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Depth-Dependent Scaling of Fracture Patterns Inferred from Borehole Images in GPK3 and GPK4 Wells at Soultz-sous-Forêts Geothermal Site

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ABSTRACT

Engineering an Enhanced Geothermal System (EGS) requires a proper understanding of the fracture network properties from small to large scales in order to create a reliable geological model for reservoir simulations. As deterministic identification of all fractures in a reservoir is practically impossible, stochastic approaches known as Discrete Fracture Networks (DFN) are used. This consists of parametrizing a statistical realization of fracture networks constrained by direct observations from borehole images and/or outcrop data, if available. DFN models can be used to study the thermo-hydro-mechanical (THM) properties of fractured rocks and to simulate the processes associated within: I) fluid circulation, II) flow and heat production as well as III) seismic response to hydraulic stimulations.

Fractal DFNs are based on multiscale fracture network characteristics and are constrained by the scaling properties of fracture network attributes such as length (or size) and spatial distribution. The dual power-law model is a mathematical representation of fractures that parametrize fractal DFNs with two scaling exponents: 1) scaling of spatial distribution using two-point correlation dimension of fracture centers in three dimensions and 2) power-law exponent of fracture length distribution. Direct measurements of fracture length exponents from borehole images or cores are an unresolved challenge and the resolution of geophysical investigations is not sufficient to image the natural fracture networks. In contrast, the spatial distribution of fractures may be precisely characterized using borehole image logs and cores.

Currently, the depth-dependence of spatial clustering of fracture patterns in the earth's crust is not fully understood, although it may be required to anticipate deep reservoir conditions from shallower datasets. Here, we study such a depth dependency by using the two-point correlation dimension of fractures along the boreholes as a reliable estimate of the fractal dimension. We investigate the data stemming from two deep boreholes, GPK3 and GPK4, drilled into the crystalline basement rocks at the Soultz-sous-Forêts geothermal site. Recent analyses unraveled no systematic variation of fractal dimension with depth in any of the boreholes at the one standard deviation level of uncertainty. This conclusion may support the hypothesis of generating fracture network models with only a single correlation dimension using the stereological relationships in reservoirs up to 5 km depth in crystalline basements.

1. INTRODUCTION

The global challenge to develop renewable energies has made geothermal energy a promising potential energy resource. The vast unexploited amount of energy stored in the earth's crust (e.g. Tester et al. 2006), demands extensive efforts to develop the necessary technologies for widespread heat extraction and electricity production. Current operational geothermal plants are limited to certain geological settings, where ideal temperatures are found in relatively high permeability host rocks. Enhanced Geothermal Systems (EGS) aim at creating a reservoir at high temperature depths, typically between 2-5 km depth, to circulate fluids (e.g. water) between injection and production boreholes, where the flow occurs mainly in the fracture network (Genter et al. 2010). Reservoir creation is achieved by enhancing (i.e. artificial increase) the permeability of the rock mass with massive fluid injections in the target zones, referred as hydraulic stimulation. It has been reported that hydraulic stimulation results in 2-3 orders of permeability enhancement at site scale (e.g. Evans et al. 2012), which results in a considerable increase of flow rate. On the other hand, hydraulic stimulation is typically accompanied with induced seismicity, that may be felt by public and lead to project suspension as in Basel (Häring et al. 2008) and St. Gallen geothermal projects in Switzerland (Edwards et al. 2015). Hence, operational parameters in hydraulic stimulations must be designed to enhance the permeability while keeping the seismicity in low levels. Since the matrix permeability of the target zones is usually not sufficient to transfer fluids, the flow occurs mainly within the pre-existing or newly generated fracture network (Genter et al. 2010). The thermo-hydro-mechanically coupled processes activated during hydraulic stimulation of fractured rocks are very complex and not fully understood, yet (Amann et al. 2017). However, two main stimulation mechanisms control the permeability enhancement: 1) hydraulic shearing, if the fluid pressure drives slip on pre-existing fracture network and 2) hydraulic fracturing, if the injection pressure is sufficient to generate new tensile fractures (e.g. Evans et al. 2005). Both these mechanisms may be concomitant in hydraulic stimulation operations, while one mechanism is mostly dominant (e.g. Gischig and Preisig 2015). The scientific efforts must address optimizing the operational parameters of hydraulic stimulation to sustainably enhance the permeability, while keeping the seismicity in low levels. This is achieved by developing numerical models that can simulate the associated physical processes in complex structural geometries of the fractured rocks.

Characterization of natural fractures is a preliminary step to build a representative geological model. Fracture network geometry is believed to largely control not only the flow and transport patterns, but also the rock mass deformation and heat exchange between the fluid and the host rock. Therefore, the knowledge on the natural fracture network is a critical element in designing and evaluating stimulation scenarios in deep geothermal systems. Such a characterization of EGS reservoirs is a challenging task, because no direct observation of the fractures is possible. Geophysical techniques from surface are limited in resolution, when dealing with great depth and the dimension of fractures is typically lower than the resolution of imaging techniques. Furthermore, the reflection seismic technology is difficult to interpret in crystalline basement rocks, because potential reflectors are inherently not well defined. More relevant data can be acquired when a deep well is drilled through the target rock mass with geophysical logging techniques (i.e. image logs). Image logs identify the position and orientation of fractures along the borehole. However, fracture network characterization is challenging at early project stages, especially when data from only a single exploration well penetrating the target reservoir may be available. Valley and Evans (2015) provided a summary of the state-of-the-art in reservoir characterization from borehole measurements and identified the gaps in knowledge. Deterministic reconstruction of 3D fracture network from 1D fracture datasets derived from borehole images (e.g. acoustic televiewer logs), is a challenging task (Afshari Moein et al. 2019). Thus, stochastic realizations known as Discrete Fracture Network (DFN) models are implemented and conditioned by statistical parameters observed from the wellbore fractures including the spatial distribution and orientation of fractures. DFN models may also be constrained with other sources of information including hydraulic data (e.g. Ringel et al. 2019; Somogyvári et al. 2017), and in situ stress perturbations observed in image logs (Afshari Moein et al. 2018a; Valley et al. 2014). Among various DFN models presented in literature, fractal DFNs have gained a large attention, since they allow generating multiscale fracture patterns following similar statistics at different scales. An extensive amount of field observations also supports the hypothesis that fracture network attributes such as spatial patterns, length distribution, spacing and aperture follow power-law statistics (e.g. Allegre et al. 1982; Barton and Zoback 1992; Boadu and Long 1994; Bonnet et al. 2001; Lei and Wang 2016; Moein et al. 2016; Tezuka and Watanabe 2000; Torabi and Berg 2011). In order to parameterize fractal DFN models, it is crucial to reliably estimate the scaling exponent (i.e. fractal dimension) of different attributes particularly spatial distribution. Proper application of fractal DFN models at the scale of a geothermal reservoir demands adequate understanding on the potential depth dependence of spatial patterns in earth's crust. Such a depth-dependence may be implemented to anticipate deeper reservoir conditions from shallower datasets.

In this paper, we briefly present the dual power-law model as a 3D fractal DFN model. Then, the fractal behavior of fracture patterns is demonstrated from two 1D fracture datasets. The data is derived from borehole image logs of two deep wells (GPK3 and GPK4) drilled into crystalline basement at Soultz-sous-Forêts geothermal project in France (Valley 2007) and study the depth-dependence of scaling exponent of spatial distributions. Finally, we outline the applications of such analysis to EGS applications and future research directions.

2.1 Discrete Fracture Network Model

The dual power-law model is a versatile and efficient mathematical representation of fractures that combines the spatial and size distribution of fractures in a 3D cubic volume in three dimensions of side length L following equation 3,

$$n(l,L)dl = \alpha . L^{D_{3D}} l^{-a_{3D}} dl, \quad l \epsilon [l_{min}, l_{max}] \tag{3}$$

where $n(l,L)dl$ is the number of fractures having a length between l and $l+dl$, α is a constant of fracture density, D_{3D} is the correlation dimension of fracture centers in space, and a_{3d} is the length exponent (Davy et al. 1990). Dual power-law model has been widely used to study the hydromechanical properties of fractured rocks using fractal DFNs (e.g. Harthong et al. 2012; Lei and Gao 2018). Bour et al. (2002) have successfully verified this model by evaluating the scaling properties of multiscale fracture maps taken of outcrops in the Hornelen Basin (Norway). This DFN model has also the capability of forecasting the maximum magnitude of induced seismicity based on clustering of size distribution of early patterns (Afshari Moein et al. 2018b). A detailed step-by-step methodology to generate synthetic DFNs in 1D, 2D and 3D following equation 4 is presented in previously research papers (e.g. Afshari Moein et al. 2019; Darcel et al. 2003b). Figure 1 presents a 3D DFN model generated using the dual power-law model with the following parameters $D_{3D} = 2.7$, $a_{3D} = 2.8$ and $\alpha = 0.1$. Note that the orientation of fracture planes is random.

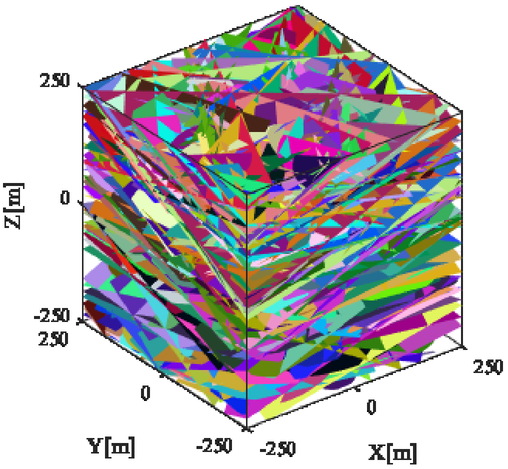

Figure 1: An example of a DFN model generated using dual power-law model with the $D_{3D} = 2.7$, $a_{3D} = 2.8$ and $\alpha = 0.1$.

2. SCALING OF FRACTURE PATTERNS

Fractal geometry has been widely utilized to characterize the scaling properties of fracture patterns in geological media (e.g. Bonnet et al. 2001; Torabi and Berg 2011). Since data obtained from a deep geothermal reservoir is typically 1D fracture datasets including the location and orientation of fractures intersecting the borehole, it is necessary to characterize the available data to gain insights in the geometrical properties of the fracture network and its distribution. The spatial distribution of 1D fracture patterns may be characterized by a scaling exponent, known as fractal dimension D, which is a measure of clustering degree. The fractal dimension of 1D patterns is a number between 0 and 1, of which lower values indicate higher degree of clustering. However, we briefly introduce and illustrate the methodology to estimate the fractal dimension of 1D borehole datasets from a deep borehole.

2.1 Two-point Correlation Function

Two-point correlation function or correlation integral (referred as correlation function later on) defines the probability of finding a pair of fractures separated by a given center-to-center distance (Hentschel and Procaccia 1983). Correlation function may be applied to characterize the clustering of fracture centers in 1D, 2D and 3D fracture networks through equation 2,

$$C(r) = \frac{2}{N(N-1)} N_p(r) = \Lambda r^D \tag{2}$$

where, N is the total number of fractures, N_p is the number of pairs of fractures whose center-to-center distance is less than r and the total number of pairs of fractures is $\frac{N(N-1)}{2}$. D is the correlation dimension (1D, 2D or 3D spatial distribution) and Λ is a constat. Λ is an interesting parameter that can distinguish the fracture patterns with the same correlation dimension. We adopt the hypothesis that the fracture network is monofractal system and the correlation function method permits a reliable and stable estimation of fractal dimension over a large range of scales for 1D and 2D datasets (Afshari Moein et al. 2019; Bour et al. 2002). Note that the correlation function has also been applied to characterize the scaling properties of microearthquake hypocenters (e.g. Hirata et al. 1987).

3. STUDY SITE AND FRACTURE DATASETS

Soultz-sous-Forêts geothermal site, also known as European EGS project, is located close to the western fringe of the Upper Rhine Graben in France. The Upper Rhine Graben (URG), a Cenozoic rift system (Dèzes et al. 2004), has been known as the most promising region to develop geothermal power plants in central Europe. Figure 2 shows an overview of deep geothermal projects in the URG and Soultz-sous-Forêts is located almost in the center of the map. This geological map highlights the importance of URG in the recent geothermal developments in Europe. Note that not all the projects in this figure are operational.

The granitic rocks at Soultz-sous-Forêts are late Hercynian granitoids with various grades of hydrothermal alteration containing phenocrystals of alkali feldspars in a matrix of quartz, biotite, plagioclase and minor amphibole (Dezayes et al. 2010; Sausse et al. 2008). Two main granitic rocks are commonly found in Soultz: 1) Mega K-Feldspar monzogranite that is typically found between 1420 to 4700 m depth, 2) fine-grained two-mica granite from 4700 m to 5000 m (Dezayes et al. 2005). Valley (2007) analyzed the borehole images from two 5 km deep wells (i.e. GPK3 and GPK4) and defined seven fracture sets based on their orientation. Here, the same fracture datasets were used without taking their orientation into account. Figure 3 presents the isodensity (lower-hemisphere and equal angle) projection of poles of fractures observed in GPK3 and GPK4. Table 1 presents an overview of the available fracture datasets in this analysis, including the study interval of crystalline basement at each well, the source of fracture datasets and the number of identified natural fractures.

Table 1: The relevant information of the fracture datasets from GPK3 and GPK4 wells in Soultz-sous-Forêts geothermal site

Well	Study Interval MD [m]	Source of information	Number of fractures
GPK3	1420-5000 m	Image Log	1926
GPK4	1420-5000 m	Image Log	2115

4. FRACTAL ANALAYSIS

In order to perform a comparable fractal analysis, normalized two-point correlation functions of fracture intersection depths along each borehole were computed for 500 points logarithmically distributed uniformly in the range 0.1-10,000 m. The local slopes of the log-log plots of the *C(r/L)* function were computed for 25-point wide windows that were progressively moved across the *C(r/L)* curves without overlap. The normalized correlation and slope functions of all fractures in GPK3 and GPK4 datasets are shown in Figure 4. Note that all fractures are included in the computation of correlation function regardless of their orientation. The log-log slopes plots show a constant value for more than three orders of magnitude of *r/L*. The fractal dimensions are 0.88 for both. The associated errors are less than 0.05 for the two wells.

5. DEPTH-DEPENDENT FRACTAL ANALYSIS

The geometrical characteristics of fracture network influence the hydraulic response of the system (Bonneau et al. 2016; Darcel et al. 2003a). Knowledge of the spatial distribution of the fractures along deep boreholes helps us to understand the structure of discontinuities in the crust. Here, we applied the two-point correlation function method to successive depth intervals taken along GPK3 and GPK4 boreholes to assess whether any systematic variation in fractal dimension of fracture spacing is resolved.

In the intervals with 200 fractures, normalized two-point correlation functions were computed for 100 points uniformly spread logarithmically between 0.1 and 1000 m (i.e. 20 points per decade). The local slopes of the correlation functions were calculated by performing a linear fit over a 10-point wide window moved along the data with 75% overlap so as to give 20 slope values for every order of magnitude. Each log-log slope function was inspected to identify the range over which its value was reasonably constant, and a linear regression with a horizontal line performed to identify the correlation dimension and the standard deviation. In all cases, the plateau was seen to span at least 1.5 orders of magnitude in *r/L*. For both datasets, 200 fractures were included in each window, and the latter moved along the profile in steps of 100 fractures, giving a 100 fracture overlap on successive windows so as to increase the number of D_{1D} determinations. The fracture density and cumulative fracture density profiles of two wells are shown in Figures 5 and 6. There are some slight variations of the cumulative fracture density slopes versus depth. In GPK3, there are two variations in 2960 m and 4750 m. In addition, There are similar shifts in GPK4 in a depth of 3350 m and 4500 m.

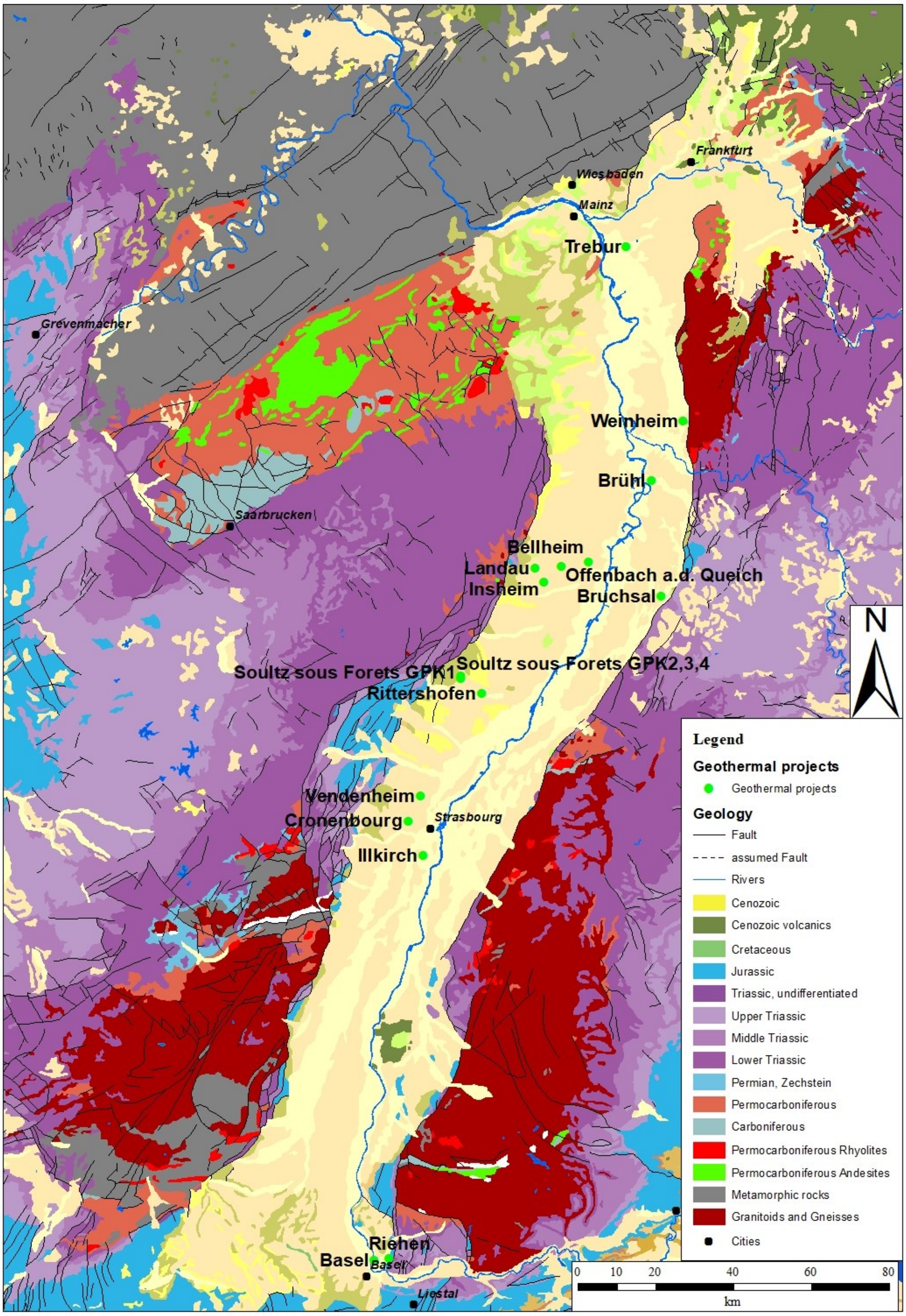

Figure 2: Overview of deep Geothermal Projects in the Upper Rhine Graben. Overview of deep Geothermal Projects in the Upper Rhine Grabe; Geology after Voges et al (1993). Note that not all projects are operational.

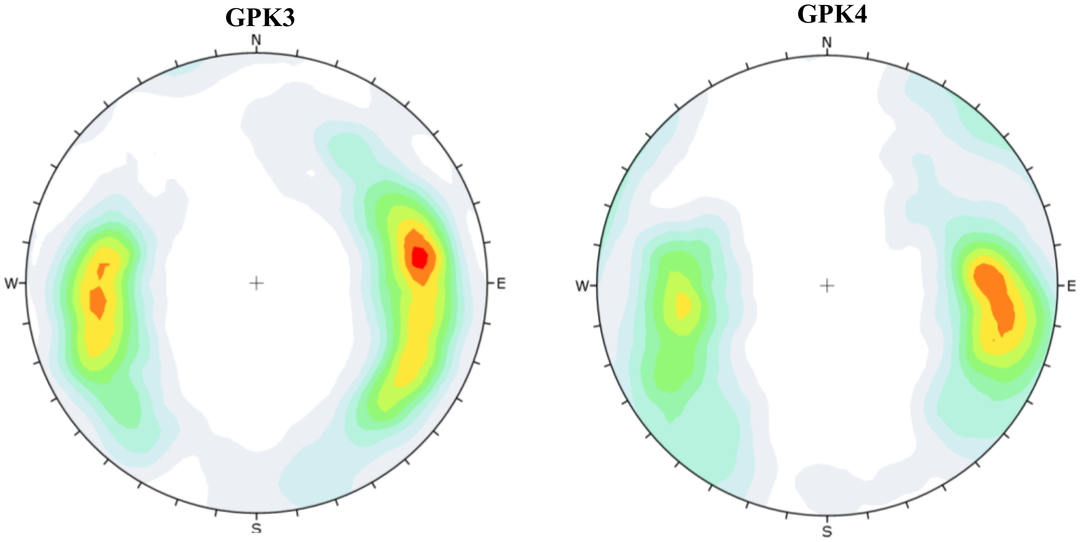

Figure 3: Isodensity (lower-hemisphere and equal angle) projection of poles of fractures observed on image logs in the wells drilled into Soultz-sous-Forêts geothermal site GPK3 GPK4 (data from Valley, 2007).

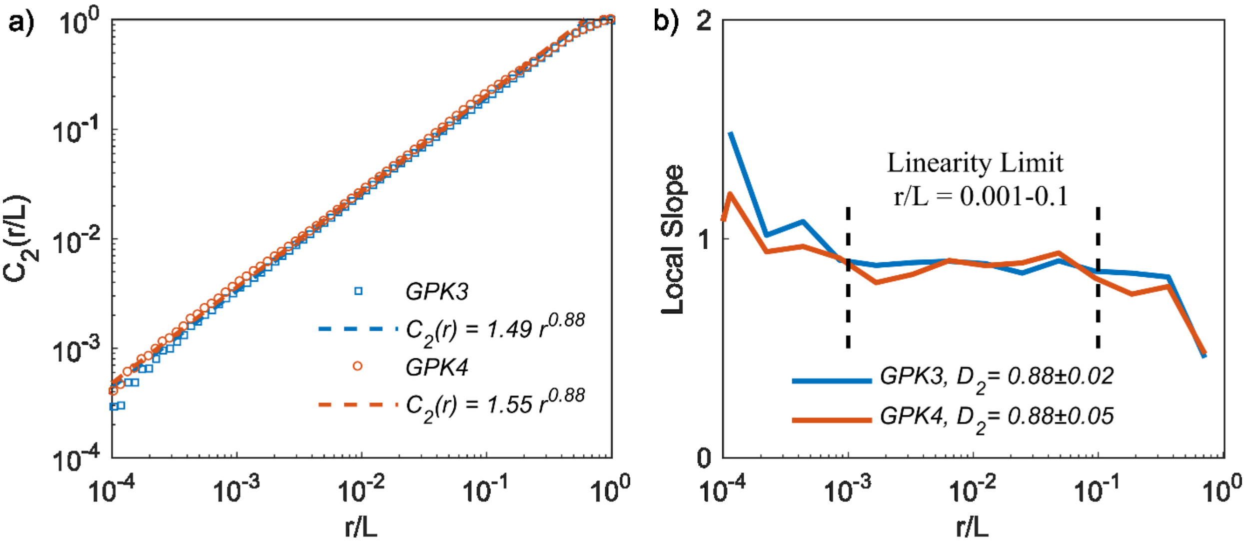

Figure 4: (a) Correlation and (b) log-log slope functions derived from all fractures intersecting the GPK3 and GPK4 wells.

6. DISCUSSION AND OUTLLOOK

Setting up Discrete Fracture Network models conditioned to the data from boreholes or outcrops are essential to subsurface rock mass characterization programs including EGS developments (e.g. Watanabe and Takahashi 1993). The computation of 1D correlation dimension for the fracture datasets derived from borehole images of two deep boreholes showed that fracture populations in GPK3 and GPK4 follow fractal statistics in more than two orders of magnitude. The resulting correlation dimension of both wells are very close (0.88±0.02 and 0.88±0.05 for GPK3 and GPK4 respectively). Such a similarity may be justified by the same tectonic settings (i.e. the Upper Rhine Graben system) that both wells are located in. The inter-well distance between two wells increases up to 700 m toward the bottom of the boreholes. Thus, the persistence of the correlation dimension in these boreholes indicate not only a depth homogeneity of the fracturing fractal characteristics, but although a lateral homogeneity within the sampled volume between the boreholes.

Genter et al. (1997) performed a comparative study of the fracture datasets from cores and image logs. They concluded that image logs can only detect about 20% of the fractures that are detected by cores. This imposes a large uncertainty on fracture network characterization from image logs. In a similar study, Fernández-Ibáñez et al. (2018) have also reported a 50 % coverage of the image logs in carbonate rocks. Note that the number of fractures strongly influences the fractal dimension estimations. Despite these limitations, the scaling parameters are valid over more than two orders of magnitudes, i.e. typically in the range of 2 to 200 m. This constitutes a strong evidence and supports that the fracture networks investigated in granitic rocks follow a fractal organization. One advantage of such a fractal organization is that available stereological relationships provide the initial estimates of 3D spatial distribution of fractures. However, such relationships may include an inherent uncertainty when going from 1D to 3D for the expected range of the fracture length exponents in three dimensions.

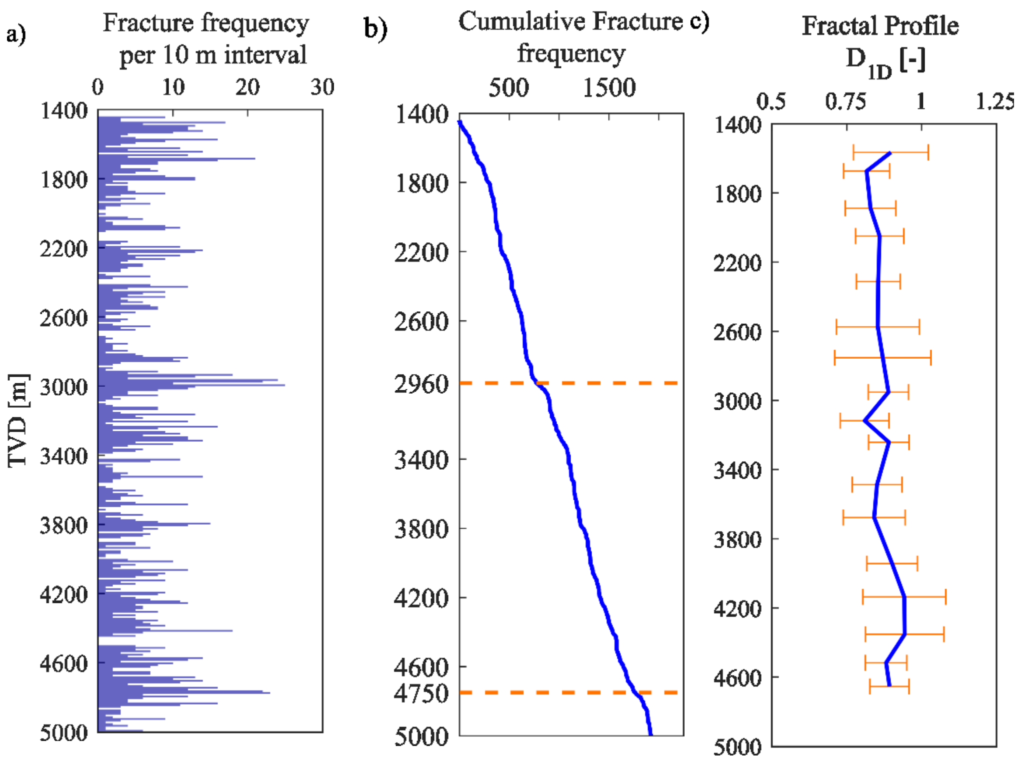

Figure 5: (a) Profile of the number of fractures per 10 m identified in the GPK3 from image logs (b) Profile of the cumulative number of fractures versus depth in the GPK3 from image logs (c) Variation of correlation dimension in moving windows containing 200 fractures with 100 overlaps in GPK3. The estimates are drawn in the center of the data windows, and the error bars represent the standard deviation of the local slope within the fractal range.

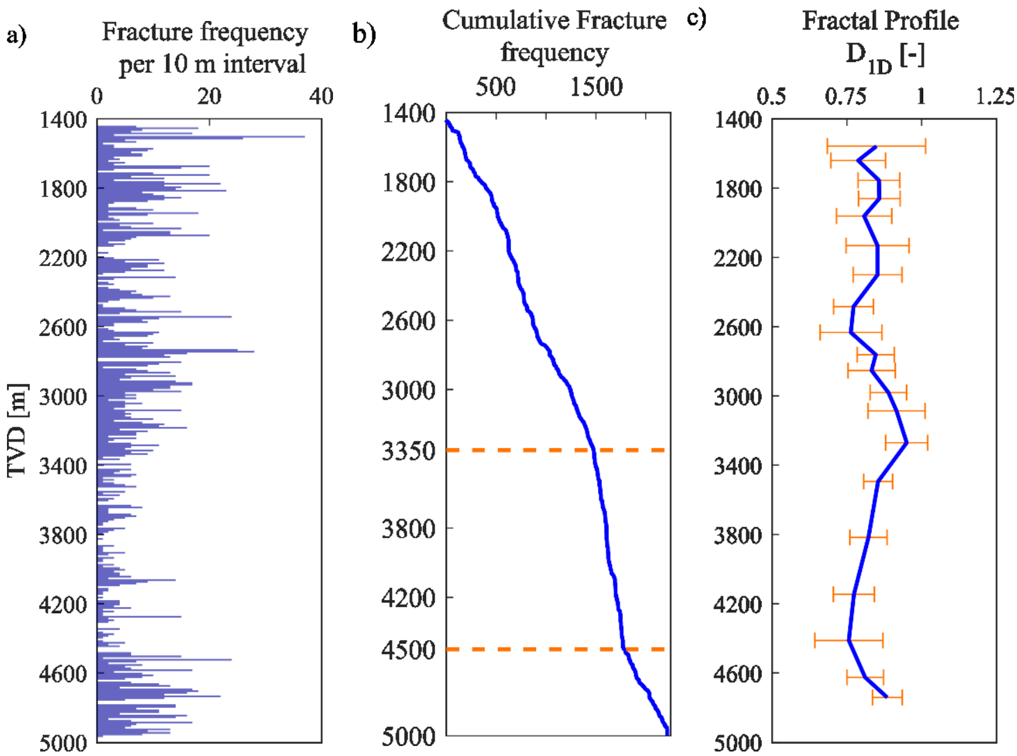

Figure 6: (a) Profile of the number of fractures per 10 m identified in the GPK4 from image logs (b) Profile of the cumulative number of fractures versus depth in the GPK4 from image logs (c) Variation of correlation dimension in moving windows containing 200 fractures with 100 overlaps in GPK4. The estimates are drawn in the center of the data windows, and the error bars represent the standard deviation of the local slope within the fractal range.

The detailed analyses of the fracture patterns GPK3 and GPK4 demonstrate variations of fracture frequency with depth. However, no systematic trend is observed. No clear trend of fractal dimension is resolved. The depth-dependence analyses of the fractures in both boreholes indicate that a unique fractal model, such as dual power-law model, may be implemented to represent the fracture population in a rock mass. However, the change in the fracture frequency must be considered by changing the fracture density or intensity parameters. For the case of dual power-law model, the parameter of α must be adjusted. Furthermore, fracture intensity for 3D networks may be defined as ratio of the total fracture area to the domain volume (P_{32}). If the continuum approach is chosen to model THM within the crystalline basement rock, then this may imply that the whole section could not be modelled as one homogeneous block. Therefore, it would make more sense to define three model units with different properties to better reflect the geothermal target zones of both wells (Figures 5b and 6b). Also, a correlation with geothermal gradients or breaks in the slope of the geothermal gradient may also support the presented hypothesis, that will be performed within the future scope of research project.

Further developments of this research require more datasets from deep boreholes in crystalline basement rocks to validate the proposed conclusions. Despite being rare, the datasets derived from continuous cores will improve our understating about the fracture network properties in depth. The findings may also be compared to synthetic fracture datasets from dual power-law model or similar DFN models in literature.

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