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Genetic-like modeling of fracture network honoring connectivity data in the geothermal heat exchanger at Soultz-sous-Forêt (France).

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Abstract

This paper reports on our investigations to integrate reservoir connectivity data in a genetic-like modeling of discrete fracture networks (DFN). DFNs are built using a three-step workflow to mimic fracture growth process: (1) initialization, (2) growth and (3) termination. Location and density of fractures are then iteratively updated using a fast-marching algorithm in order to match DFN connectivity and tracer test data. This methodology is applied to the fractured granitic geothermal heat exchanger at Soultz-sous-Forêts (France).

1 Introduction

Fracture network connectivity is a parameter very influent on fluid flow in naturally fractured reservoirs. Constraining connectivity in numerical models is a fundamental yet challenging task to accurately predict fluid flow in fractured reservoirs. In this work, a discrete fracture network (DFN) is modeled to represent the geothermal heat exchanger at Soultz-sous-Forêts, eastern France. This modeling is based on a genetic-like simulation of DFN (Henrion and Caumon, 2009) constrained by the large database of geological data, well logs, microseismicity recording, vertical seismic profiles (VSP) and dynamic test tracer data (see Sanjuan et al., 2006; Dorbath et al., 2009; Dezayes et al., 2010 and Sausse et al. [2010] for review of these diverse data).

The Soultz geothermal exchanger is composed of deep fractured granite. Its fracture network has been widely studied, so DFN simulation can use a large database further described in section 2. DFN modeling using the genetic-like method creates DFN honoring static parameters and reproducing connectivity patterns observed on natural analogs (section 3). However, produced DFN has to be iteratively calibrated to honor connectivity data (section 4).

2 Model presentation and constraining data.

The Soultz reservoir is studied through a 3D grid covering the volume around geothermal production wells (GPK2, GPK3 and GPK4) and the location of microseismic events (Dorbath et al., 2009) (Figure 1). The final Cartesian grid dimension is 880(u)x2600(v)x1580(w) m with top and bottom sections respectively at $Z = 3630\text{m}$ and $Z = 5210\text{m}$ TVDSS (True Vertical Depth Sub Sea). The grid resolution is $2.9 \times 13 \times 15\text{m}$, yielding $300 \times 195 \times 105$ grid cells.

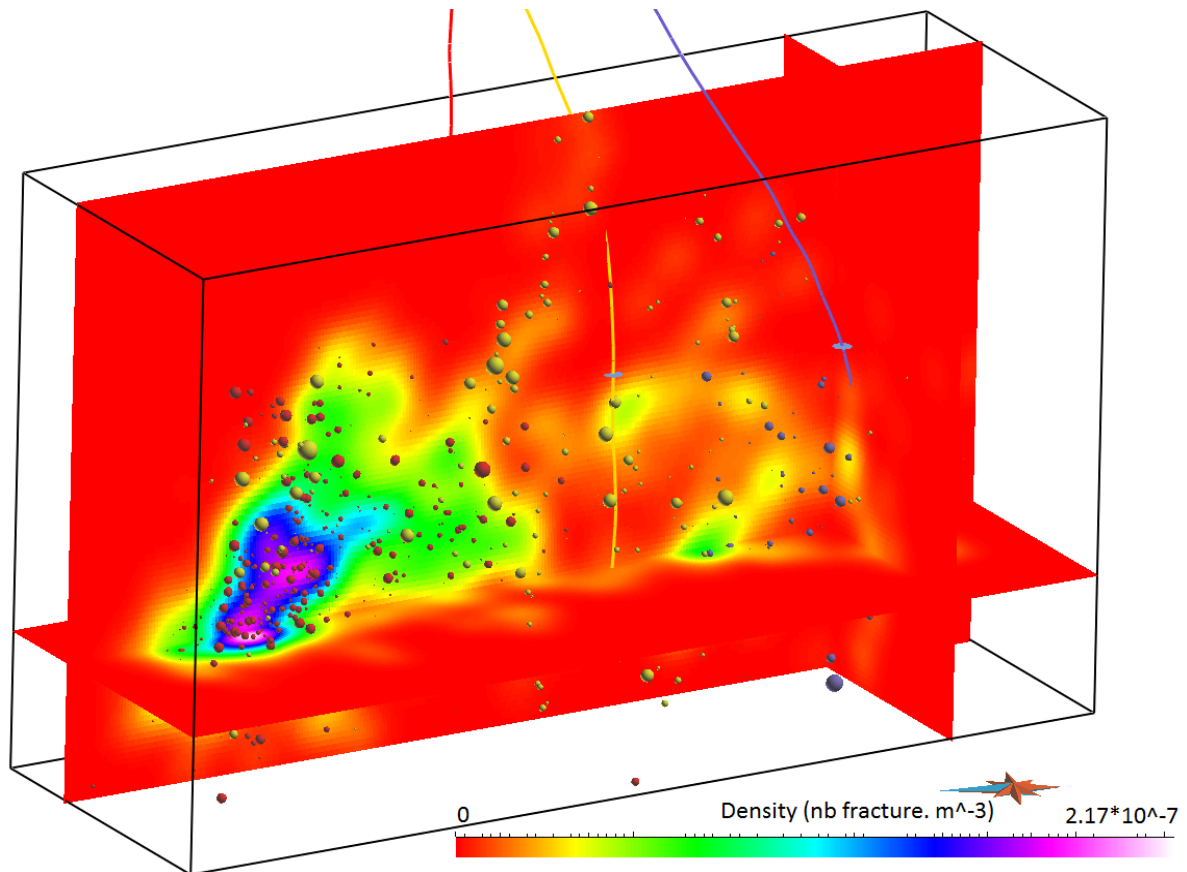


Figure 1 Cartesian grid built from microseismic cloud around wells (GPK2 in red, GPK3 in yellow and GPK4 in blue). The property on grid is the fracture density map obtained by kernel smoothing of the microseismic cloud.

By analyzing the large database concerning the Soultz geothermal exchanger, fractures and fracture set parameters are extracted. Fracture dip and strike statistic distribution are directly obtained from this analysis (Figure 2). Fractures are mostly subvertical oriented North-South. The wide variety of fracture dimensions, estimated from aperture statistics, does not allow us to extract any particular fracture length distribution. The choice was made to simulate square fractures using a Gaussian length distribution (mean = 100 m and standard deviation = 10) and to constrain their connectivity. In the absence of other sources of information, a fracture density map has been computed using a kernel smoother algorithm from microseismic cloud (Figure 1).

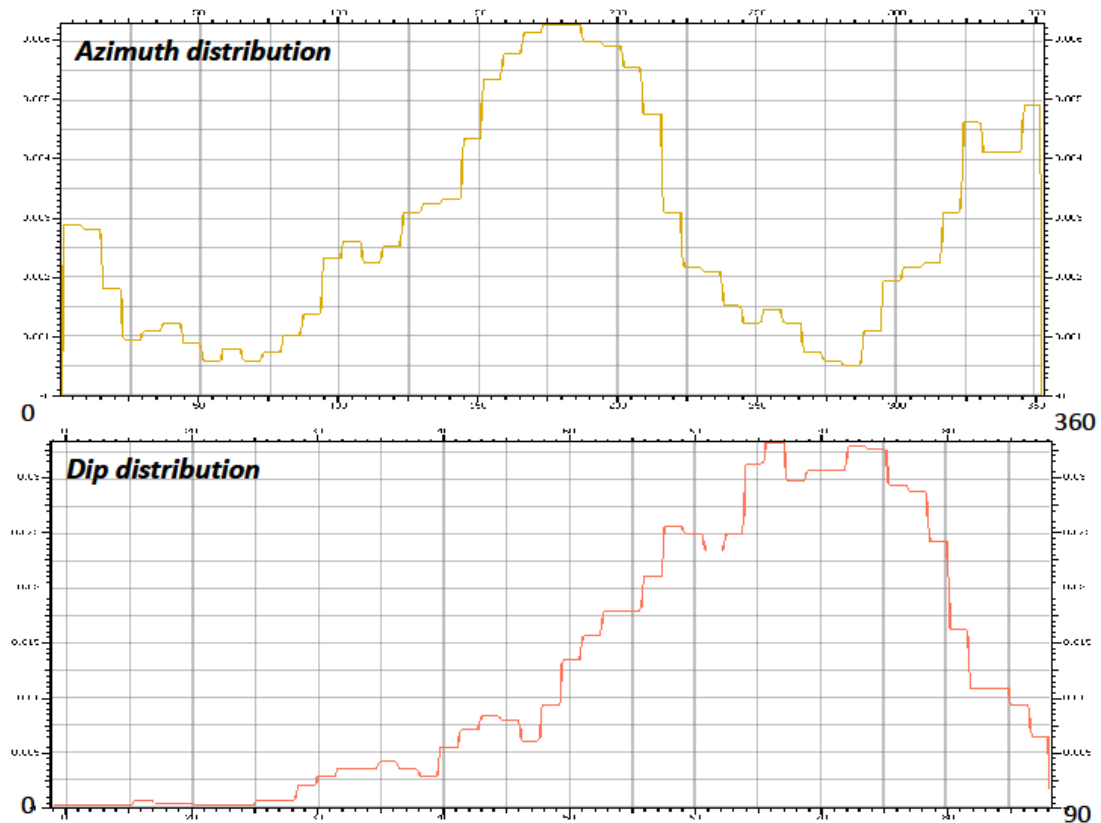


Figure 2 Dip and strike distribution from Soultz database.

Sanjuan et al. (2006) have analyzed dynamic tracer tests and have deduced connectivity data. Tracer tests have shown that GPK3 and GPK2 are highly connected, whereas the connection between GPK3 and GPK4 is not as effective. Tracer data also indicate fluids loss zones on GPK2 (between 4550m and 4725m) and on GPK3 (between 4660-4710m and at 4905m).

3 Genetic-like modeling of DFN

Among DFN modeling approaches, one is probabilistic. Its purpose is to stochastically generate fracture networks using descriptive statistics of fractures (density, orientation, length and width). Several authors use simple object based methods (Baecher et al. [1977], Macé [2006]), when others use genetic methods (Hu and Jenni [2005], Jenni et al. [2007]). Most of these methods simulate planar fractures, but this leads to underestimate the network connectivity (Figure 3, Odling & Webman, 1991).

Srivastava et al (2005), Henrion and Caumon [2009] have proposed hybrid approaches which initialize fractures and fracture network parameters from statistics and then propagate fractures to mimic their growth process. In this work, we build upon the approach of Henrion and Caumon (2009; 2010), which emulates the physics of fracture growth:

1. Initialization: an object-based simulation initializes fracture parameters and simulates fracture seeds. Fracture seeds are drawn using a Poisson point process following a fracture density map and fracture parameters are drawn from distribution laws. At the end of this step, fractures are in their initial state.
2. Propagation: initial fractures are propagated to their final state. The growing direction is defined by neighboring fractures. Fracture growth creates highly constrained zones which drive their growth and their interconnections.

3. Termination: the propagation stops when the fracture reaches its final dimension or when it becomes connected to another fracture.

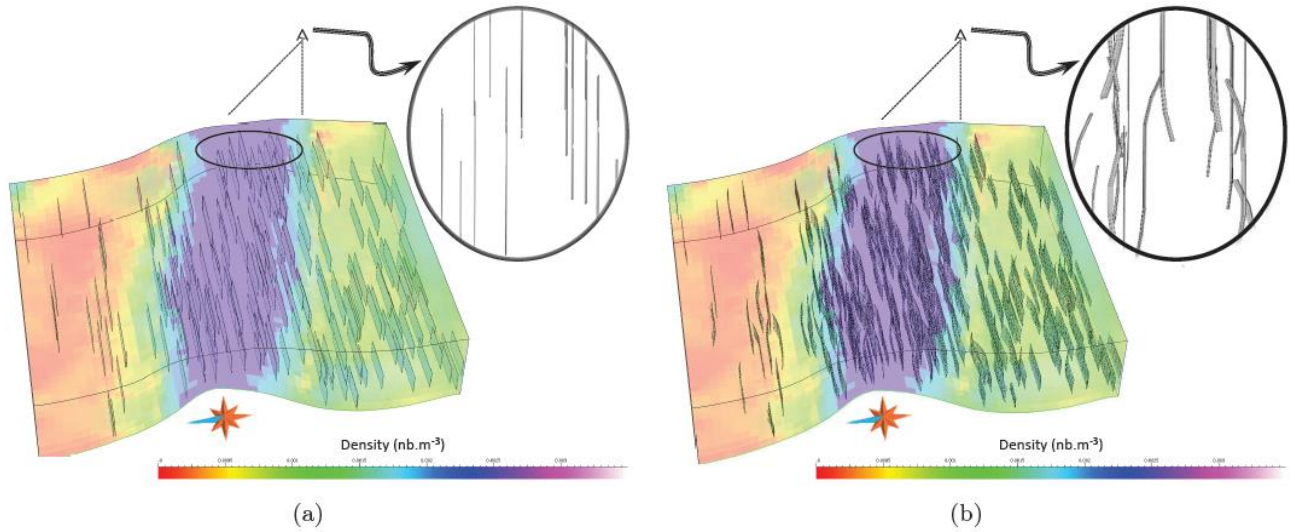


Figure 3 Improvements of the genetic-like method. (a) DFN simulated using an object based method (Macé [2006]) and (b) genetic-like method (Henrion and Caumon [2009]). (b) presents a more realistic geometry and a higher connectivity.

This genetic-like method is used to simulate the fracture network in the Soultz geothermal reservoir. Initializing object based simulation is based on fracture density map and parameter distributions presented in Section 2. From fractures simulated in their initial states, four propagation steps build the final fracture network. The obtained DFN does not respect network connectivity data from tracer tests: there is no connection between fluids losses on GPK2 and fluids losses on GPK3 (Figure 4).

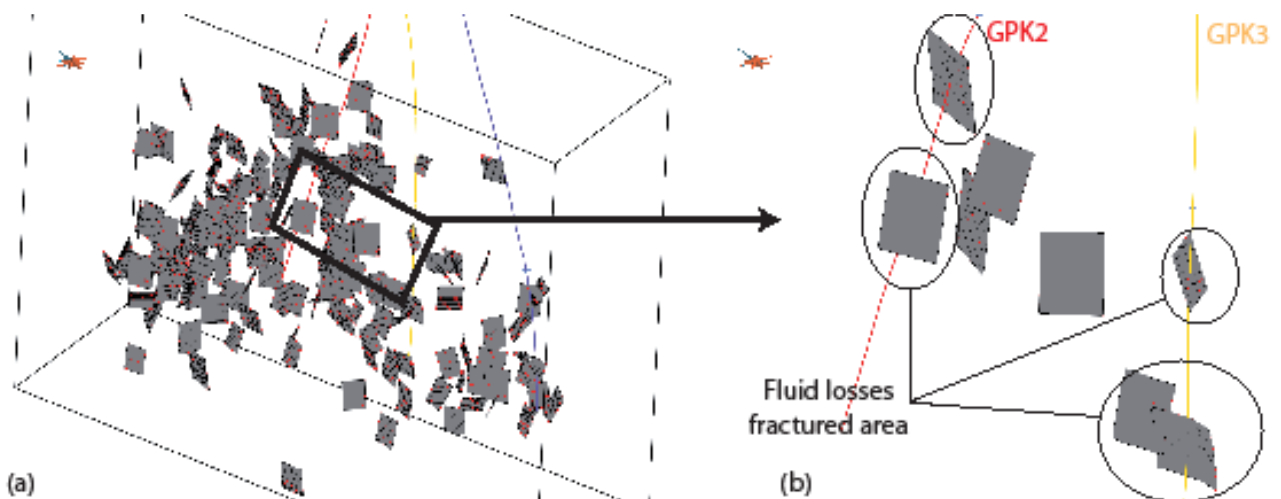


Figure 4 Genetic like modeling of DFN in deep Soultz reservoir. (a) is the global fracture network and (b) is a loop focusing on fractured path between GPK2 and GPK3 fluid losses areas. The fractured path present a lot of gap, GPK2 and GPK3 are not connected.

4 Calibration of the DFN connectivity

To ensure the connectivity between GPK2 and GPK3, we propose an iterative workflow which increases the number of fractures to connect them along the least effort path between fluid losses areas.

The workflow starts from a DFN (Figure 4 a) which is modified at each iteration. Fractures and clusters already simulated affect the location where new fractures are initiated. Fractures are added in most probable areas to connect them to existing objects. Inspired by Borghi et al. [2011], a fast marching algorithm is used to extract the shortest path between wells, considering simulated fractures with a high velocity and matrix with a small velocity. New fractures will be implanted around this path, in areas not affected by fractures. This implantation follows a local Poisson point process in a reduced and unpopulated area whose size depends on the fracture size distribution. If this area is too small, a fracture is implanted at the central position. Then, the whole fracture growth process is run again using both the initial seeds and the seeds added along the shortest path. Three iterations are sufficient to obtain a hardly connected fractured path, but some misconnections are still observed (Figure 5).

Connectivity gaps can be filled using a thinner Cartesian grid to avoid connectivity approximation during the Fast Marching step. Indeed, unconnected fractures are considered as clusters if the distance between them is smaller than the grid resolution. A problem of this solution is to get a very high density of fractures along the shortest path without necessarily obtaining connected fractures. In fact, adding a fracture very close to another can change the connection patterns when the fracture growth is simulated again. Therefore, another idea is to run a post-processing step after fracture propagation. This step acts on fracture length and propagates once more some fractures if it improves the path connectivity (Figure 5 (b)). This last step is also motivated by fracture mechanics: the energy needed for propagating the tip of a fracture is smaller when the tip is close to an existing discontinuity than when the fracture is isolated.

5 Conclusion

The genetic-like modeling method simulates fractures from statistics but takes into account mechanical rule of fracture propagation. DFN geometry is more realistic and the network connectivity is better estimated. This work goes further by also constraining DFN geometry with connectivity data. The chosen workflow starts from a stochastically simulated network and updates it to get a denser fractured path which honors connectivity data. Modifying the initial network will modify the connected network. Thus, the method may produce a set of heterogeneous DFN honoring both static data (fracture density map, fracture parameters law...) and connectivity data. A tradeoff is that input statistics are not as strictly honored as with classical DFN simulations. However, we do not see this as a major limitation because target statistics are quite difficult to obtain and affected by much uncertainty.

Using dynamic data to understand fluid flow, and making sure the static fracture model honors first-order dynamic observations seems to be a very promising method, much more efficient than classical inverse methods. Respecting fracture network connectivity data should improve flow simulation results. But, there is a lot of dynamic data giving interesting information (break-through time, recovery percentage, production and pressure history...) connectivity tracer tests are only one of them. Further work will aim at take other dynamic data into account in order to better calibrate DFN through history matching.

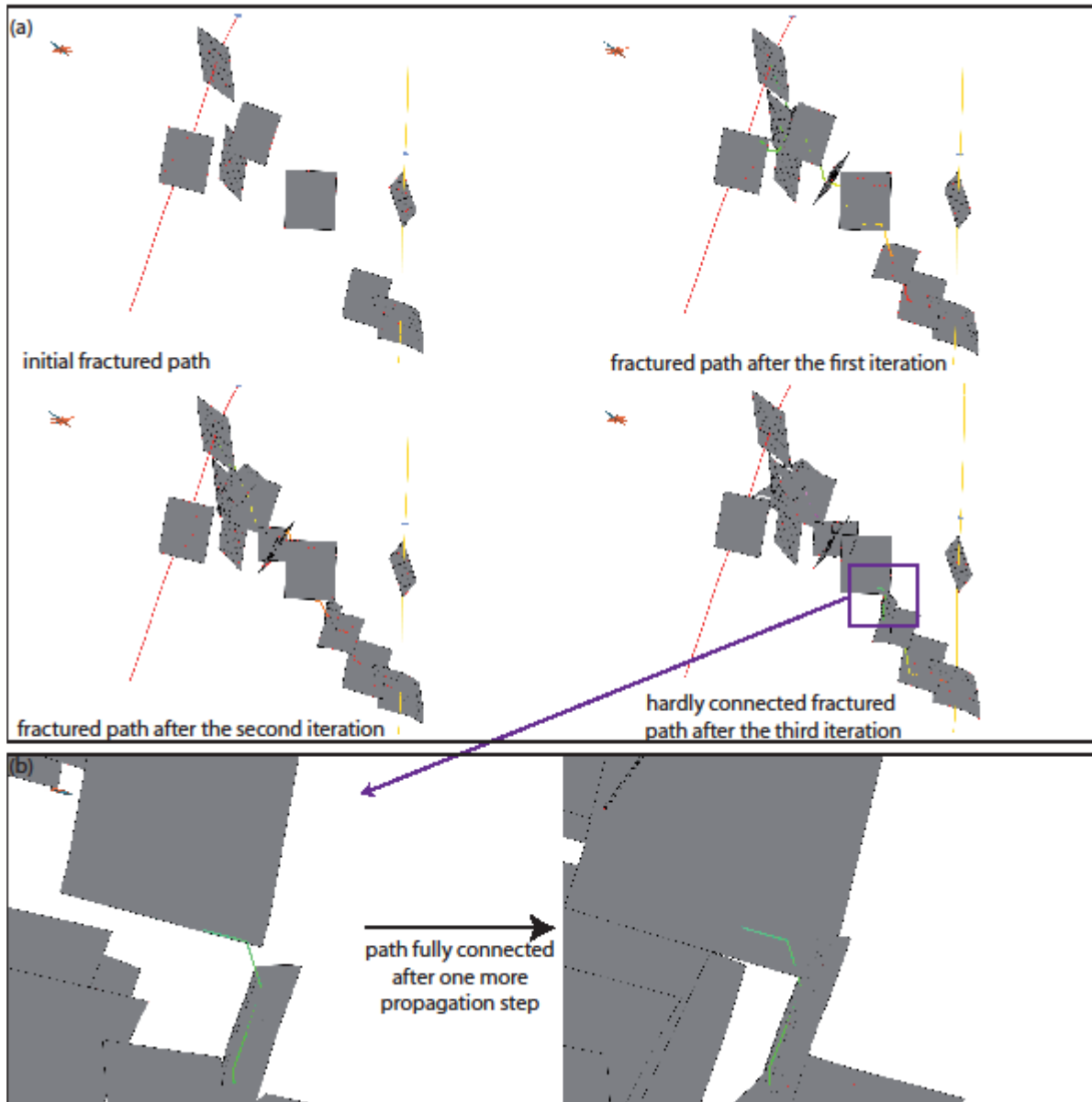


Figure 5 DFN connectivity calibration. (a) connected fractured path built from initial network to an hardly connected one. All the three iterations are shown. (b) loops on one connectivity gap. This problem can be solved by a post-processing step acting on fracture length.

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