PROCEEDINGS, Thirty-Ninth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 24-26, 2014
SGP-TR-202

Applicability of GEOFRAC to model a geothermal reservoir: a case study

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ABSTRACT

The Rock Mechanics Group at MIT has developed a stochastic fracture pattern model, GEOFRAC. This is based on statistical input on fracture patterns from the field. GEOFRAC has been applied and tested by estimating the fracture intensity and estimated fracture size from tunnel records and from borehole logs. Since its original development, GEOFRAC has been expanded by including an intersection algorithm, a flow model and, most recently, a thermal model. The fracture-, flow- and thermal models have been tested, and a parametric study was conducted in order to check the sensitivity of the output results to the inputs.

The aim of this paper is to show the applicability of GEOFRAC to a real case. Data of a geothermal power plant obtained from the energy company, Landsvirkjun, Iceland, are implemented in GEOFRAC. Assumptions are made in order to determine the unavailable parameters to input in GEOFRAC, such as the fracture intensity P32 (fracture area per volume) and the best estimate fracture size E[A]. The assumptions and the results of the simulation are presented in this paper.

The analysis shows that GEOFRAC produces reasonably close results to the real geothermal conditions. The estimation of important factors such as flow rate and energy extraction rate are reasonable. However, GEOFRAC has still limitations that need to be assessed. The analysis conducted and reported in this paper allowed our group to detect limitations of our model ~~but~~ as well as its strong points.

INTRODUCTION

GEOFRAC is a model created by the Rock Mechanics Group at MIT. It is a three-dimensional, geology-based, geometric-mechanical, hierarchical, stochastic model of natural rock fracture systems. Fractures are represented as a network of interconnected polygons and are generated by the model through a sequence of stochastic processes. GEOFRAC takes a series of inputs that take into account the geometry of the reservoir, fracture characteristics, flow and thermal data.. GEOFRAC has been applied and tested by estimating the fracture intensity and estimated fracture size from tunnel records and from borehole logs (Ivanova et al. 2004, Einstein and Locsin 2012). A parametric analysis was also conducted in order to check the consistency of the model and determine which parameters have the greatest effects on the final results (Vecchiarelli et al. 2012). A heat transfer model in GEOFRAC, was then introduced (Li et al. 2013), and a simple case study on the Fenton Hill project was conducted.

The aim of this paper is to present results of GEOFRAC tested with real data made generously available by the energy company, Landsvirkjun, Iceland. This allows us to verify the reliability of this model for representation of hydrothermal reservoirs, to understand the limitations and to implement possible changes in the associated code.

The geological-hydro-thermal description of the geothermal field selected is presented in the first part of the paper. The parameters selected for the simulation will be then presented and discussed. Then the results and conclusions will end this paper.

CASE STUDY

<u>Námafjall geothermal field</u>

The Námafjall geothermal field is located in NE-Iceland about 5 km northeast of Lake Myvatn as shown in Figure 1. Precisely, it is located in the southern half of the Krafla fissure swarm and it is associated with the Krafla volcano. The Krafla geology is characterized by active rifting, forming a graben zone through its center, where volcanic craters, volcanic pyroclastics and lava flows, all of basaltic composition, dominate. The fissure swarm that intersects the Krafla central volcano (100 km long and 5 to 8 km wide) is part of the neo-volcanic zone of axial rifting in N-Iceland (Figures 2 and 3), (Malimo, 2012).

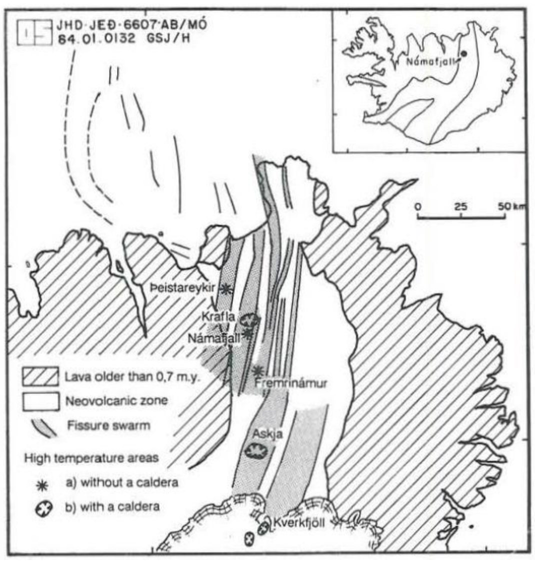

Figure 1 -The high temperature areas in North Iceland and location of the Namafjall geothermal reservoir (from Isabirye, 1994)

Magma from the Krafla caldera traveled horizontally in the SSW direction along the fissures and fractures all the way down to Námafjall, and it serves as the heat source for the hydrothermal system. The Námafjall field is characterized by the Námafjall ridge, about 0.5 km wide and 2.5 km long. There are several fractures and faults in this area, such as the Krummaskard and Grjótagjá, and often surface manifestations are clearly aligned with the fractures. The geological characteristics of the Námafjall field indicate that the Námafjall ridge is part of the Námafjall-Dalfjall-Leirhnjúkur ridge, and it has an overall length of about 15 km and width of about 1 km (Ragnars et al., 1970).

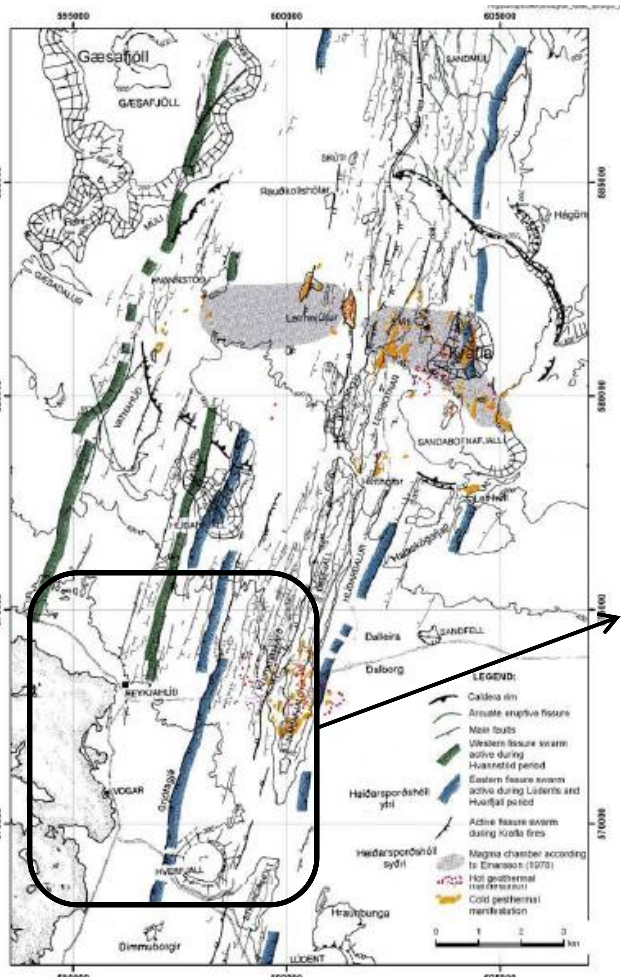

Figure 2 - Structural map of Krafla and Námafjall geothermal areas showing the Krafla caldera and associated fissure swarm.

(from Sæmundsson, 1991).

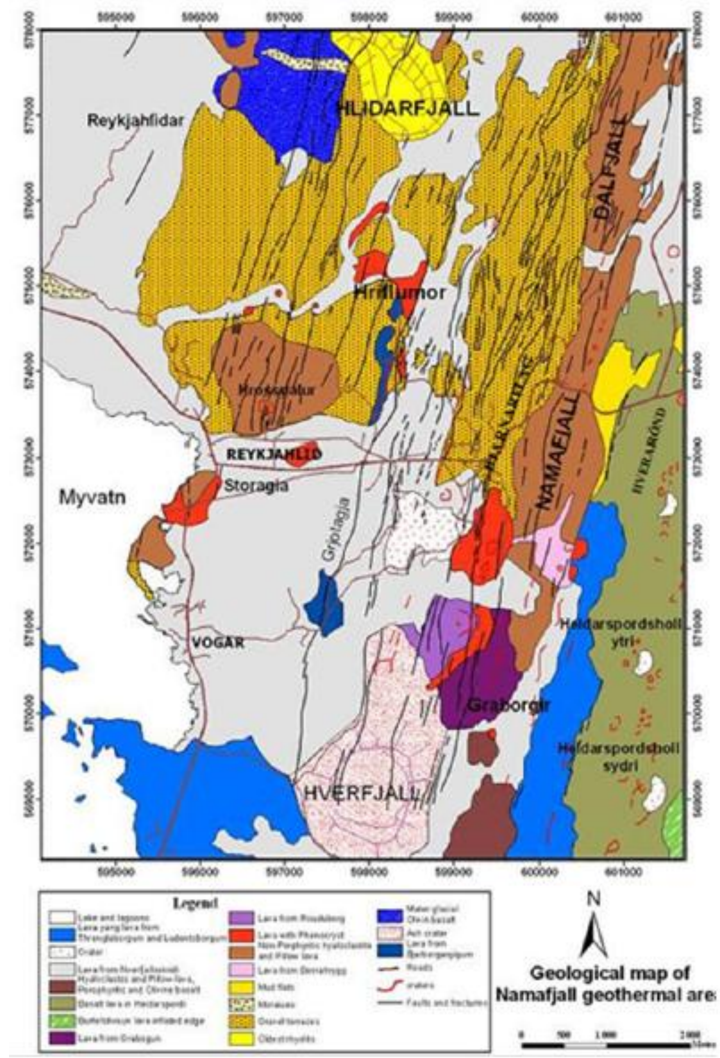

Figure 3 - Geological map of the Námafjall area. (from Sæmundsson, 1991).

The surface rocks in the study area are highly permeable. The postglacial lava flow acts as good aquifer. There are numerous open fissures and large active faults with a NNE/SSW strike, like Grjótagjá and Stóragjá (Ragnars et al. 1970) that add to the already permeable nature of the lavas. Figure 4 shows a possible groundwater flow model. There is a relation between the direction of the lava flows and the direction of groundwater flow probably caused by the fact that the fissures developed during the cooling of the lava, are mostly parallel to the direction of the lava flow.

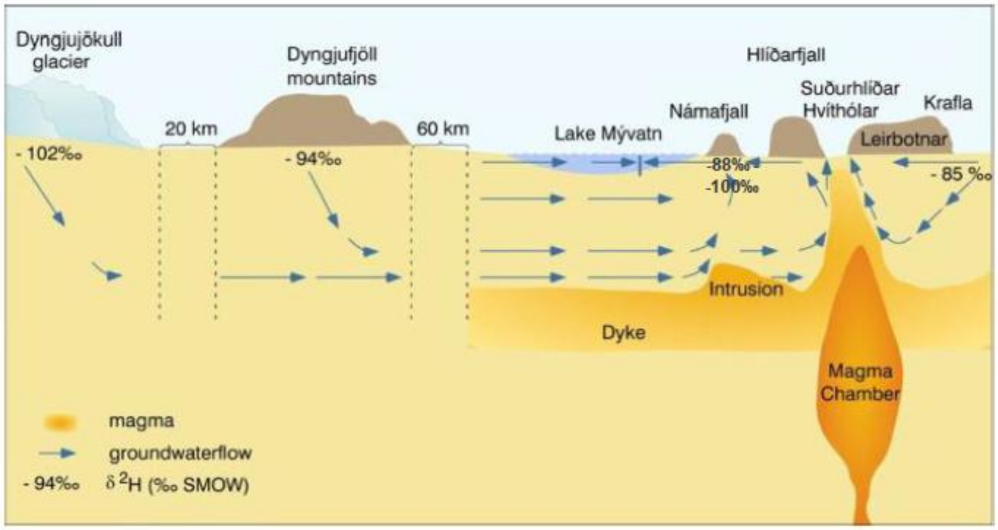

Figure 4 - Possible groundwater flow model to Námafjall and Krafla (Malimo, 2012)

Inputs selected for the simulation in GEOFRAC

Deep drillings conducted in this area have provided important information ~~of~~ on the sources and composition of geothermal fluids, thermal properties of the fluids and the geology and fracture system of this geothermal area. Numerical models of the reservoir engineering can help with the characterization and optimal use of the geothermal resources. In general the parameters used in application of GEOFRAC can be found from a preliminary survey and exploration: P32 can be obtained from fracture spacing information obtained in boreholes and on outcrops. Best estimate fracture size E(A) can be obtained from fracture trace lengths on outcrops with suitable bias corrections. Distribution and estimates of fracture size can also be obtained subjectively. The list of the inputs needed in GEOFRAC is listed in Figure 5.

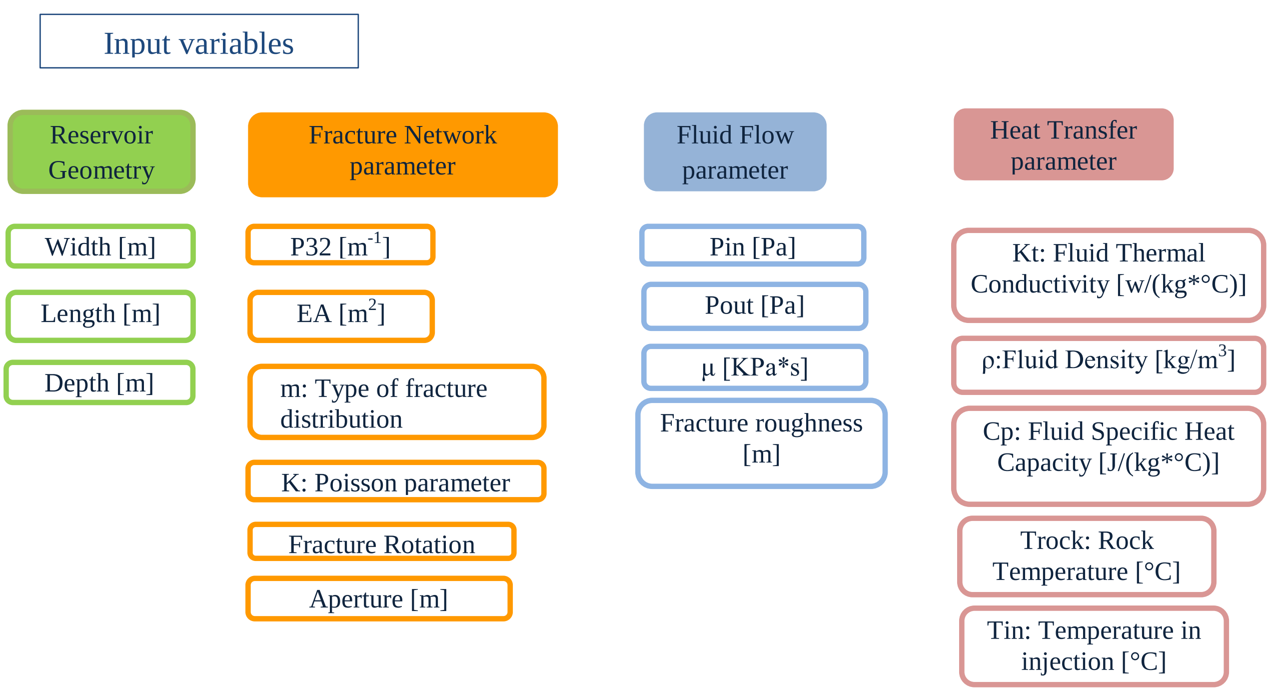

Figure 5 - Inputs for GEOFRAC

The inputs selected for the Námafjall simulation are reported and explained in the next sections. All the physical data described in this paper were obtained from the Rivera Ayala, 2010 report, from boreholes and measurements given by Landsvirkjun and from other references mentioned.

Reservoir geometry

The Namafjall geothermal field is a large reservoir formed by the Krafla caldera. It is about 10 km long and 5-8 km wide. The magma chamber is at a depth 3-7 km under the caldera.

In our model the dimension X, Y, Z (Figure 6) express the size of the reservoir that we want to simulate. Z in particular refers to the injection length. We conducted simulations on the slice from 1000-2000m depth; this is in fact the fractured zone in this particular field (Isabirye, 1994). For our simulation we therefore assume:

X=1 km

Y= 2 km

Z= 1 km

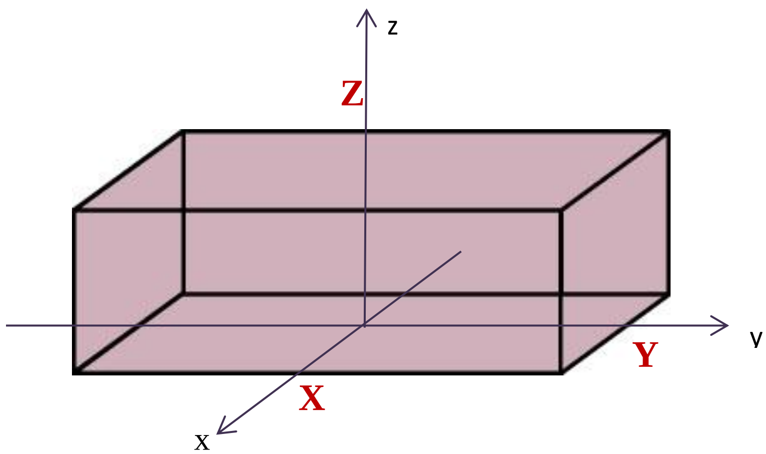

Figure 6- Coordinates of the controlled volume according to GEOFRAC

Fracture network parameters

In GEOFRAC fractures planes are generated in the volume V with a Poisson plane process of intensity μ where μ= P_{32}. P_{32} is given as sum of the areas of all fracture i ($A_{f,i}$) over the total modeled volume (Equation 1):

$$P_{32} = \frac{\sum_{i=1}^{N} A_{f,i}}{V} \qquad \textit{Equation 1}$$

The other fracture parameter E(A) is the mean area of fractures.

According to the geology survey and boring logs, the hydrothermal reservoir is fractured by major faults fissures and manifestations (Rivera Ayala, 2010). The boring data indicated very big spacing between the fractures. So a low value for P32 and high value for E[A] is chosen to simulate this geologic condition. The values are:

The values selected are:

$P_{32} = 0.02\ m^{-1}$

$E(A) = 800000\ m^2$

The orientation of the planes generated with a stochastic process, can be specified with the Fisher distribution. Lower values of the Fisher parameter *k* indicates more randomly oriented planes; higher *k* indicates that the planes are mostly parallel to each other. From borehole data, the major planes in this area appear to be mostly parallel to each other; for this reason a k=20 was chosen for this simulation. The mean pole of the major fractures is (π/2, 0), because the field data indicates that the fractures are mostly horizontal, as show in Figure 7.

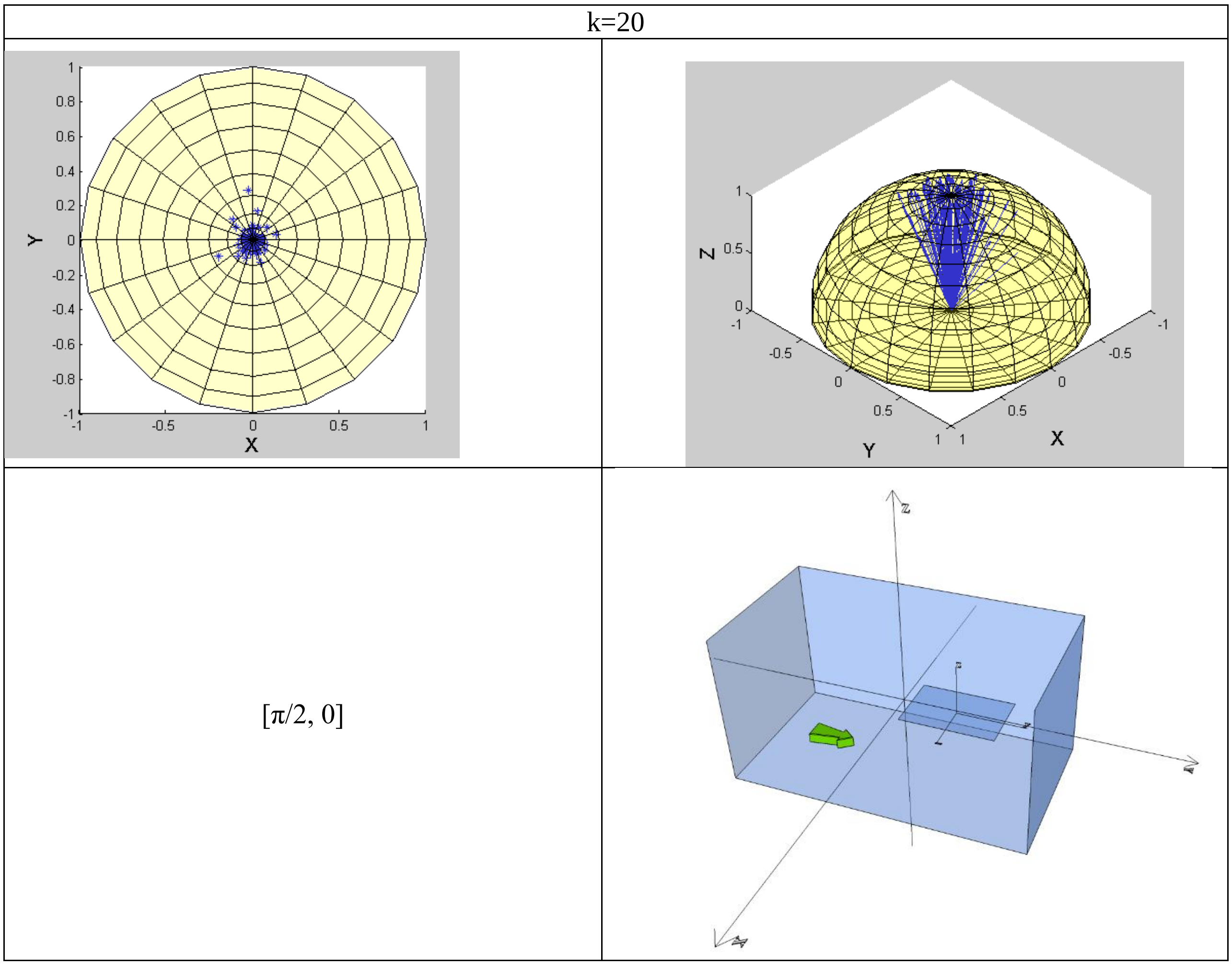

Figure 7- Schematic representation of the mean orientation of the major fracture planes

Random translation and rotation (see Vecchiarelli, 2012) of the fractures (polygons) conducted to represent the local variation of fracture position and orientation of minor fractures. A new algorithm in GEOFRAC was added to the model to allow the user to model fractures with or without random rotation. Because the simulation presented here is concentrating on simulating the major planes, we assume that the fractures are all in the same plane and no rotation of the single fracture is considered.

No data are available for the aperture of the fractures in this reservoir. GEOFRAC has three models available to be used in order to generate fracture aperture. For this case the probabilistic approach is used. According to the statistical study done by Dershowitz and Einstein, (1988), the apertures of fractures follow a truncated lognormal:

$$f_{TR}(h) = \frac{f(h)}{\int_{\min}^{h_{\max}} f(h)\,d(h)},\ h_{\min} \le h \le h_{\max} \qquad \textit{Equation 2}$$

Where h_{min} and h_{max} (in meters) are the minimum and the maximum aperture values. This relation is presented in Figure 8.

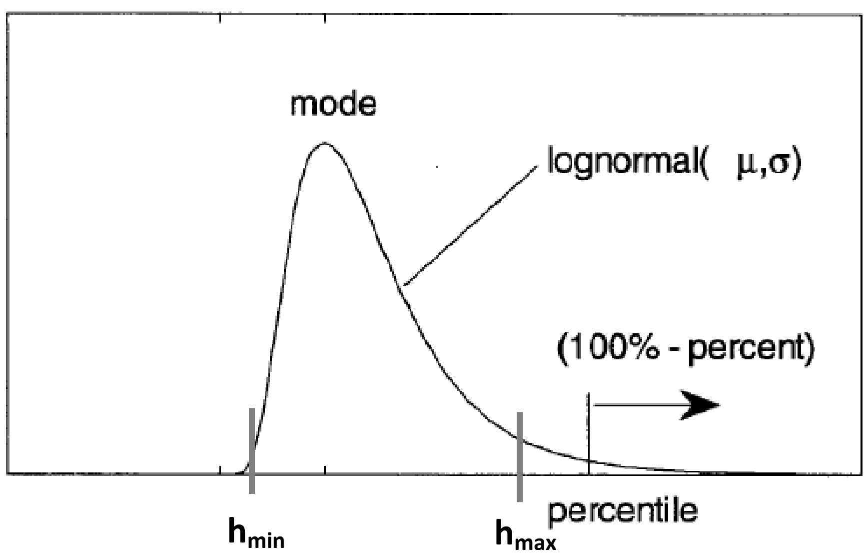

Figure 8 - Truncated lognormal distribution

For the simulation h_{min} = 0.00002 m, mode=0.004m and h_{max} = 0.01 m is used to shape the distribution curve. The distribution of the apertures is shown in Figure 9.

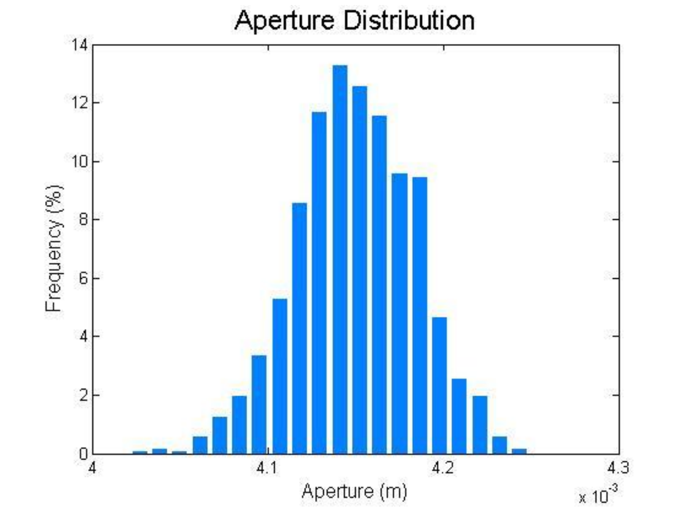

Figure 9- Aperture distribution that follows a truncated lognormal distribution

Fluid flow parameters

The flow equations used to model the flow through the fractures are those of laminar flow between parallel plates. The water flows only in the x direction between two parallel plates with the no-slip condition for viscous fluids forming the parabolic velocity profile in the y direction. The roughness of the fracture (as shown in Figure 10) considered in the simulation is ε = 0.4 m.

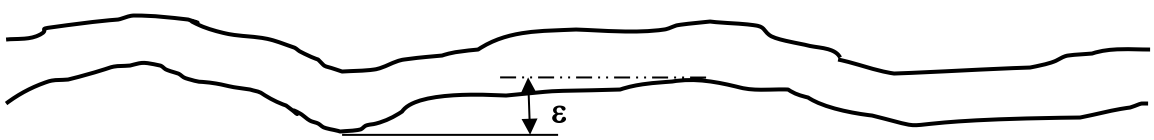

Figure 10 – Schematic representation of the roughness

The initial thermal condition of the water is assumed to be 60°C. So the value of the viscosity is $\mu=0.468\times10^{-3}$ Pa·s and the fluid density, ρ=983kg/m3.

Heat transfer parameters

Figure 11 shows selected temperature logs obtained in the well B-9 in the period 1970 - 1993. In the first years, the logs near surface are influenced by cooling during drilling and thus do not show real rock temperature. At 1300 m the temperature was higher than 250 °C. Looking at all the logs the average temperature below 300 m is around 200-250 °C.

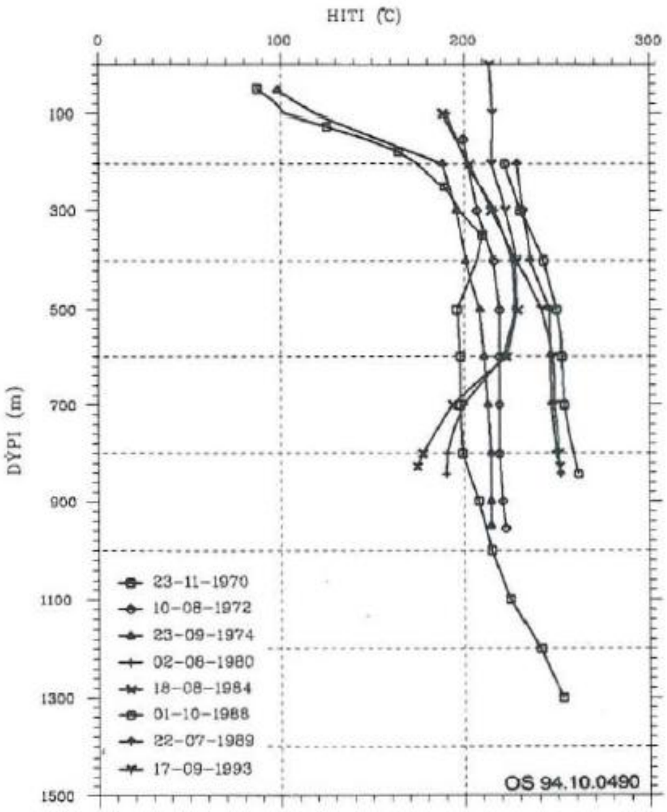

Figure 11 - Temperature measurements in well B-9, 1970-1993 (Isabirye, 1994)

In the area the majority of the wells predict temperatures of 240°C - 260°C (Rivera Ayala, 2010). For the simulation T_{rock}= 250°C is used. The magma chamber is located below 3-7 km under the caldera, and it serves as a source of heat for the hydrothermal system; so the assumption of constant temperature of the surrounding rock is reasonable.

For a typical heat exchanger, the outlet temperature, which is also the temperature of the injected water, is around 60 °C, so the injection temperature is assumed to be 60 °C. The thermal properties of the fluid do not change much with temperature, so constant values are used:

Fluid Thermal Conductivity Kt=0.6546 w/(kg*°C)

Fluid Specific Heat Capacity, Cp = 4185 J/(kg*°C)

Results

Figure 12 is a schematic representation of the possible flow paths in one simulation. The purple numbers represent the temperatures (°C) in each branch while the blue numbers represent the flow rates (l/s). This figure shows that GEOFRAC, as a discrete fracture model, calculates the flow rates and temperatures explicitly.

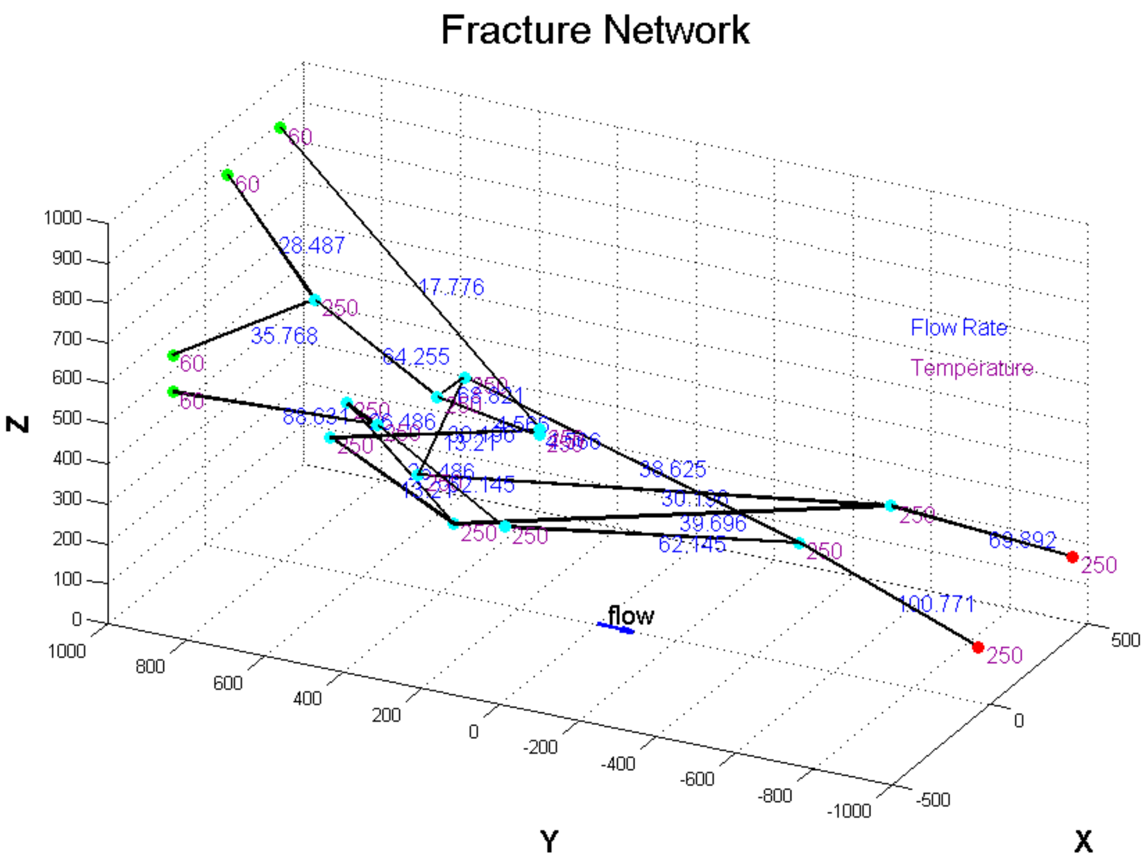

Figure 12 - Schematic representation of the fracture flow system obtained in one simulation

Because of the stochastic processes used in GEOFRAC, the results are not deterministic. To draw reliable conclusions, a moderate number of simulations has to be run. Here, 20 simulations are run and analyzed as follows.

The average value of the total flow rates is 0.21 m^3/s. This value is in line with the production flow this actual power plant is producing (ISOR, 2013). The standard deviation of the results is $0.14 m^3/s$, which indicates that GEOFRAC can provide results that do not deviate much from the real data. The Reynolds number of all the branches is checked to make sure that the assumption of laminar flow in the flow model is satisfied.

Because of the small apertures and large areas of the fractures, the heat transfer between the rock and the flow is very efficient. As we can see from Figure 12, the temperature of the water reaches that of the rock at the first node after the injection boundary. One has to keep in mind, however, that the thermal model in GEOFRAC assumes a constant rock temperature, so the results can only model the beginning stage of the injection. Still, the results indicate that the large area and small apertures of fractures are very helpful in extracting the heat from the underground.

The average energy extraction rate estimated by GEOFRAC is 116,224 KW; it is much higher than the capacity of the power plant, which is around 10 MW (Ragnars et al., 1970). This is quite understandable given that the energy conversion efficiency of a geothermal plant is often around 20%. In addition, the heat transfer model is based on the above mentioned assumption that the temperature of the rock is constant, but in reality, there is temperature drawdown in the rock. The heat extraction rate cannot be maintained for a long time. Although the results GEOFRAC overestimate the power of the plant, they provide the upper bound of the power. Future work on the thermal model is needed to produce a long term temperature prediction of the reservoir.

When the parameters used in GEOFRAC are varied, the changes in the results reflect the sensitivity of the model. We conducted such parametric studies and these studies indicate that the fracture parameters such as fracture intensity, best estimate of fracture area, and orientation have a very large influence on the fracture network. The number of fractures, number of flow paths and their geometry are all dependent on these fracture parameters. Aperture plays a very important role in determining the flow rate and heat transfer mainly because the cube of the aperture appears in the governing equation. In other words the resulting flow rate is very sensitive to the aperture distribution. These parametric studies, therefore indicate that the choice of parameters has to be done extremely carefully.

CONCLUSIONS

The simulation of a real case with GEOFRAC, showed that this model can be used to represent a hydrothermal reservoir. When selecting the inputs in the model is important to understand that the model is very sensitive to the aperture parameter as well as to the orientation of the fractures.

Another goal of this research was to understand the uncertainty of field predictions and to detect possible limitations and necessary improvements of GEOFRAC. The main limitation in the modelling effort was the lack of data concerning fracture intensity P32 and best estimate fracture area EA. Other restrictive assumptions in the present GEOFRAC are the homogeneity of the parameters for the entire reservoir and the assumption of a single phase fluid.

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