PS Does Anisotropy in Fracture Clustering Translate into Anisotropy in Intrinsic Permeability?*

Ankur Roy[1], Edmund Perfect[1], Jitendra Kumar[2], and Richard T. Mills[2]

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[1] Earth and Planetary Sciences, University of Tennessee, Knoxville, Knoxville, TN (aroy1@utk.edu)
[2] Computational Earth Sciences Group, Oak Ridge National Laboratory, Oak Ridge, TN

Abstract

Lacunarity is a parameter that can quantify the clustering of spatial patterns. Two of the authors have previously used it to differentiate between a set of 7 nested natural fracture maps with the same fractal dimension, but different visual appearances. In the present study, we investigate the use of lacunarity for determining if differences in clustering of fractures along the NS and EW directions of the same maps control the differences in steady-state 2-dimensional Darcy flow along those directions. Directional lacunarity was found by computing the average lacunarity values of scanlines laid every 10 pixels in these respective directions. PFLOTRAN, an open-source, massively parallel simulator for reactive flows in geologic porous media, was used to compute steady-state Darcy flows. Structured computational grids were constructed from rasterized fracture maps. Each pixel of a map was considered a cell, which was assigned porosity and permeability values based on whether it represented a fracture or matrix such that a 1042 x 1042 pixel map was modeled as a domain comprising 1042 x 1042 x 1 cells. In order to determine the effective intrinsic permeability in the EW direction, a pressure gradient was set up in that direction, while the NS edges were considered no-flow boundaries. The flow system was then rotated to give the NS values. The simulations were run using 120 processor cores on Jaguar, a Cray XT5 system housed at the Oak Ridge National Laboratory. The results from these flow simulations and lacunarity analyses indicate a relationship between anisotropy in clustering of fractures in a network and anisotropy in the intrinsic permeability values.

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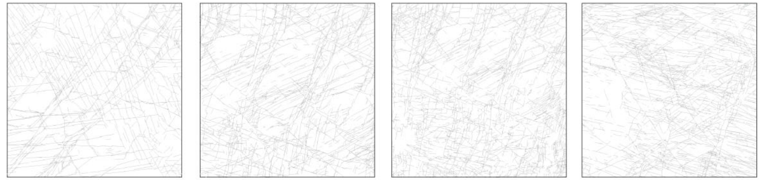
[1]Dept. of Earth and Planetary Sciences, University of Tennessee, Knoxville; [2]Computational Earth Sciences, Oak Ridge National Lab.

1. Introduction

Connectivity of fracture networks depends on clustering (Davy et. al., 2006). Since fluid flow is controlled by connectivity, it may be postulated that clustering of fractures in a specific direction would control the flow in that direction. Lacunarity is a parameter that measures clustering at different scales (Plotnick, et. al., 1996). Roy et. al. (2010) used it for differentiating between a set of nested fracture maps from the Devonian sandstone of Hornelen Basin, Norway that have the same fractal dimension. Four of these maps (fig. 1) and a set of fractal-fracture models are used to test the hypothesis that differences in lacuarity (clustering) along X and Y directions control the differences in steady-state 2D Darcy flow along those directions.

FIG 1 Fracture maps from Hornelen Basin (Odling, 1997)

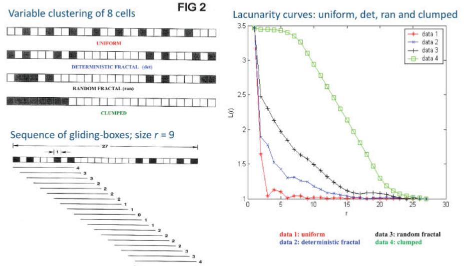


map 1: 18m x 18m   map 2: 55m x 55m   map 3: 90m x 90m   map 4: 90m x 90m

2. Lacunarity & Clustering Anisotropy

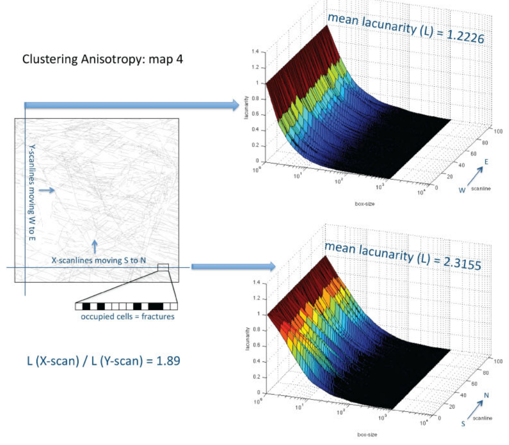
Consider 8 occupied cells in an array of 27 cells with different arrangements: uniform, deterministic fractal (cantor-bar), random fractal and clumped (fig. 2). Lacunarity is calculated by gliding boxes from size 1 to 27 across each pattern. A box is moved an increment of one cell and the number of occupied cells, S is counted. These counts yield a distribution of occupied cells S(r) for the box-size, r whose mean and variance is calculated as $\bar{S}(r)$ and $s^2_s(r)$ respectively. The Lacunarity for a box-size, r is given as: $L(r) = s^2_s(r) / \bar{S}(r)^2 + 1$; for uniformly distributed patterns L(r) = 1 for all box-sizes

FIG 2



modified from Turcotte (1997)

FIG 3



In fracture maps, directional clustering or lacunarity in a specific direction (X or Y) is found by laying scanlines along that direction (fig 3). Instead of a curve, the lacunarity of a given scanline is expressed as a single number $L_{int} = \Sigma L(r)*(r/r_{max})$. Scanlines are laid at fixed intervals (every 10 pixels) and the arithmetic mean of L_{int} is reported as the mean lacunarity (L).

The ratio of mean lacunarity (L) along the X and Y directions yields the clustering anisotropy. Fig 3 also shows two lacunarity surfaces computed from the lacunarity curves of scanlines along X and Y.

3. Fracture Continuum Model & PFLOTRAN

As opposed to Discrete fracture network (DFN) models where fractures are represented as continuous lines, the Fracture continuum (FC) model is based on the conversion of discrete fractures to permeability structures on a model grid (Reeves et. al., 2008). Fractures are overlain on a grid (fig. 4a) and fracture occupied cells (gray) are assigned porosity-permeability on the basis of fracture properties while the others are assigned matrix porosity-permeability. The maps (1042 X1042 pixels) are digitized on a regularly spaced 10m X10m X 9.6E- 03m domain (each cell ~ 0.96cm X 0.96cm X 0.96cm). To facilitate flow across the corners the grid is coarsened (fig. 4b) but still preserves the network geometry. Finally, PFLOTRAN, a massively parallel simulator for modeling flow in geologic porous media (Mills et. al., 2009), is used for running the flow simulations. They are run in parallel using 120 processor cores on JAGUAR (a CRAY XT5 system housed at ORNL). The following specifications are used:

- Matrix Porosity: 10-5
- Matrix Permeability: 10-30 m^2

} matrix flow ~ 0

- Fracture Porosity: $\Phi = (\sqrt{2}*b/r) / c = 0.004$
  - c = coarsening factor = 3.3 (maps 2-4); 3.6 (map 1); 1 (models)
  - b = fracture aperture = 100μm(maps); 300μm (models)
  - r = cell length(0.96cm)

- Fracture Permeability:
  - $k = b^2/12$ (cubic law)
  - for b = 100μm (Odling, 2001) k = 8.33E-10 m^2

- Pressure (Dirichilet boundary): 201325 Pa - 212508 Pa
- Pressure gradient: 1118.3 Pa/m

FIG 4a. FC model from a fracture network (Reeves et. al., 2008)

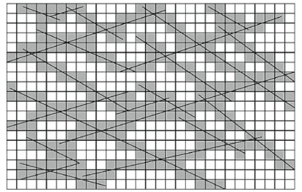
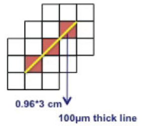


FIG 4b



4. Flow Anisotropy

FIG 5

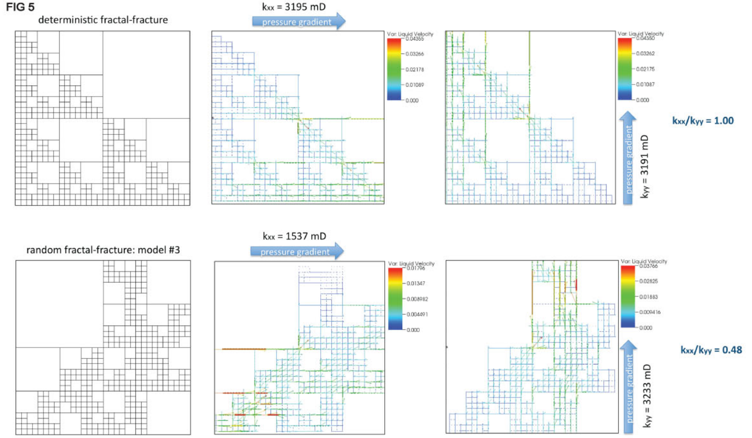
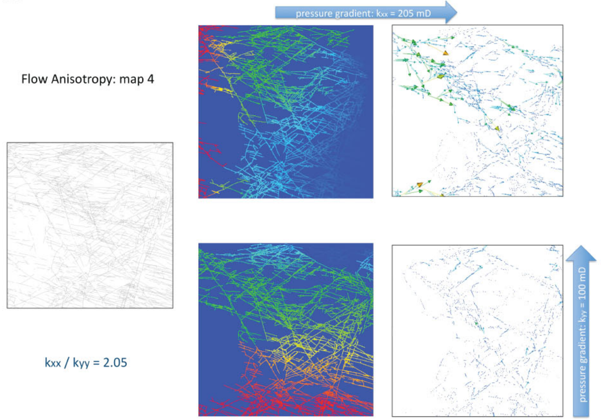


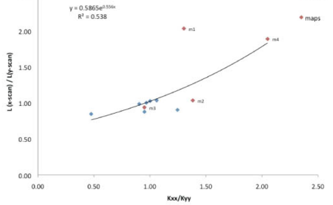
FIG 6



- Flow in X-direction is simulated by assigning a pressure gradient in that direction (EW) and creating no-flow boundaries along the northern and southern edges. Likewise, flow is simulated in the Y-direction by assigning a pressure gradient in that direction.
- The equivalent intrinsic permeability is calculated from the velocity distribution of the cells along the boundaries that allow flow and plugging the value in Darcy's law.
- The flow anisotropy is calculated from the ratio of k_{xx} (intrinsic permeability in X) and k_{yy} (intrinsic permeability in Y)

5. Preliminary Results

FIG 7. Permeability anisotropy vs. lacunarity anisotropy

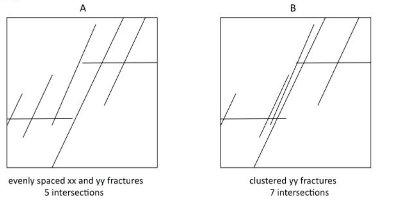


- Anisotropy in fracture clustering is related to anisotropy in flow (intrinsic permeability)
- An increase in one leads to an increase in the other
- Both maps and models show a similar trend

6. Discussions & Conclusions

- A model (fig 8) can be used to explain how clustering anisotropy is related to flow anisotropy
- Clustering in a particular direction leads to more intersections hence increases the possibility of connectivity in that direction leading to higher flow
- Lacunarity analysis does not take into account aperture values: same network with different apertures can have different flow anisotropies

FIG 8



evenly spaced xx and yy fractures
5 intersections

clustered yy fractures
7 intersections

$$\left.\begin{array}{l}(K_{yy})_A = (K_{yy})_B\\(K_{xx})_A = 0\\(K_{xx})_B > (K_{xx})_A\end{array}\right\} \left(\frac{K_{xx}}{K_{yy}}\right)_B > \left(\frac{K_{xx}}{K_{yy}}\right)_A$$

$$\left.\begin{array}{l}(L_{xx})_A \sim (L_{yy})_A \sim 1\\(L_{xx})_B > (L_{yy})_B\end{array}\right\} \left(\frac{L_{xx}}{L_{yy}}\right)_B > \left(\frac{L_{xx}}{L_{yy}}\right)_A$$

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