	1.35E-13
0.5	213.36	2	2.11E-13

K reservoir permeability[mD]	Xf Desirable[m]	FCD	K_fW [m^2-m]
1	121.92	2	2.41E-13
5	91.44	2	9.02E-13
10	57.912	2	1.14E-12
20	45.72	2	1.80E-12
50	30.48	2	3.01E-12
100	15.24	2	3.01E-12

Analysis and discussion:
According to the dominant theory of the petroleum industry, the Pohang and Rotliegend reservoirs need fractures with lengths over 55 m. That is important because the permeability is related to the quantity of fluid that can be given for the reservoir and the capacity of transport of the fracture. In the case of the Pohang reservoir, notably, there is no analysis of FCD or dimensions of fracture design. In contrast, in the Rotliegend reservoir there is an analysis of geometry, but the simulation of the fracture is too conservative. *Table 6* shows the geometry of the fractures: in the design of Rotliegend reservoir the fracture length considered was 32 m, while in the Pohang reservoir X_f was 15 m. Consequently, the geometry of the fracture is important but it is not the only important parameter for geothermal reservoirs. In other words, the geometry has to be analyzed with the geothermal gradient because it provides a limit to the rate of fluid it is necessary to produce and bears on the profitability of the geothermal reservoir. For profitability, the geothermal theory should have a minimum geothermal gradient of 30 °C/km, assuming a 4 km reservoir with the rate of fluid production of 20 kg/s [10]. However, the design will be more successful if it resembles that of the reservoir geometry design indicated in *Table 5*.

Table 6
Main data of the geometry of the fracturing applied in the reservoirs

Pohang Reservoir			Rotliegend Reservoir		
W (width)	0.00006–0.00012	m	W (width)	0.0016	m
H (height)	30–150	m	H (height)	72	m
Xf (length of fracture)	15–75	m	Xf (length of fracture)	32–36	m

2.6 Recommendations for application to Ecuadorian reservoirs

Ecuador is a small country located in the west of South America. Of Ecuador's 11 prospective geothermal-energy sites, six are especially important: the Galápagos Rift, Galápagos Hot Spot, Northern Andes, Southern Andes, Coastal Fore-arc basin, and Oriente Foreland basin. This paper will analyze the geothermal resource located in the northern half of the Andes Cordillera, considered Ecuador's best prospect [7]. The geothermal resource is located in extensive active quaternary volcanism. Within this area there are four high temperature plays, namely Chachimbiro, Chacana-Jamanco, Chacana-Cachiyacu and Tufiño-Chiles (there is another low temperature prospect in Chalpatán). A 1978 m well was drilled in Chachimbiro (PEC 1), which revealed basaltic andesite and andesite pyroclastic rock and a bottom temperature of 235 °C.

There are four main recommendations if hydraulic fracturing were to be applied in this play. (1) The fluid and equipment used for fracturing must be resistant to high temperatures. Packers, tools, and fluid – and especially the proppant used – must be able to withstand high temperatures (over 300 °C). (2) The play is located in a zone of active volcanism and the rock is not very malleable, so it is possible to find a lot of natural fractures. It is important to study the geomechanical (rock mechanical) properties for active tectonism, so as to avoid extremely disorganized fractures and find the best location for the wells. (3) The calculation of FCD, FOI and Geothermal Gradient is important in order to get productive fractures. (4) Finally, given the well's depth, it is possible that excessive fluid loss could occur through horizontal fractures in the reservoir. For that reason, the choice of well location must take into account the reservoir's horizontal stress directions.

3. Conclusions

The basement in the Pohang site in South Korea had a change of stress regime that caused hydro-shearing during the moment of applied hydraulic fracturing: subsequently, there were earthquakes and the project was put on hold. That example shows the importance of analyzing the stress regimes and their change over time when evaluating geothermal resources. The coefficient of fracture conductivity (FCD) and folds of increase (FOI) in the Pohang site revealed an extremely large fracture that could cause problems with earthquakes. It is also fundamentally important to analyze the temperature gradient in geothermal reservoirs, since the FCD, FOI and temperature gradient are complementary features. In the Rotliegend sedimentary reservoir a complete analysis was done, including calculations of the FCD, FOI and geothermal gradient, but in that case the simulation was too conservative. The sedimentary reservoir needed bigger fractures to get the optimum volume. Therefore, if the analysis joins the characteristics of a sedimentary reservoir with the necessity of bigger fluid rates, the simulation should be less conservative . However, the FCD values recommended – between 2 and 10 – must be verified in different kinds of geothermal reservoirs because these values are intended for conventional petroleum reservoirs.

The analysis of FCD and FOI in the Ecuadorian geothermal reservoirs is extremely important because the active tectonism in the place may have created different natural fractures in several directions. Consequently, it is recommended that calculations of the main stresses be updated before applying hydraulic fracturing. The high temperature of Ecuadorian geothermal plays will require high-specification hydraulic fracturing equipment.

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