Outcrop-based Geomechanical Fracture Aperture and Flow Modeling: The Importance of Shear on Flow*

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Abstract

Outcrop analog studies of fractured reservoirs provide the 3-D geometry of fracture systems that cannot be fully obtained in the subsurface, as outcrops provide the full fracture size, spacing and orientation distributions. Modeling of fluid flow through large, high-resolution outcropping fracture networks may provide a better understanding of the fluid flow patterns encountered in subsurface analog reservoirs, as the relation between fracture geometry (e.g., length, density) and subsequent flow can be studied in detail.

Finding an accurate aperture distribution model for these outcropping fractures is, however, a challenge. Generally, only burial-related veins are considered to give an accurate description of pre-exhumation fracture aperture, whereas the majority of outcropping fractures generally consist of barren fractures, whose apertures are not representative of pre-exhumation conditions. In terms of subsurface stresses, which have a significant impact on fracture aperture and flow, veins only record information for one stress situation. The relation between geomechanical reservoir conditions and subsequent aperture is poorly understood.

Alternatively, fracture aperture can be modeled as a function of principal stresses using geomechanical numerical models, for which we apply an empirical fracture aperture model (e.g., Olsson and Barton, 2001). This model predicts both mechanical and hydraulic fracture aperture under compression taking into account normal and shear displacement along the fractures. The aperture normal to the fracture is a function of initial fracture roughness, strength and normal stress acting on the fracture, while a shear opening component is defined using the shear displacement.

We incorporate this fracture aperture model into geomechanical Finite-Element models of large 2-D outcropping fracture pavements. We calculate fracture aperture in these complex fracture systems as a function of different reservoir conditions, including a wide range of rock properties and principal stress magnitudes. The resulting models consist of complex deterministic fracture patterns with heterogeneous hydraulic fracture aperture distributions. These are then used as input for fluid flow modeling, using a hybrid Finite-Element Finite-Volume approach (e.g., Matthäi et al., 2009).

By quantifying the results in terms of effective permeability, which captures the combined impact of fracture and matrix flow, we obtain a direct relation between geomechanical reservoir conditions and the resulting permeabilities (e.g., Nick et al., 2011). Both variations in reservoir conditions as well as small variations in the fracture network geometry have a strong impact on the resulting effective permeability. Most notably, the orientation of the fractures with respect to the main direction of compression has a strong impact on aperture and subsequent fracture permeability. Fractures oblique to compression have the largest aperture, which results from shear displacement along irregular fracture planes.

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Outcrop-based geomechanical fracture aperture and flow modeling:

The importance of shear on flow

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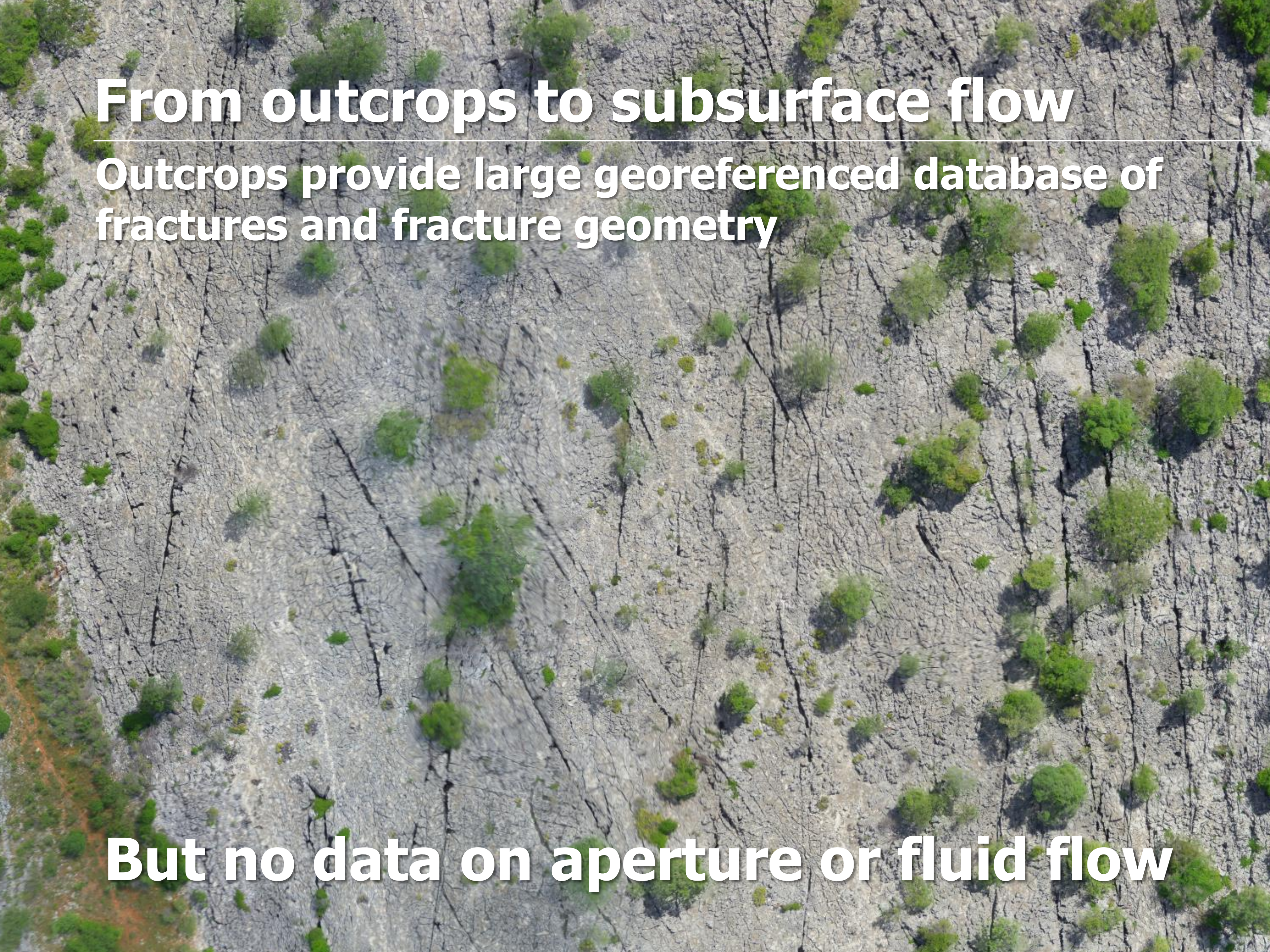
From outcrops to subsurface flow

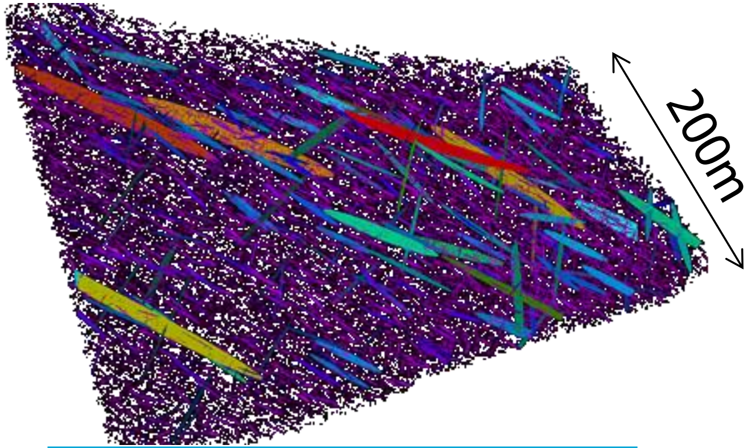
Outcrops provide large georeferenced database of fractures and fracture geometry



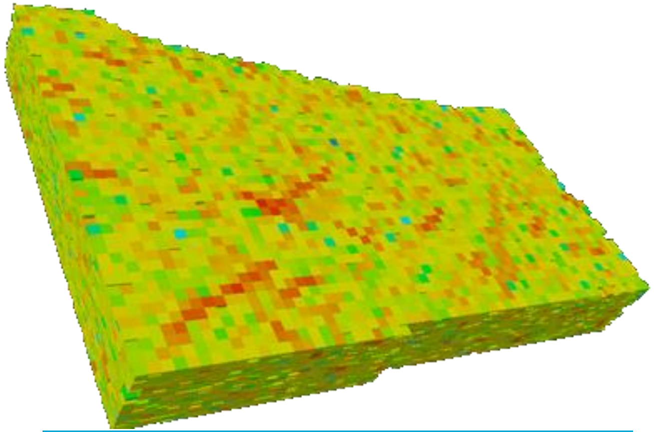
But no data on aperture or fluid flow

Fracture permeability modeling

Geometry, connectivity and aperture are key



Discrete Fracture Network (DFN)



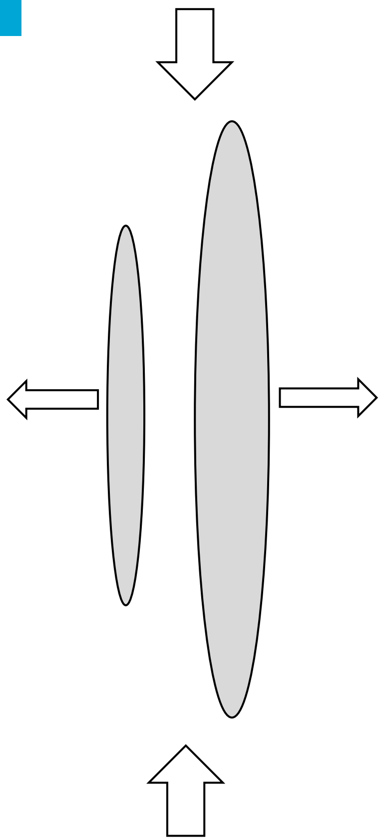
Fracture permeability grid

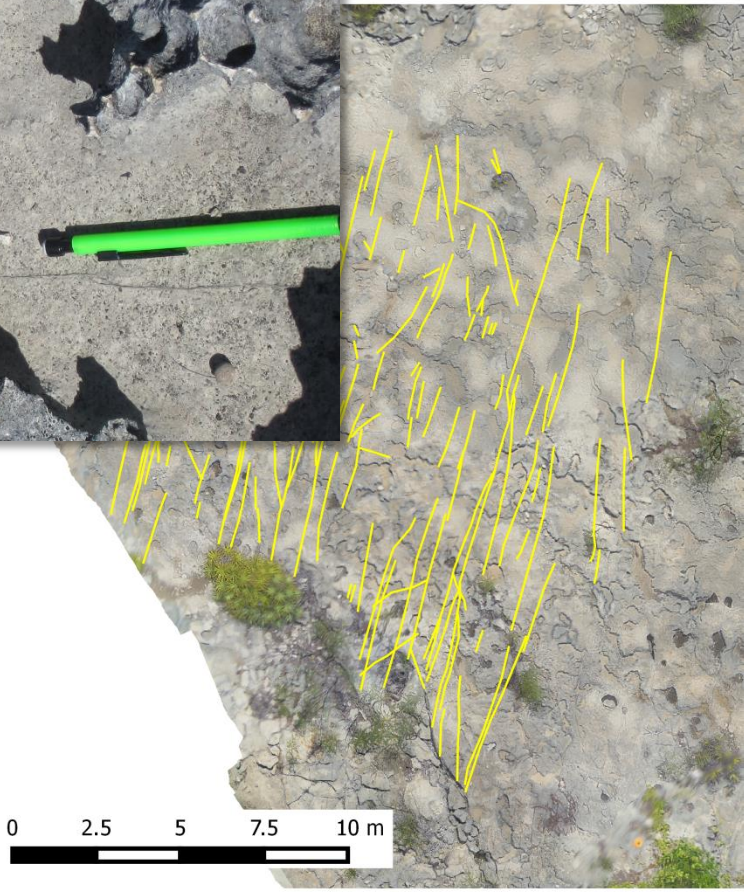
Geometry-based fracture permeability upscaling methods are still popular in industry (e.g., Oda, Oda gold):

- fracture density
- connections (sigma factor)
- Aperture linked to geometry; most fractures assumed open

Fracture aperture modeling

Field observations do not match conventional thinking



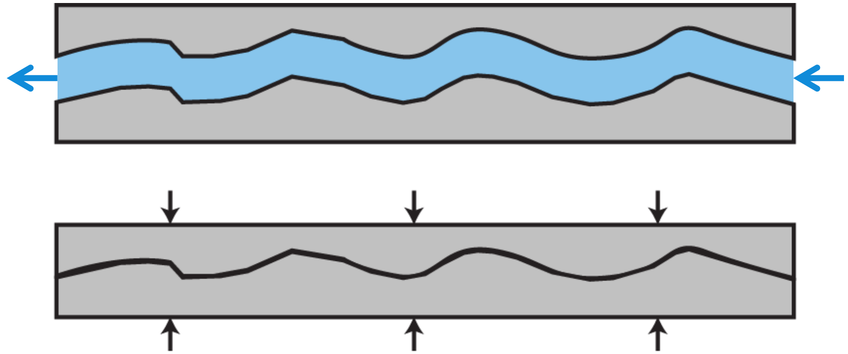


Aperture is often assumed:
- Elliptical
- Related to fracture length

Veins in Brazil show:
- Constant aperture along fracture
- Constant aperture for all (nearby) fractures

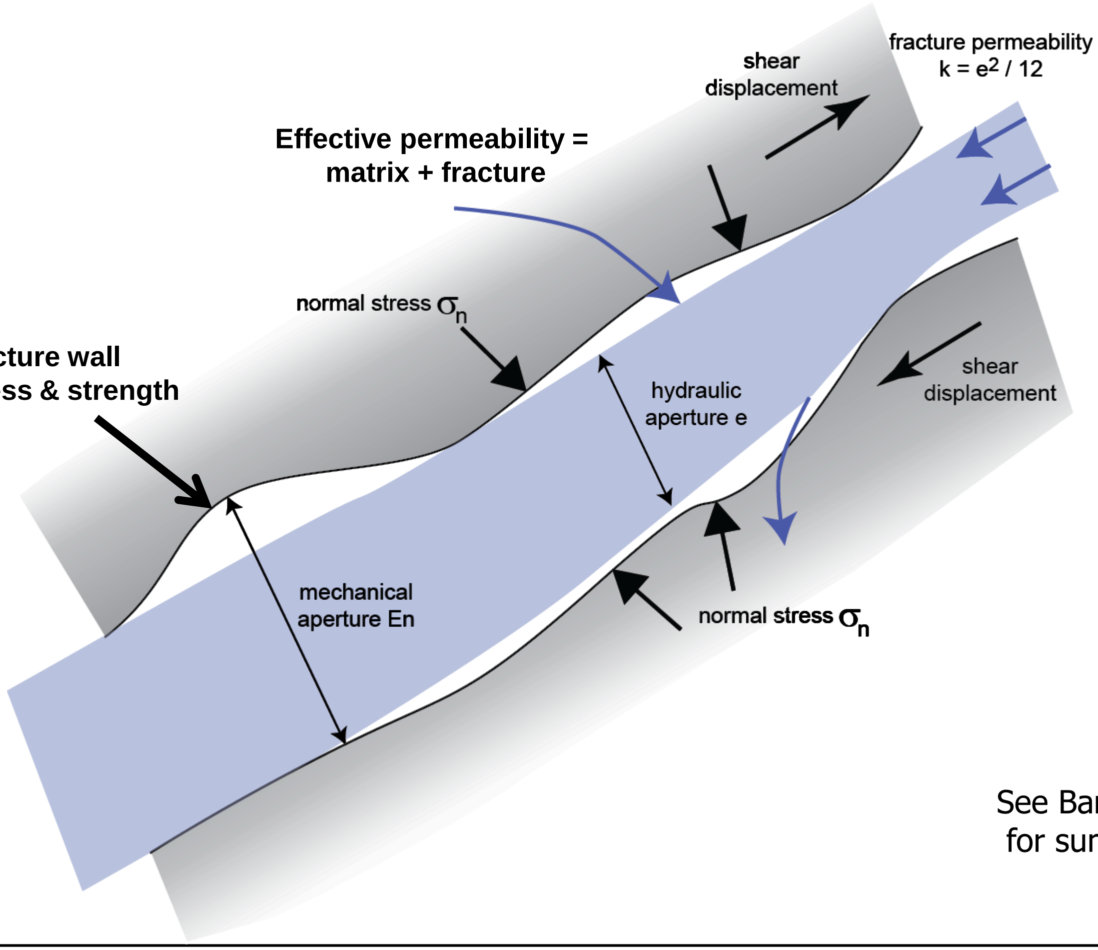
Micro-aperture vs. macro-aperture

Micro-aperture: ('residual') fracture aperture in the absence of sufficient pore pressure



Empirical model for aperture

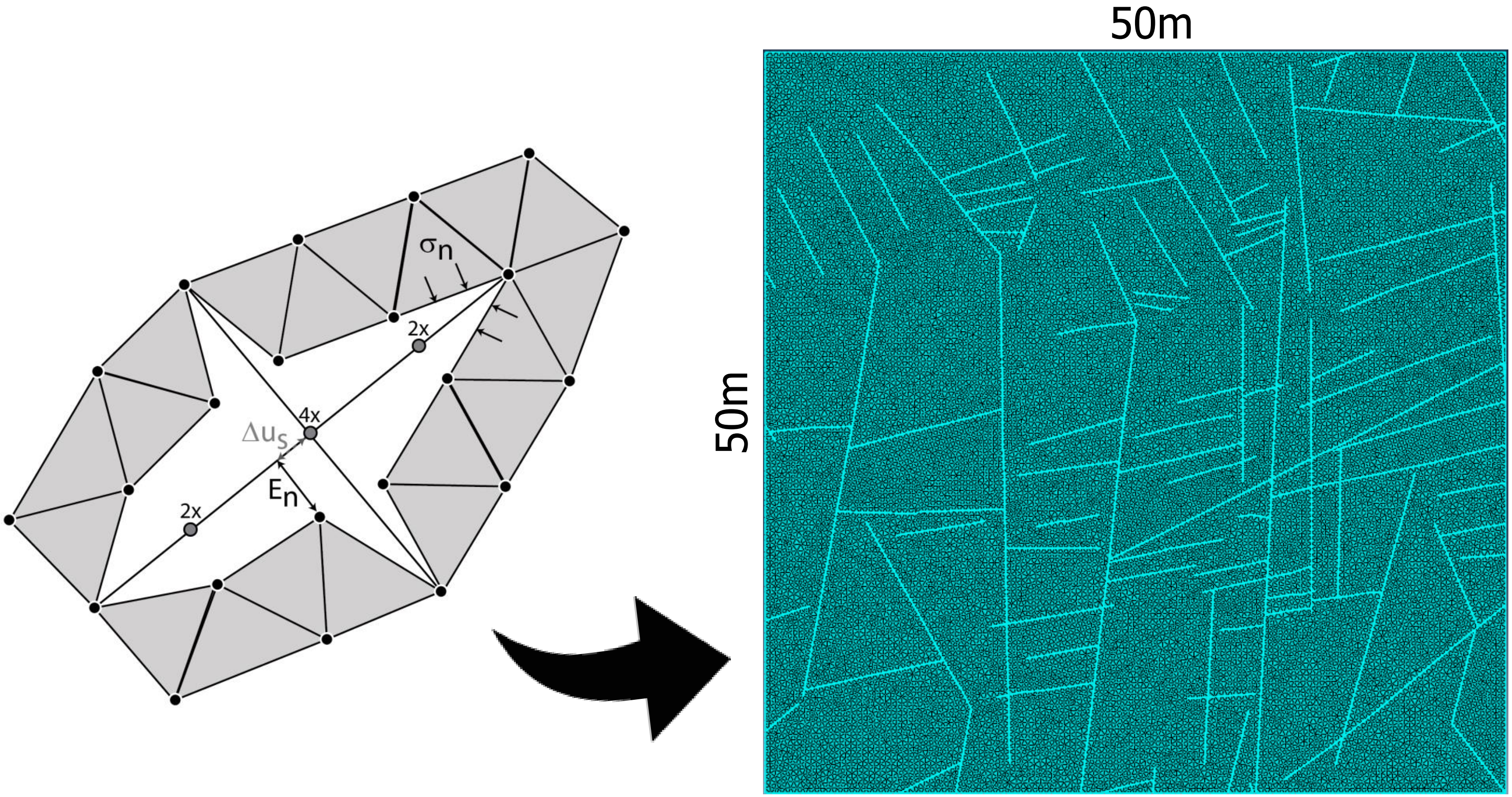
Mechanical and hydraulic microscopic aperture



See Barton (2014, First Break)
for summary of methodology

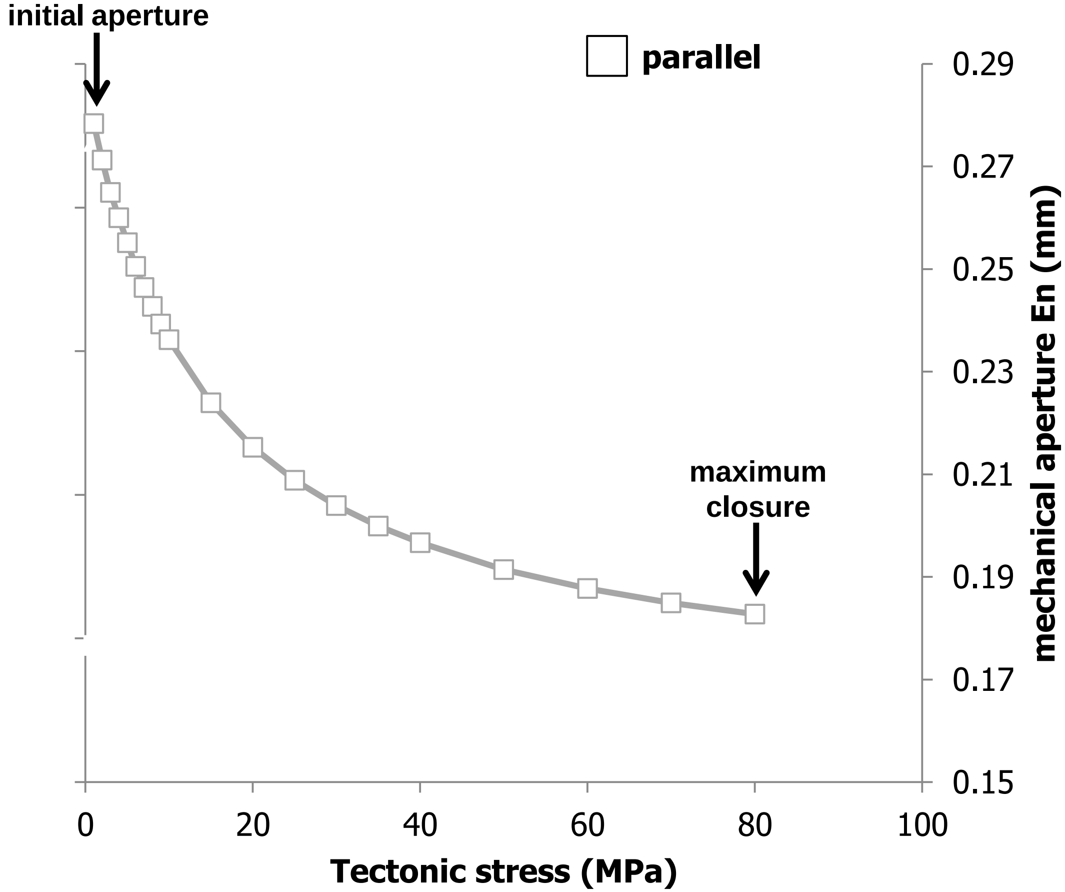
2-D Numerical implementation

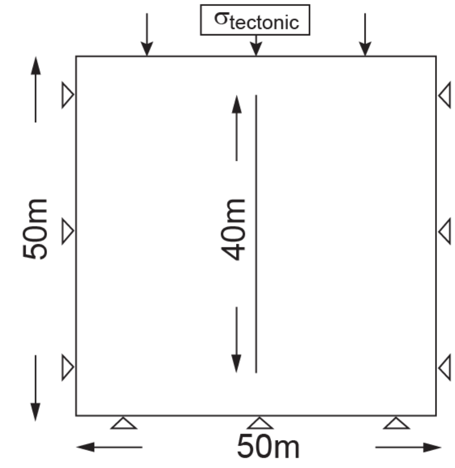
Implemented into ABAQUS mechanical simulator



Behavior of mechanical aperture

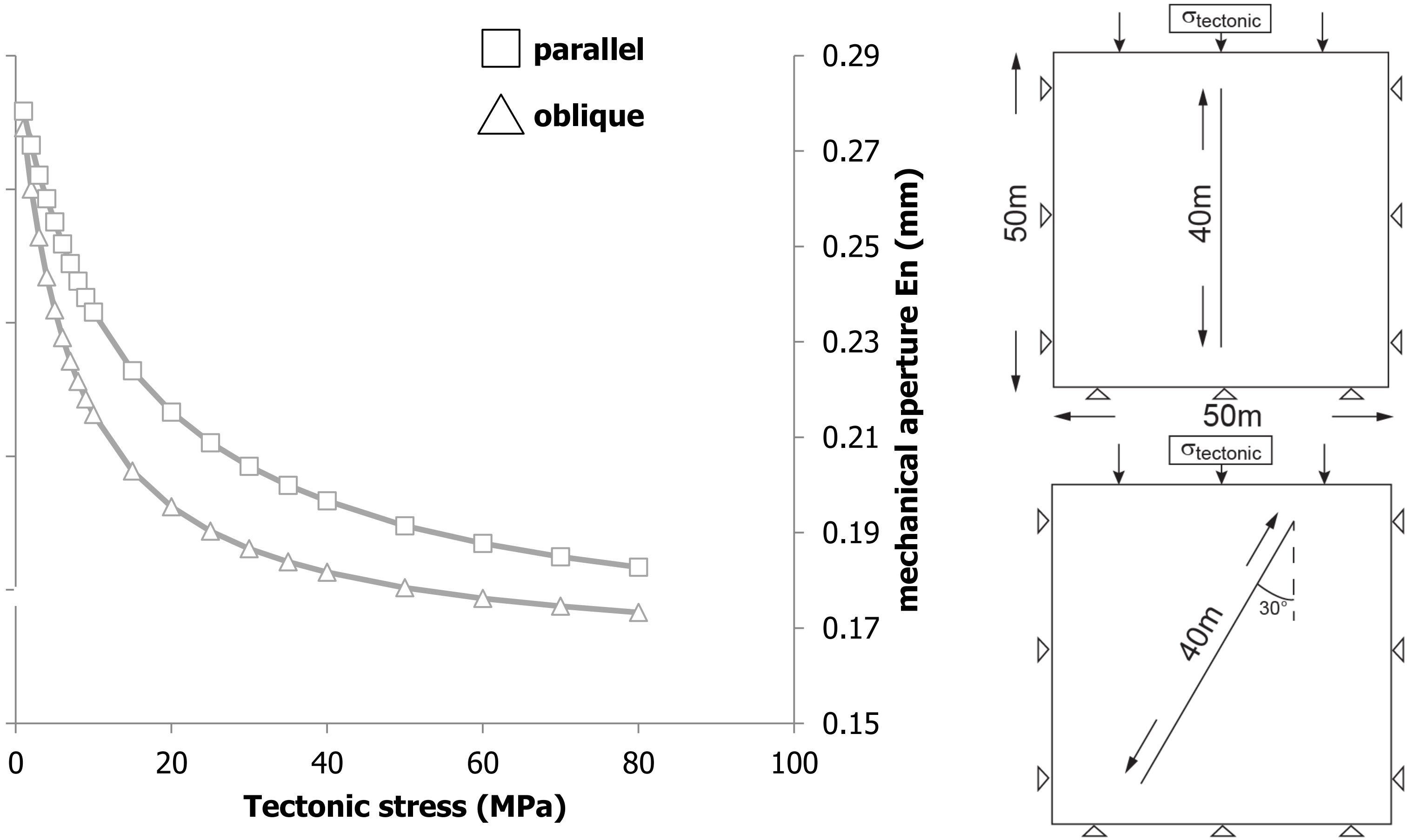
Negative exponential relation with stress





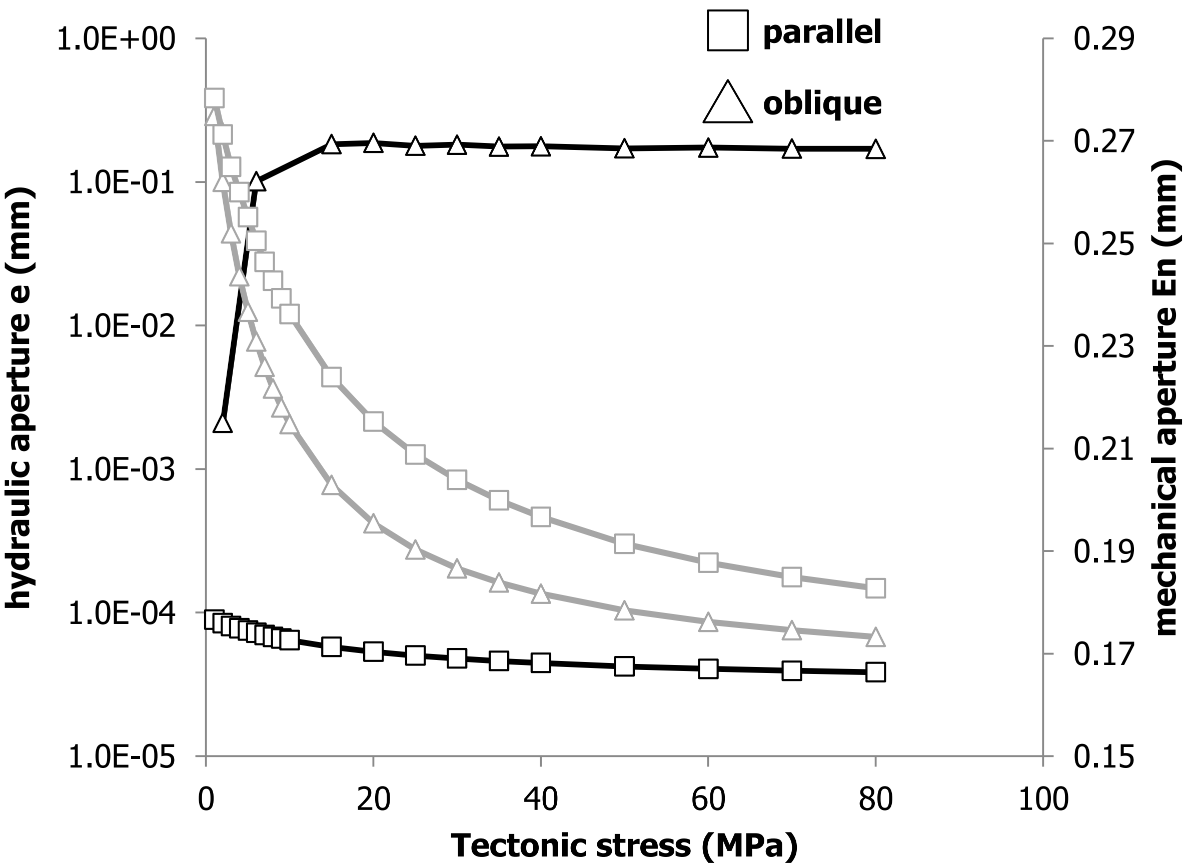
Behavior of mechanical aperture

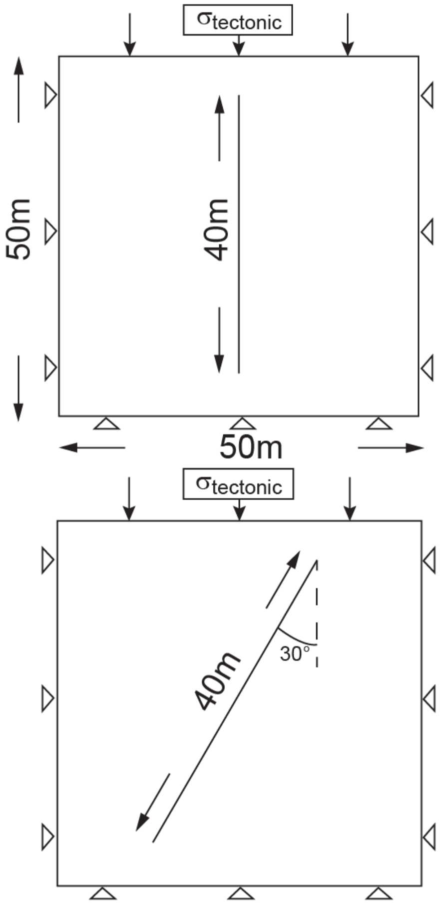
Impact of fracture vs. stress orientation



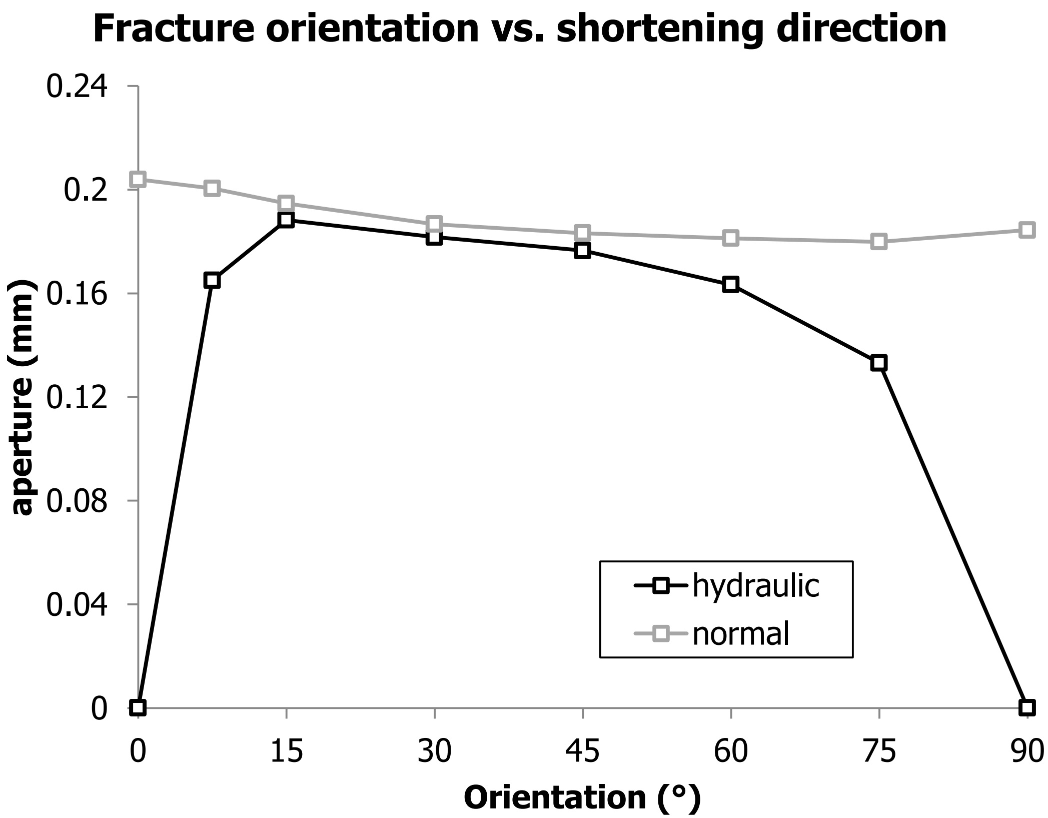
Behavior of hydraulic aperture

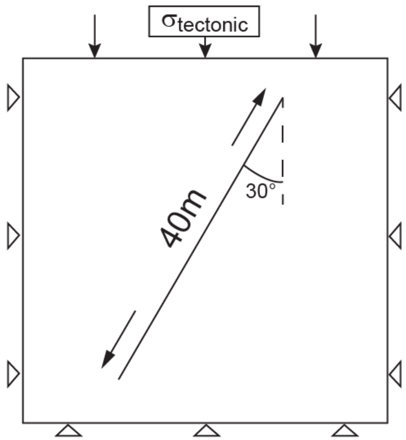
Mechanical vs. hydraulic aperture





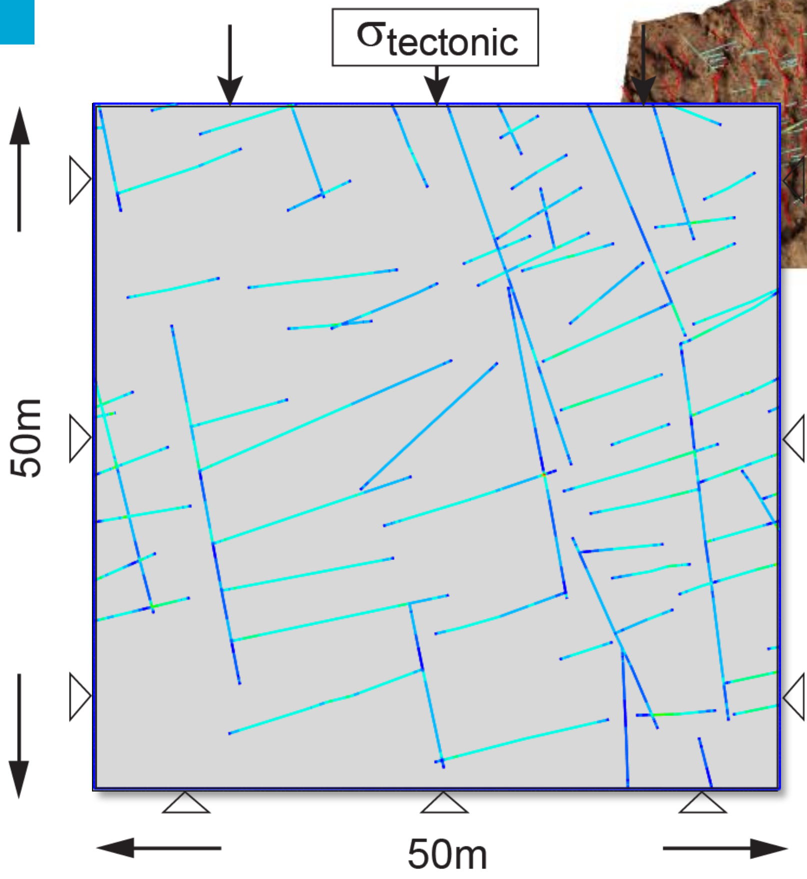
Importance of stress direction

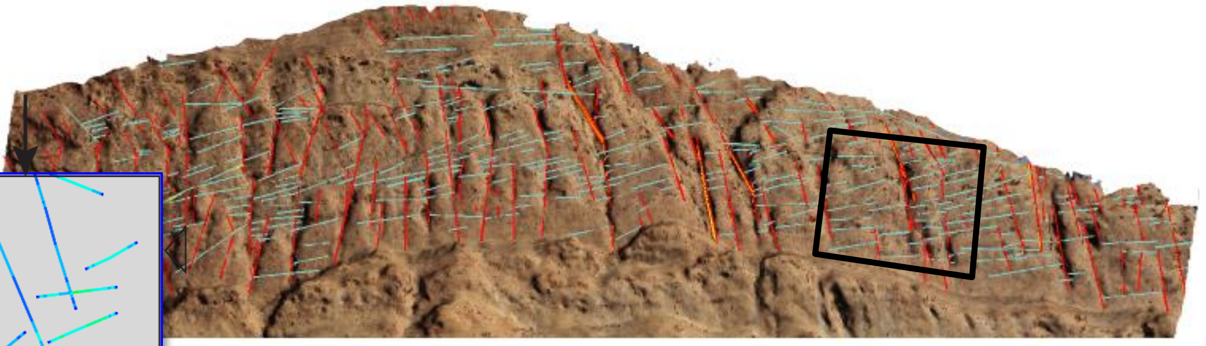


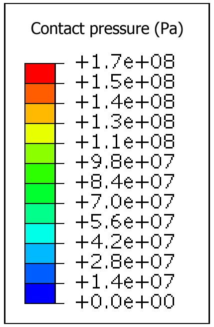


Fracture network aperture modeling

Numerical stress-based aperture for deterministic fractures



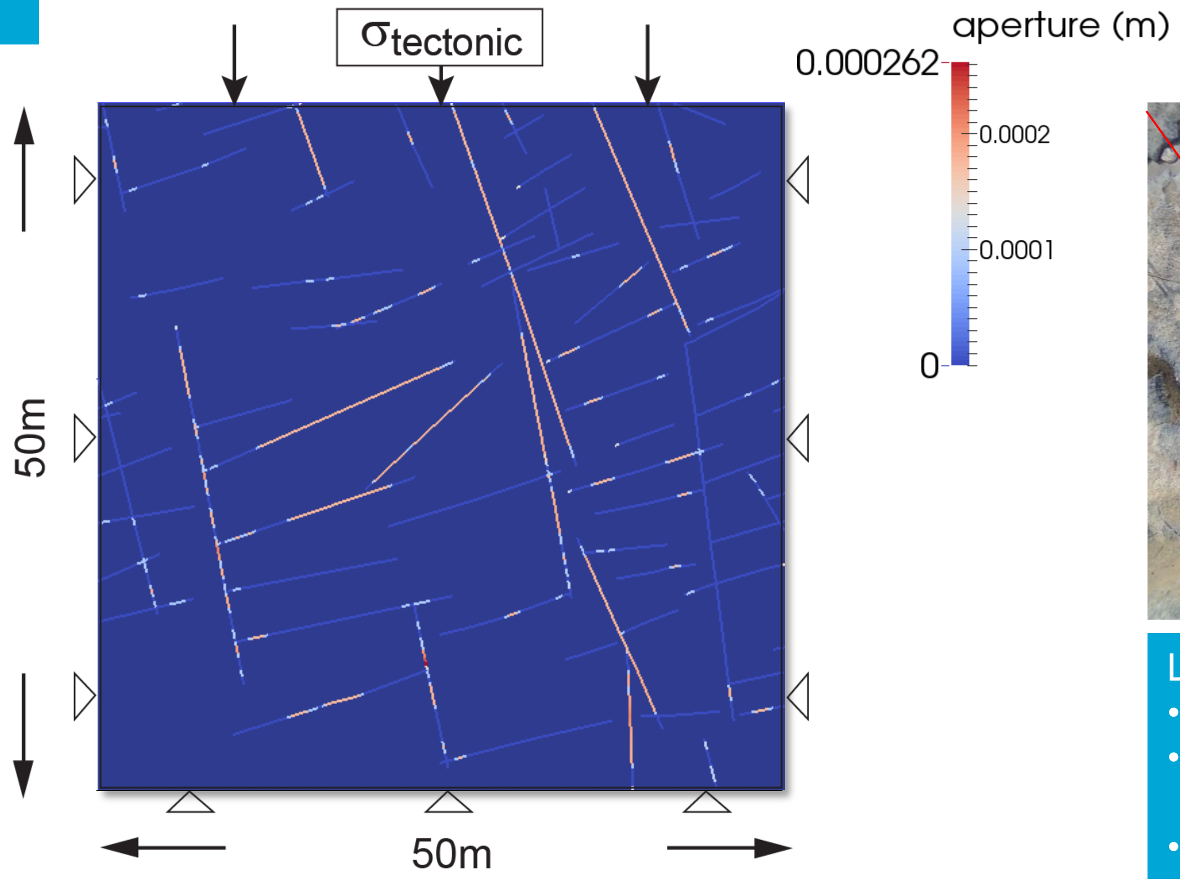




- 60,000 elements
- Elastic and Elastic-plastic models
- Variables:
    - Stress magnitude & direction
    - Young's Modulus
    - Poisson's ratio
    - Cohesion

Hydraulic aperture distribution

Function of shear vs. peak shear

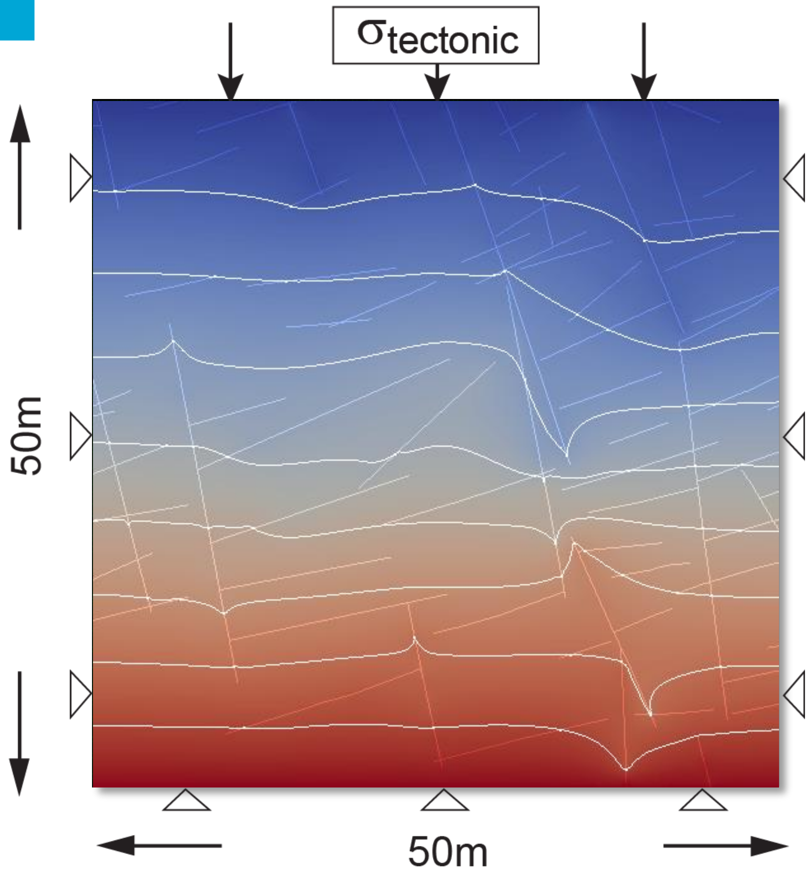


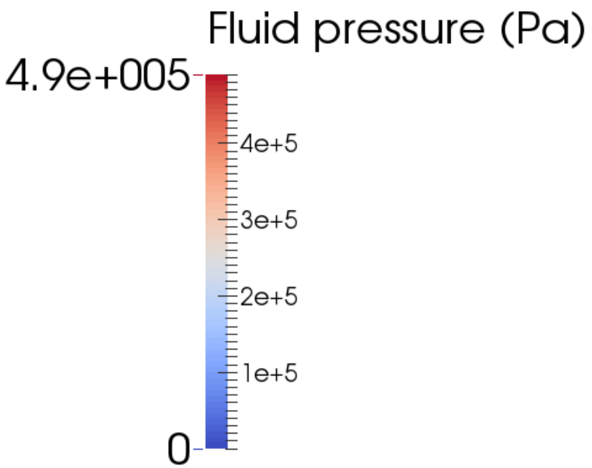
Link to field observations:

- Long, narrow veins (L>5m, a<1cm)
- Partial opening and closing within one vein
- i.e., not 'ellipse-shaped' aperture

Quantification of matrix-fracture flow

Single-phase pressure, homogeneous matrix





- Effective permeability = fracture permeability + matrix permeability
- Homogeneous matrix: 10 mD
- A few fractures contribute to improved effective permeability

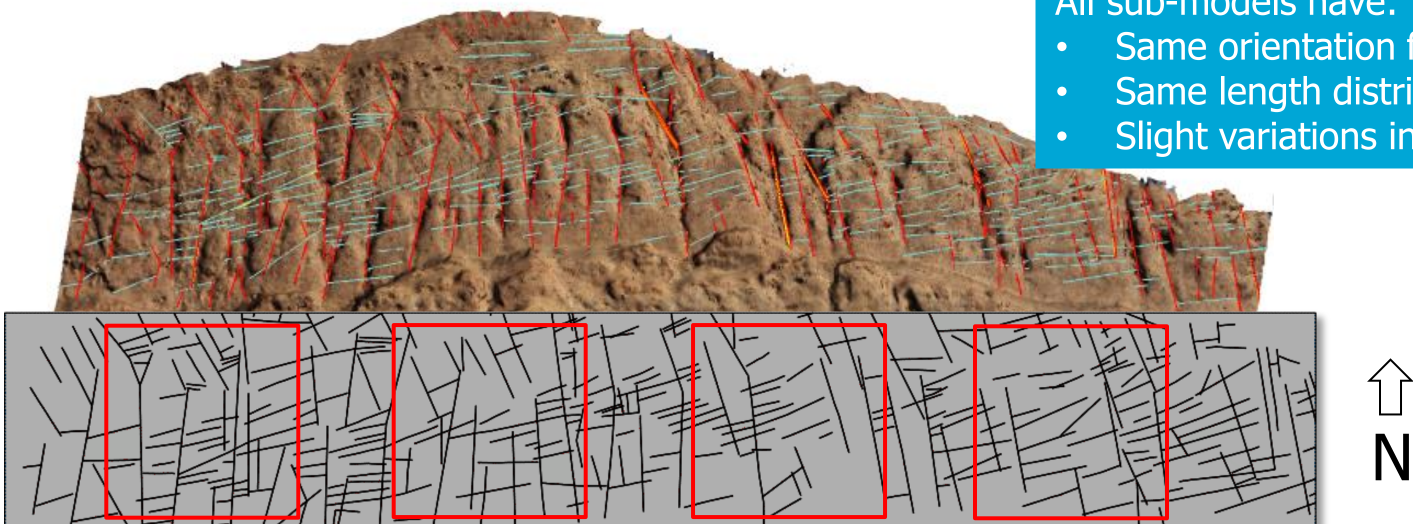
Regional fractures in Tunisia

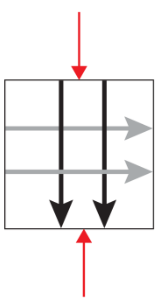
Pavement with homogeneous fracture geometry

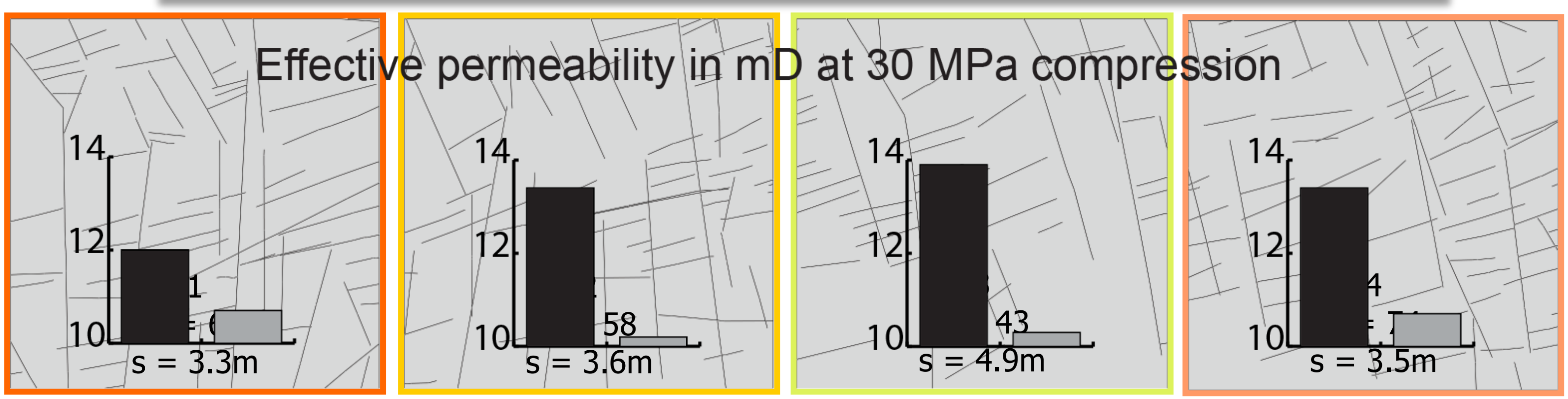
All sub-models have:

- Same orientation families
- Same length distribution
- Slight variations in spacing

50x50m models

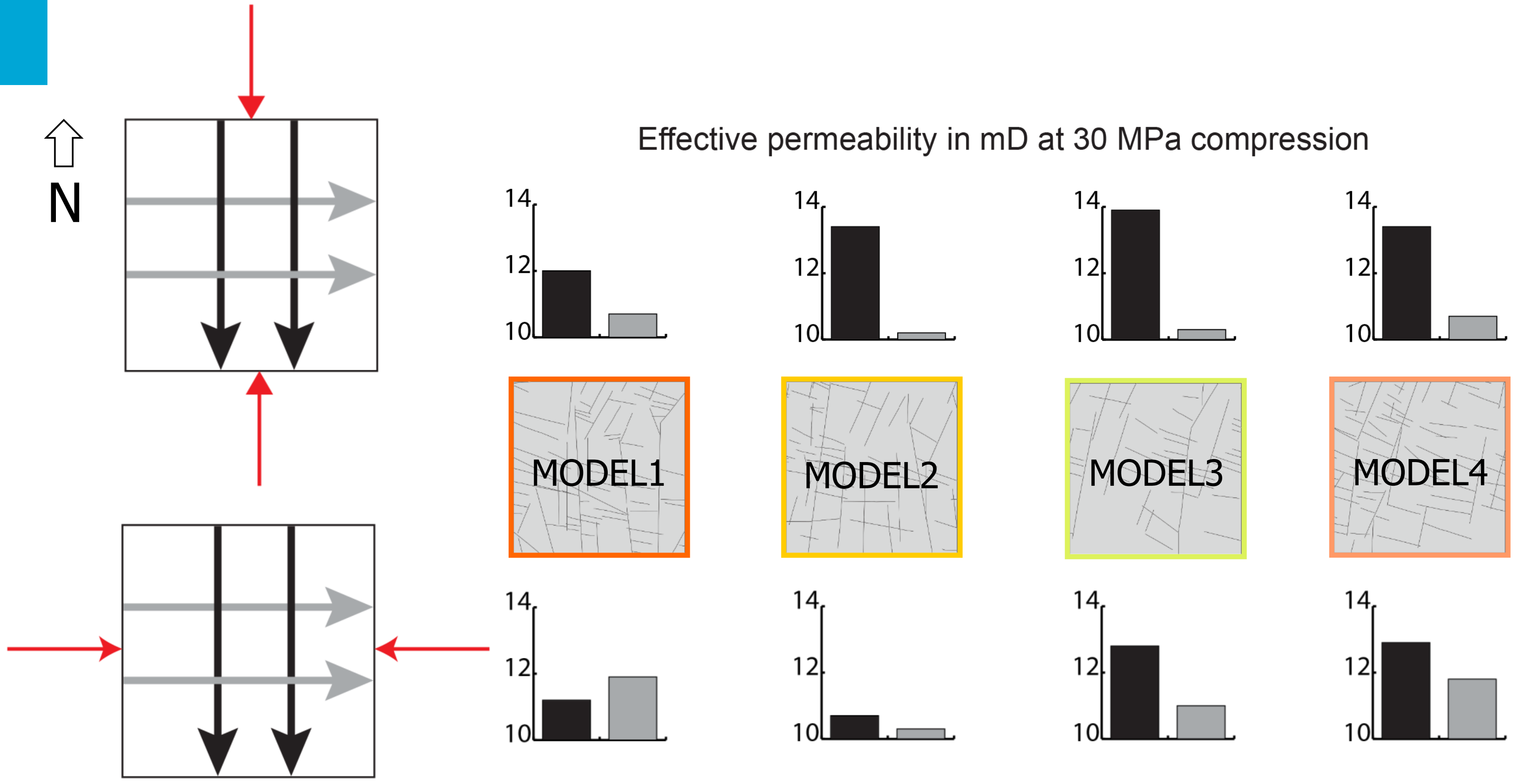






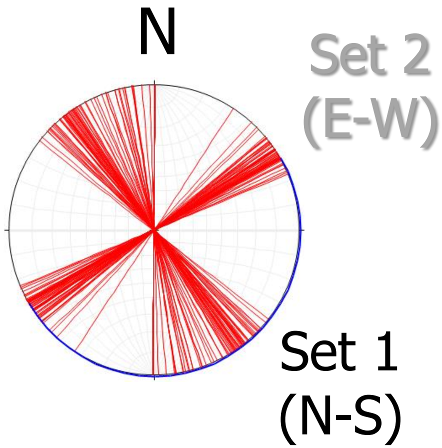
Relation between geometry and flow

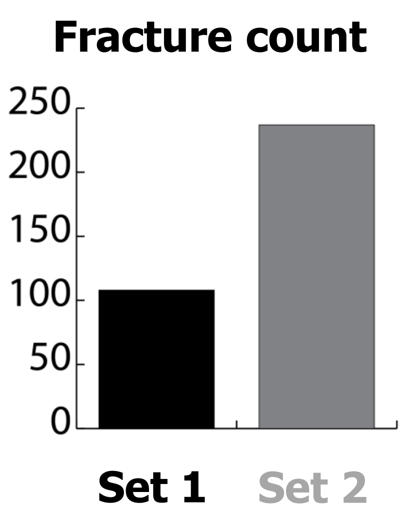
Large anisotropy in N-S vs. E-W flow

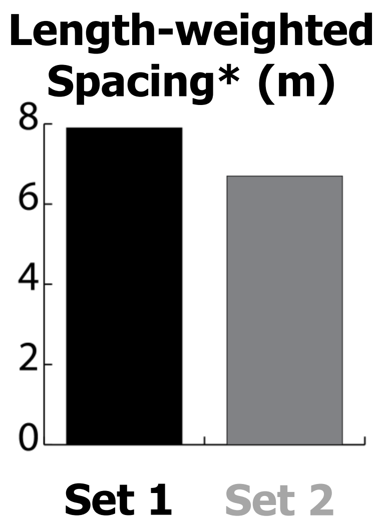


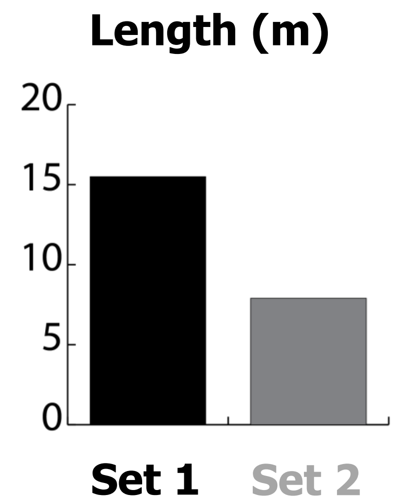
Impact of length vs. spacing

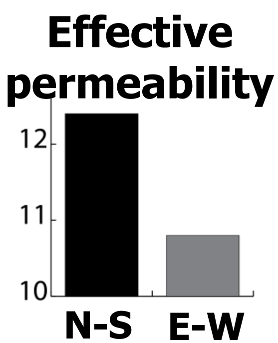
Few large fractures are more important than many small fractures











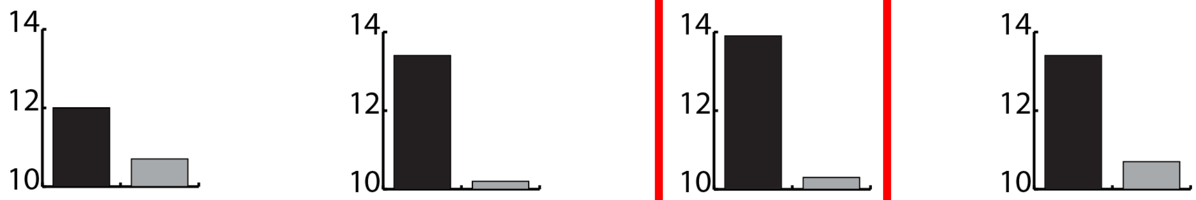
*Calculated using 2-D fracture spacing from Wu and Pollard (2002)

Role of ‘conventional’ flow predictors

Spacing and connectivity do not predict permeability

1	2	3	4
n = 69	n = 58	n = 43	n = 74
spacing = 3.3m	spacing = 3.6m	spacing = 4.9m	spacing = 3.5m

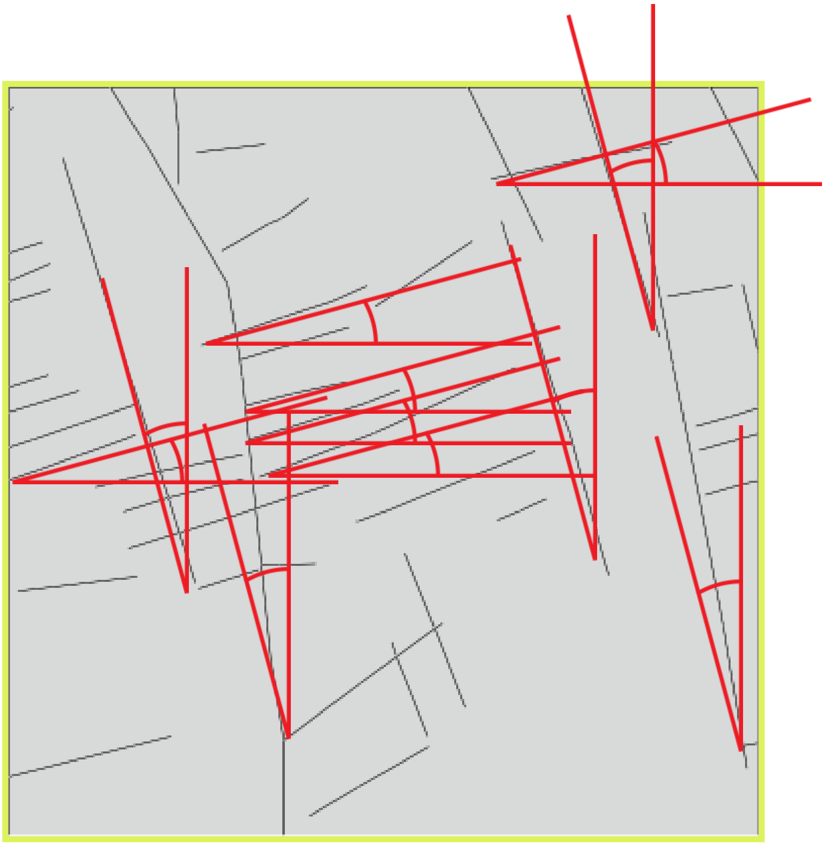
Effective permeability in mD at 30 MPa compression

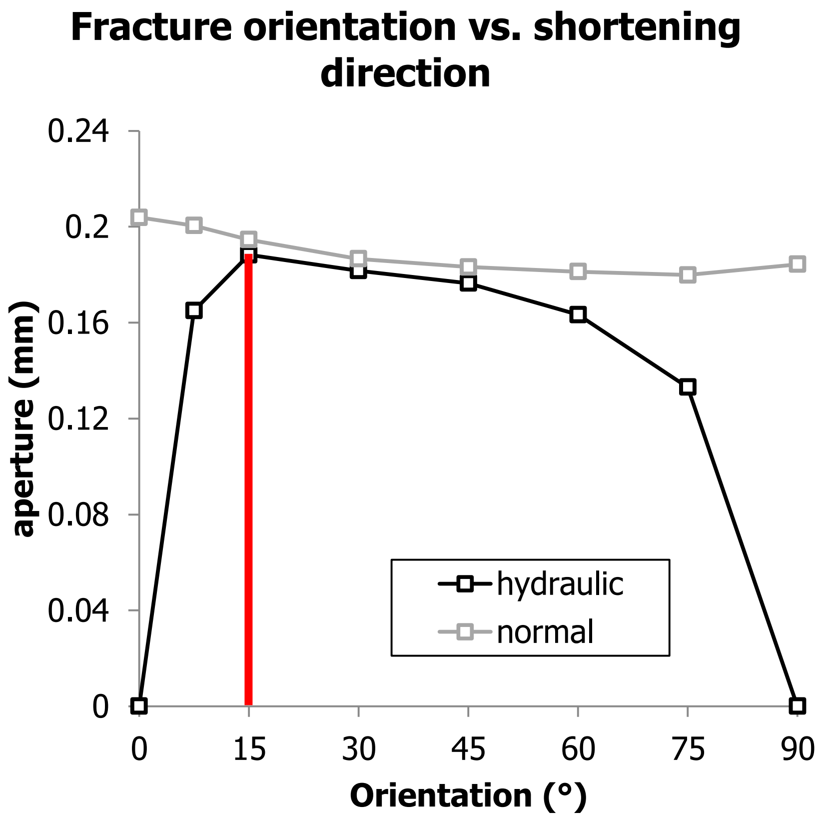


Intersections: **48** **41** **16** **43**

What makes this model so productive?

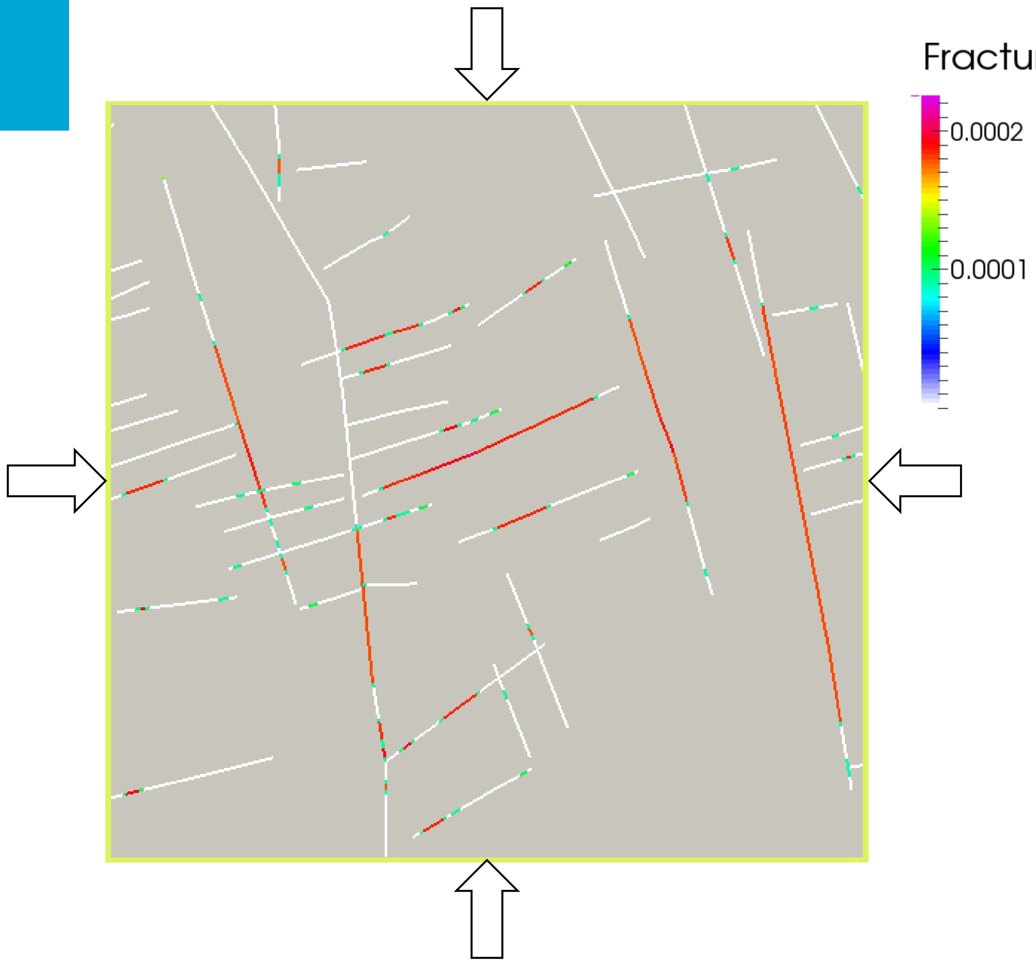
Lowest density, few intersections

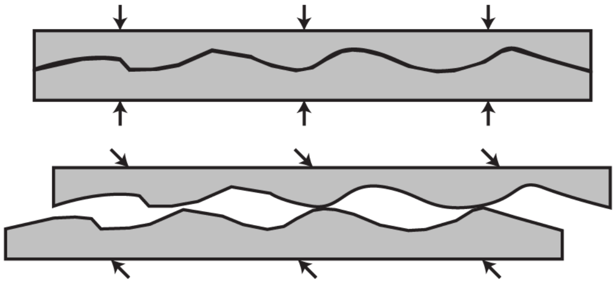




Importance of fracture orientation

With respect to shortening direction

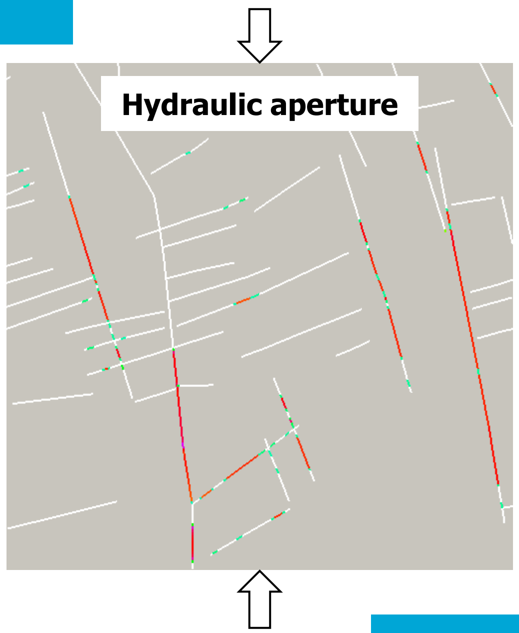


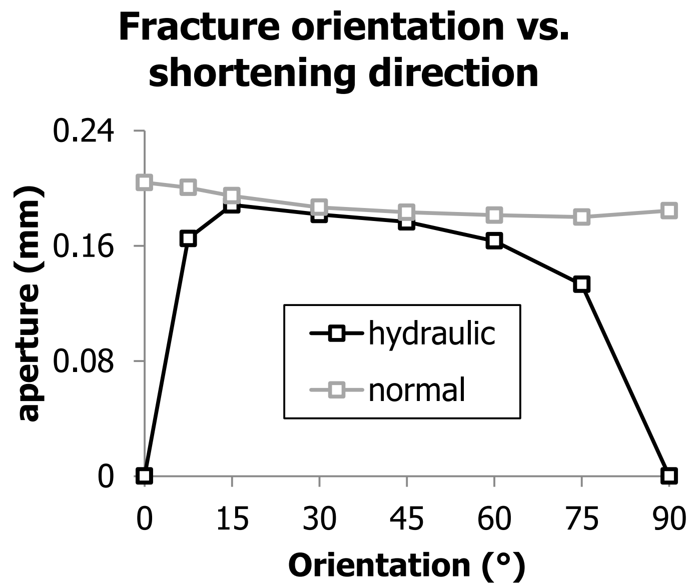


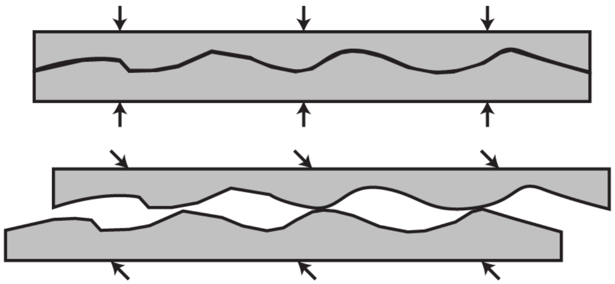
- Angle between fracture strike and direction of shortening is key for hydraulic aperture
- More shear displacement → larger aperture

Conclusions

Stress-based aperture distribution



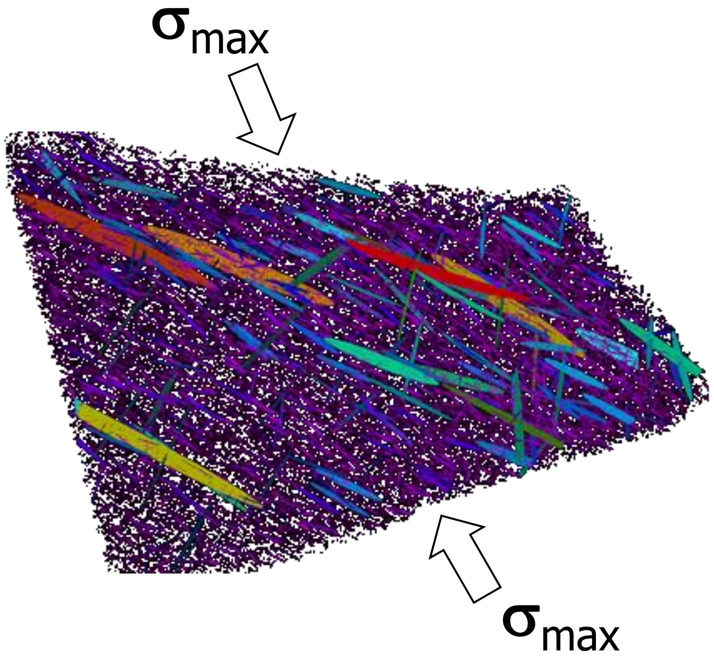


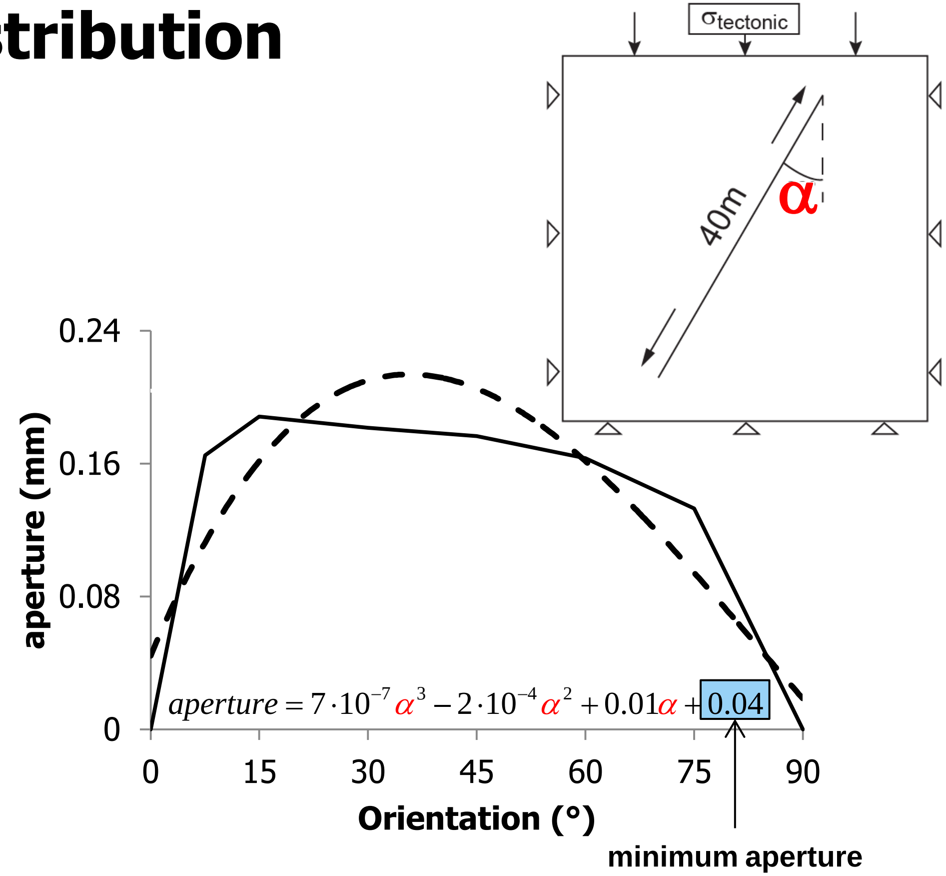


- Without sufficiently high pore pressure, microscopic aperture still attributes to flow
- Micro-aperture depends on fracture-stress obliquity
- Only a small part of fractures are hydraulically open:
    - Few large fractures preferred over many small

Recommendations for NFR modeling

Stress-based aperture distribution





- Hydraulic aperture as function of 'fracture-stress obliquity'
  - Irrespective of fracture length
  - Only requires direction of max. principal stress

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