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Published in:
Tectonophysics

Link to article, DOI:
10.1016/j.tecto.2016.04.006

Publication date:
2016

Document Version
Peer reviewed version

Citation (APA):

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The impact of in-situ stress and outcrop-based fracture geometry on hydraulic aperture and upscaled permeability in fractured reservoirs

Kevin Bisdom¹, Giovanni Bertotti¹ and Hamidreza M. Nick¹,²

¹ Department of Geoscience & Engineering, Delft University, Delft, Netherlands

² Technical University of Denmark, The Danish Hydrocarbon Research and Technology Centre, Copenhagen, Denmark

Corresponding author: K. Bisdom, Department of Geoscience & Engineering, Delft University of Technology, Stevinweg 1, 2628CN, Delft, Netherlands (k.bisdom@tudelft.nl)
Abstract

Aperture has a controlling impact on porosity and permeability and is a source of uncertainty in modeling of naturally fractured reservoirs. This uncertainty results from difficulties in accurately quantifying aperture in the subsurface and from a limited fundamental understanding of the mechanical and diagenetic processes that control aperture. In the absence of cement bridges and high pore pressure, fractures in the subsurface are generally considered to be closed. However, experimental work, outcrop analyses and subsurface data show that some fractures remain open, and that aperture varies even along a single fracture. However, most fracture flow models consider constant apertures for fractures. We create a stress-dependent heterogeneous aperture by combining Finite Element modeling of discrete fracture networks with an empirical aperture model. Using a modeling approach that considers fractures explicitly, we quantify equivalent permeability, i.e. combined matrix and stress-dependent fracture flow. Fracture networks extracted from a large outcropping pavement form the basis of these models. The results show that the angle between fracture strike and $\sigma_1$ has a controlling impact on aperture and permeability, where hydraulic opening is maximum for an angle of $15^\circ$. At this angle, the fracture experiences a minor amount of shear displacement that allows the fracture to remain open even when fluid pressure is lower than the local normal stress. Averaging the heterogeneous aperture to scale up permeability probably results in an underestimation of flow, indicating the need to incorporate full aperture distributions rather than simplified aperture models in reservoir-scale flow models.
Keywords

- Aperture
- Naturally fractured reservoirs
- Equivalent permeability
- Fracture geometry
- Discrete Fracture Networks
1. Introduction

Naturally fractured reservoirs are thought to have a large potential for increased hydrocarbon recovery (Nelson, 2001). This potential is, however, largely untouched partly because of the difficulty of predicting flow along complex fracture networks such as those occurring in nature (Berkowitz, 2002). The difficulty mainly lies in the heterogeneous sub-seismic-scale characteristics of fractures, which can only be partially sampled by core data or image logs (National Research Council, 1996; Wu and Pollard, 2002; Laubach, 2003). Therefore, outcrops are often used to better characterize the fracture spatial distribution, including length, height, orientation, spacing and aperture (Bonnet et al., 2001; Chesnaux et al., 2009; Agosta et al., 2010; Guerriero et al., 2010; Wilson et al., 2011; Hooker et al., 2013, 2014).

Out of these parameters, the fracture aperture distribution is one of the main factors controlling flow, as aperture defines fracture porosity and permeability (National Research Council, 1996; Guerriero et al., 2013). A wide range of studies, mostly based on outcrops where the aperture distribution can be studied in full, have shown that aperture size varies within fracture orientation sets and along the length or height of individual fractures (Laubach and Ward, 2006; Hooker et al., 2012, 2013, 2014; Iñigo et al., 2012). The most common observation in these studies is that the aperture-size distribution is best described by power-law scaling (Hooker et al., 2014). These outcrop observations have also been observed in subsurface datasets (Laubach, 2003; Hooker et al., 2009; Becker et al., 2010).

Stress, in the form of relatively high fluid pressures, can drive generation and propagation of cracks in the subsurface (Atkinson, 1987), but the propagation of fractures in the absence of high fluid pressures is most likely driven by a coupled process of stress and cement precipitation (Laubach et al., 2004a; Alzayer et al., 2015). Moreover, partial cementation, and particularly the occurrence of cement bridges, is crucial in ensuring that fractures remain hydraulically open, even if fluid pressure is low (Laubach et al., 2004b). By
modeling cement precipitation, the rate of fracture growth or propagation can be quantified, to better understand how fracture networks grow (Philip et al., 2005; Lander and Laubach, 2015).

Although models and outcrop descriptions of heterogeneous apertures along single fractures exist, they are only rarely included in Discrete Fracture Network (DFN) models, which typically consider a constant aperture per fracture or even per orientation set, with some notable exceptions (Philip et al., 2005; Olson et al., 2009; Nick et al., 2011; de Dreuzy et al., 2012; Lei et al., 2014). Using a heterogeneous aperture distribution derived from the local stress acting on a fracture surface, we aim to illustrate the impact of a heterogeneous versus homogeneous aperture distribution on permeability. The relation between stress and aperture is quantified using the Barton-Bandis method, which has been shown to produce highly heterogeneous aperture distributions (Lei et al., 2014).

The Barton-Bandis model is an empirical approach that quantifies the aperture that remains when irregular mismatching fracture walls are partially closed under compression (Barton, 1982; Bandis et al., 1983). Whereas the critical stress model used for faults and fractures requires high pore pressures, such that the stress within the fracture is close to the least principle horizontal stress (Barton et al., 1995; Rogers, 2003; Zoback, 2007), the Barton-Bandis model predicts that fractures can be hydraulically open in the absence of high fluid pressures (Olsson and Barton, 2001). Barton-Bandis furthermore takes into account horizontal stress anisotropy during production and the subsequent heterogeneous flow behavior along fracture walls, where local stress conditions may prevent flow along some fractures (Olsson and Barton, 2001; Matsuki et al., 2008). This model does not consider the impact of diagenesis, and hence it may not be representative for chemically reactive rocks such as carbonates, but it has been successfully applied to model permeability in shales (Barton, 2014).
The aperture distribution and subsequent fluid flow through fractures predicted by the Barton-Bandis method has been studied before, but mainly in synthetic fracture networks with simplified geometries or outcrop-based models with small dimensions (Nemoto et al., 2009; Tao et al., 2009; Lei et al., 2014). We apply this aperture method to models of fractured rocks under in-situ stress conditions in 2-D horizontal cross-sections of natural fracture networks affecting bodies of up to 360m across. These fracture networks are digitized from outcropping fracture pavements in central Tunisia which display well resolved fracture geometries.

The impact of hydraulic aperture on fluid flow is modeled using a hybrid Finite-Element Finite-Volume (FEFV) approach that models single-phase incompressible flow through explicit fractures, as well as the flow exchange between fractures and matrix (Matthäi and Belayneh, 2004; Matthäi et al., 2007; Paluszny et al., 2007). Using this integrated workflow, we quantify the impact on aperture and permeability of: i) different fracture geometrical parameters, ii) variations in the magnitude and direction of horizontal principle stresses and iii) rock properties.

The last section of this paper focuses on upscaling. The Barton-Bandis method produces heterogeneous aperture distributions even along single fractures, while reservoir-scale fracture-flow models generally assume a constant aperture per fracture or sometimes even per fracture set. Models with single apertures per fracture found that a single equivalent aperture can be defined, that yields the same result as a heterogeneous aperture distribution (Nick et al., 2011). We analyze whether such an aperture can still be derived for an aperture distribution that varies even along a single fracture. Secondly, we study whether permeability calculated for small-scale (i.e. single reservoir grid cells) models accurately predicts the permeability of a larger-scale model with heterogeneous apertures.
2. Stress-induced Barton-Bandis aperture modeling

The Barton-Bandis method defines aperture based on fracture mechanical properties and the local shear and normal stresses (Barton and Choubey, 1977; Barton and Bandis, 1980; Bandis et al., 1983; Barton et al., 1985). The full set of equations used to translate stress into aperture are discussed in Bisdom et al. (in press). Here, we provide a brief recap of the main functions defining aperture, followed by describing how the aperture model is implemented into the Finite Element (FE) modeling workflow.

2.1. Barton-Bandis aperture model

The Barton-Bandis method is based on an initial aperture, which is a function of fracture roughness (JRC) and strength (JCS) (Barton and Bandis, 1980). An overview of all variables and their meaning is presented in Table 1. The initial aperture is defined by $E_0 = \frac{JRC}{50}$.

By applying in-situ compression, the initial aperture decreases, whereby part of the fracture may remain open by poorly interlocking irregular fracture walls (Figure 1). The resulting physical or mechanical aperture is a function of normal, i.e. perpendicular to two sub-parallel fracture walls, and shear-related opening. In this study, we focus on normal aperture $E_n$ and the shear-related hydraulic aperture $e$, which is the opening that effectively contributes to fluid flow under given in-situ stress conditions, controlled by the amount of shear-induced dilation. Normal and hydraulic apertures are defined by (Bisdom et al., in press):

$$E_n = E_0 - \frac{1}{\frac{1}{\nu_m} + \frac{K_{ni}}{\sigma_n}}^{-1}$$  \hspace{1cm} (1)

$$e = \begin{cases} \frac{E_n^2}{JRC^{2.5}} \frac{u_s}{u_{peak}} & \text{for} \quad u_s \leq 0.75 \\ \sqrt{E_n JRC_{mob}} \frac{u_t}{u_{peak}} & \text{for} \quad u_t \geq 1 \end{cases}$$  \hspace{1cm} (2)
The $u_s / u_{peak}$ term quantifies the shear displacement as a function of a peak shear displacement, which depends mainly on the block size of a fracture. The block size $L$ is the spacing between fractures that intersect the fracture of interest (Barton, 1982). The domain in between $0.75 \leq u_s / u_{peak} \leq 1.0$ is interpolated linearly (Olsson and Barton, 2001). The normal stress $\sigma_n$ and shear displacement $u$ required for calculating aperture in the above equations are quantified using FE models.

2.2. Governing equations

Numerical models such as FE or Finite-Element Discrete-Element (FDEM) have proven to be efficient for modeling different aspects of fracture behavior, including growth and opening (e.g. Latham et al., 2013; Lei et al., 2014). Many solutions exist in both the commercial and academic domain for FE modeling of fractured media (Paluszny and Zimmerman, 2011). In this study we use the commercial ABAQUS code, which has been proven effective in modeling of geological discontinuities at a small (i.e. fracture) scale (e.g. Smart et al., 2014).

We consider plane-strain models with a minimum and maximum horizontal stress component applied to the boundaries of the system. The local stress state inside the body is solved taking into account non-linear behavior resulting from the fracture interactions. The stress-strain relationship of a multi-dimensional linear elastic material is written as (Dassault Systemes, 2013):

\[
\sigma_{ij} = \frac{E}{1+\nu} \varepsilon_{ij} + \frac{E\nu}{(1+\nu)(1-2\nu)} \delta_{ij} \varepsilon_{kk} .
\]  

(3)

The normal stress acting on each fracture is calculated from its bordering elements, where for a single fracture in a fully elastic medium normal stress is defined as (e.g. Zoback, 2007):

\[
\sigma_n = 0.5\left(\sigma_i + \sigma_3\right) + 0.5\left(\sigma_i - \sigma_3\right) \cos 2\beta
\]  

(4)
We consider elastic and elastoplastic models. For elastoplastic materials a linear Mohr-Coulomb criterion is used (Dassault Systemes, 2013):

\[ \tau = c - \sigma_n \tan \phi \]  

The transition from elastic to plastic deformation is defined by the cohesion yield stress. Non-linear Mohr-Coulomb behavior may be considered as more representative of porous reservoir rocks that experience significant changes in stress during production (Barton, 1976, 2014), but the change in aperture during production is not considered in our models. Furthermore, it is assumed that no fracture growth or initiation of new fractures occurs, as the main focus is to analyze the change in opening within a fracture as a function of stress.

### 2.3. Model setup

The FE models consist of an unstructured mesh with triangular quadratic elements. The average element size is 0.01% of the smallest dimension of the model, resulting in approximately 60,000 elements for a 50×50m model, depending on fracture intensity. In all models, we introduce a buffer zone around the fractured mesh to avoid boundary effects. The validity of this mesh size is tested by looking at the discretization error as a function of the resulting hydraulic aperture. Fractures are represented by splitting the mesh along fracture lines, creating double nodes along the fracture surface, resulting in seams in the mesh, that are able to open or close (Figure 2). For each of the fracture nodes, the normal stress and shear displacement are calculated in ABAQUS.

For the rock matrix, we obtain solutions for elastic and elastoplastic Mohr-Coulomb failure behavior. The elastic properties are measured from samples of the analyzed outcrops and include bulk rock density, dry porosity, and seismic velocities, which are used to calculate the Young’s Modulus and Poisson’s ratio. To define the linear Mohr-Coulomb failure
criterion, typical values from the literature representative of the studied rock are used (Smart et al., 2010).

2.4. Single-fracture model behavior

To illustrate the change in aperture modeled by this FE Barton-Bandis approach, a tectonic stress is applied to the 2-D model in one direction. As the body is limited and no-displacement conditions are applied, representing a body of rock in the subsurface confined within a larger unit, the tectonic stress (i.e. $\sigma_1$) applied in the y-direction results in a Poisson’s stress ($\sigma_3$) in the x-direction (Figure 3). Throughout this study, we assume rough fractures with a JRC of 15, resulting in an initial aperture of 0.3mm.

For this example model, with a $\sigma_1$ of 30MPa and a $\sigma_3$ of 10MPa, the normal aperture of a single fracture decreases with increasing normal stress, whereas hydraulic aperture increases (Figure 4a,b). The aperture distribution is sensitive to model orientation, as a fracture oblique to $\sigma_1$ experiences more shear, coinciding with a decrease in normal stress (Figure 4c). This has a negative impact on normal aperture but positive impact on hydraulic aperture.

3. Modeling aperture and permeability in natural fracture networks

We apply the described workflow for heterogeneous aperture modeling to a large and complex fracture system, analyzing the relations between fracture geometry, different mechanical properties and boundary conditions, and hydraulic aperture and permeability. For geometry, we consider commonly used parameters such as spacing and size, as well as connectivity (Berkowitz and Balberg, 1993; Berkowitz, 2002).
3.1. **Regional setting and geometry of the fracture network**

We extract the fracture network used for modeling from an outcropping carbonate pavement that is part of the Alima fold (Gafsa basin, central Tunisia; **Figure 5a**) (Riley et al., 2010; Saïd et al., 2011). This basin contains several E-W trending folds with excellent exposures of fractures. The Alima fold is an E-W striking anticline with a length of 20 km and an outcropping width of 7 km (**Figure 5b**). The anticline formed during N-S regional shortening starting in the Eocene (**Figure 5c**) (Riley et al., 2010). The southern flank has been steepened to 60-70°, resulting in a large well-preserved pavement of carbonates of the Eocene Kef Eddour Fm. The width of the pavement is 360 m, the maximum height (perpendicular to the fold axis) is 70 m at the center, decreasing to 30 m at the sides (**Figure 6a**).

Fractures in the pavement are digitized on georeferenced outcrop images (Hardebol and Bertotti, 2013), resulting in 345 fractures inclusive of their length, strike, and spacing (Table 2; Bisdom, 2015). The database is supplemented with observations made at the outcrop, which indicate that fractures are generally bed-perpendicular.

The minimum fracture length captured is 1 m. Smaller fractures are present, but their distribution cannot be fully defined as they are below the image resolution, resulting in a truncated distribution (Ortega et al., 2006). Maximum measured fracture length is equal to the smallest dimension of the outcrop, resulting in censoring of the true maximum length (Ortega et al., 2006). However, the Barton-Bandis method defines aperture as a function of block size rather than total fracture length, so this method suffers less from censoring artifacts. The average 2-D fracture spacing \( s \) in meters is calculated using (Wu and Pollard, 2002):

\[
s = \frac{A}{T + d_o}
\]
The resulting spacing varies between 3.3 and 4.9m in different parts of the outcrop, with an average of 3.8m.

Low-angle stylolites attributed to early folding are crosscutting bed-perpendicular fractures, indicating that fracturing occurred when layers were horizontal. Therefore, the pavement and its fractures are rotated back to the horizontal pre-folding situation (Figure 6b-c). The resulting dataset consists of two bed-perpendicular orientation families, striking on average NNW-SSE (Set 1) and ENE-WSW (Set 2), with a scatter of 40° within each set (Figure 6c). The geometry per set is summarized in Table 2.

From the outcrop model, we extract four 50×50m sub-models (Alima1-4; Figure 6d) which are used for the analysis of the impact of fracture geometry and stress conditions on aperture. All sub-models contain comparable N-S and E-W striking fractures, but the number of fractures varies (Table 2). There are no nearby faults, nor any changes in the lithology along the pavement, so it is assumed that the variations in fracture intensity are representative of the natural variability of a fracture network (Bisdom et al., 2014). Aperture and permeability are calculated for all fractures, i.e. considering both sets.

3.2. Model set-up

3.2.1. Mechanical FE model

We model aperture in the natural fracture networks using the same fracture and stress conditions as for the basic model presented in Figure 3, with an initial aperture of 0.3mm for all fractures. Model set-up, rock properties and boundary conditions are also the same as those in Figure 3. When modeling the 50×50m sub-models, we add a buffer zone extending the models to 100×100m to avoid boundary effects interfering with the fractures.

To quantify the uncertainty in aperture modeling, we consider a range of stresses and rock properties as input. Although the regional strike of σ1 during fracturing was N-S
(Bouaziz et al., 2002), we consider also the impact of $\sigma_1$ on aperture and permeability in the E-W direction. The x-axis of the models is set perpendicular to the N-S direction. For both $\sigma_1$ directions, the maximum compressional stress varies between 1 and 80 MPa.

### 3.2.2. Coupled fracture-matrix permeability model

To quantify the impact of hydraulic aperture on flow, equivalent permeability is modeled, which is a function of combined matrix and fracture permeability (Matthäi and Nick, 2009; Bisdom et al., in press). Equivalent permeability describes the ability of the fractured formations to permit the flow of fluid through both the porous rock matrix and open fractures in each direction from one boundary to the opposite one, assuming no-flow boundary conditions at the other two boundaries parallel to the far field pressure gradient (e.g. Matthäi and Belayneh, 2004). It is calculated using the steady state continuity equation $\nabla \cdot q = 0$, which is solved for pressure using Darcy flow in a hybrid FEFV approach implemented in the Complex System Modeling Platform (CSMP++; Matthai et al., 2007). A far field pressure gradient of 10 kPa is applied in either the N-S or E-W direction of the model, after which the steady state equation is solved (Paluszny and Matthäi, 2010; Nick and Matthäi, 2011).

Fracture permeability is calculated from hydraulic aperture at each node in the mesh using the cubic law (Snow, 1969; figure 1 in Nick et al., 2011). The potential contribution from disconnected fractures is captured by including a matrix permeability of 10 mD. To limit the number of variables in the models, matrix permeability $k_m$ is assumed constant. The contrast between matrix and fracture permeability can impact equivalent permeability, but this is addressed elsewhere (Matthäi and Belayneh, 2004; Bisdom et al., submitted). Equivalent permeability for both the N-S and E-W directions is calculated by integrating the fluid flux across the model boundaries (Matthäi and Nick, 2009).
4. Results

4.1. The impact of fracture network geometry

We compare the relation between equivalent permeability and fracture attributes including intensity, size, orientation and connectivity (Table 2). The geometrical analysis is done for elastic models with a constant compression of 30MPa in N-S (Figure 7a) and E-W directions (Figure 7b). Under these constant stress conditions, there are large differences in permeability between the different sub-models, related to geometry.

4.1.1. Impact of spacing

Spacing has no strong impact on equivalent permeability, as for a N-S oriented $\sigma_1$, the outcrops with the smallest spacing (i.e. highest intensity) have the lowest fracture network permeability (Alima1), whereas the model with the largest spacing (Alima3) has the highest equivalent permeability (Figure 7a,c). The spacing distributions are similar to each other in the different sub-models, with relatively small variations in average aperture (except for Alima3), although variations in permeability are large.

In terms of spacing per orientation set, the N-S system has a larger spacing than the E-W system (Table 2), but the higher-intensity E-W system has a lower permeability, even when compression is in E-W direction (Figure 7b).

4.1.2. Impact of connectivity

Fracture connectivity does not provide a representative description of equivalent permeability, as the model with the lowest connectivity, expressed as the number of fracture intersections, has the highest permeability for a N-S oriented $\sigma_1$ (Alima3 in Figure 7a). Alima1, which has the highest connectivity, has the lowest permeability when $\sigma_1$ is in N-S direction. Models
Alima2 and Alima4 do have high permeabilities as well as a high connectivity, but it is still lower than that of Alima3, which has 50% fewer intersections compared to the other models.

With the exception of Alima4, three of the four models have percolating pathways of connected fractures (Figure 6c and Table 2). However, in terms of hydraulic aperture, there is no fully connected pathway in any of the models, so the connected fractures in Alima4 do not form a percolating pathway in terms of fluid flow.

**4.1.3. Impact of fracture length**

The large contrast in N-S versus E-W equivalent permeability is mainly related to the maximum and average fracture lengths (Table 2 and Figure 7d). Average fracture length of the N-S trending system is more than 50% larger than that of the E-W fracture system (Table 2). The longest fractures in each model are part of the N-S system. Moreover, when ranking the outcrops from large to small average length of N-S sets, the ranking is identical to the ranking of N-S equivalent permeability (Figure 7a).

Average and maximum length better describe the resulting equivalent permeability trends, compared to spacing, even though spacing is also defined as a function of length through equation (6). However, this equation does not distinguish between many small fractures and a few very large fractures.

**4.1.4. Impact of orientation**

Although length correlates to some extent with equivalent permeability, it does not explain the relatively high N-S permeability in Alima3. Fracture orientation, however, does have a positive impact on fluid flow in this model. Specifically, the fracture strike with respect to the direction of $\sigma_1$ is key for hydraulic aperture and subsequent permeability. The average strike in Alima3 is 17°, which corresponds approximately to the ideal angle between shortening direction and strike as found in Figure 4c. The other three Alima models contain more
fractures, but a smaller sub-set of these fractures is oriented ideally with respect to the shortening direction (Figure 8). As a result of this orientation distribution, and to a lesser extent block size, most of these fractures are hydraulically closed, especially in Alima1 and Alima2.

4.2. Impact of stress

We quantify the change in aperture as a function of increasing regional stress $\sigma_1$ and changing stress orientation (N-S vs. E-W). In the single fracture model it was shown that an increase in stress may lead to an increase in permeability, depending on whether the fracture experiences shear stress (Figure 4). Fractures in the Alima models have heterogeneous aperture and permeability distributions, but clear trends can still be distinguished (Figure 9).

From the curves in Figure 9 we can identify three specific equivalent permeability domains for N-S compression. These trends are similar for E-W compression, but as the contribution of fractures to flow is small, the domains are less easily observed. Focusing on N-S compression, the first domain (up to 5MPa differential stress) is characterized by a lack of change in permeability. Between 5 and 20MPa, permeability increases, and flattens again for differential stresses above 20MPa. The flattening results from the definition of hydraulic aperture, which cannot exceed normal aperture.

A second factor strongly affecting aperture and permeability is the direction of $\sigma_1$. When $\sigma_1$ is applied in the N-S direction, most E-W striking fractures experience maximum closure, resulting in lower E-W equivalent permeability (Figure 9a). However, when $\sigma_1$ is in the E-W direction, N-S permeability in three of the four models remains larger than permeability in the E-W direction, indicating that the direction of highest permeability is not only a function of stress direction, but also of other factors, such as geometry (Figure 9b).
The irregular increase in permeability, most notably in the domain between 5 and 15 MPa differential stress, is primarily the result of the relation between shear displacement and peak shear displacement. The resulting shear ratio has a major impact on hydraulic aperture, as a small change in the shear ratio may result in changing from one hydraulic aperture domain to another, as determined by equation (2).

**4.3. Impact of rock properties**

Compressive stress and the subsequent aperture and permeability distributions are functions of the mechanical behavior of the rock matrix. We analyze a range of values for the Young’s modulus and Poisson’s ratio, and compare the elastic model with an elastoplastic Mohr-Coulomb model. In all models, the applied $\sigma_1$ is constant (30 MPa). We do not consider the effect of deformation on matrix porosity and permeability, and assume that the fracture properties remain constant. The $JCS$ is also kept constant, although it is probably related to mechanical rock properties such as the Young’s Modulus, but the exact dependency of $JCS$ on other rock properties is unclear.

For an elastic rheology, equivalent permeability decreases with increasing Young’s modulus and Poisson’s ratio, irrespective of the direction of $\sigma_1$ (Figure 10). A higher Young’s Modulus results in a decrease in shear displacement and shear-induced hydraulic aperture and flow. The impact of the Poisson’s ratio is the result of the fact that the lateral boundaries of the model are fixed. A high Poisson’s ratio in combination with this boundary condition increases $\sigma_3$, and decreases normal and subsequent hydraulic opening. This effect is most clearly visible in Figure 10d, where for N-S shortening without the possibility of E-W extension, the E-W trending fractures are almost immediately closed when the Poisson’s ratio starts to increase, resulting in a large contrast in permeability in the E-W direction versus the N-S direction.
Mohr-Coulomb plasticity lowers the shear displacement on fracture surfaces and subsequently lowers the hydraulic aperture (Figure 10c,f). The relative impact of fracture permeability on equivalent permeability decreases, resulting in smaller differences in permeability between the sub-models. A detailed sensitivity analysis of the plastic parameters is outside the scope of this study but our results suggest that models with lower friction and dilation angles do not significantly change permeability. For the regional stress conditions in the studied models, the elastic properties have a stronger impact on permeability than the plastic properties. For a higher differential stress, the plastic domain may become the controlling factor, and its properties may have a larger impact relative to the elastic properties.

5. Towards reservoir-scale aperture and permeability models

The aperture distributions of the 50×50m models give an indication of small-scale permeability, i.e. within a single reservoir simulation grid cell. Using explicit fracture modeling to construct a reservoir-scale 3-D fracture model with mechanically controlled heterogeneous aperture distributions is a complex task (Geiger and Matthäi, 2012).

Alternatively, the high-resolution aperture and permeability, calculated per fracture node, of explicit fracture permeability models can be upscaled through arithmetic or harmonic averaging (Jonoud and Jackson, 2008; Cottereau et al., 2010). We test these methods in two ways using our explicit fracture aperture and permeability models: i) Within each 50×50m model, we quantify whether permeability can be characterized by a single average aperture instead of a heterogeneous distribution, and ii) we compare the average permeability of the 50×50m models with the complete Alima model, to quantify whether these small models, representing grid cells, can capture the permeability of the complete model.

5.1. Heterogeneous vs. averaged aperture in 50×50m models

For each of the four models, we calculate the weighted average aperture:
The average is a function of both open and closed fracture parts, including those that are practically closed by the first part of equation (2), and is assigned as a constant aperture to the entire fracture network. The equivalent permeability resulting from the averaged aperture distributions is modeled for elastic (N-S and E-W oriented $\sigma_1$) and elastoplastic (N-S oriented $\sigma_1$) models (Figure 11).

The average aperture yields an upward trend in permeability for increasing differential stress that is similar to that of the heterogeneous distributions, with Alima3 having the highest equivalent permeability in N-S direction (Figure 11a,b). The permeability in the E-W direction, however, has changed significantly, and is similar to the N-S permeability, as all fractures in all directions have the same aperture. Permeability resulting from average aperture in an elastoplastic model is lower, similar to that which was observed for heterogeneous apertures.

Compared to the heterogeneous aperture distributions, the averaged distributions result in a decrease in N-S permeability versus a relatively large increase in E-W permeability (Figure 11). Although the maximum of the averaged permeability is small compared to the heterogeneous distribution, the average of N-S and E-W flow of the averaged aperture is comparable to that of the heterogeneous aperture.

5.2. Upscaling equivalent permeability derived from heterogeneous aperture distributions

The 50×50m models are representative of the grid cell size of conventional reservoir simulation grids. Existing upscaling approaches commonly assume that the equivalent
permeability of the sub-models (i.e. grid cells) combined produces an accurate representation of the flow in the entire model (Matthäi and Nick, 2009).

We compare the heterogeneous and averaged aperture and permeability distributions of the four sub-models with the complete Alima model, which contains 345 fractures in an area of 328×54m (Figure 12a). In terms of geometry, the sub-models and the complete model have similar distributions, with an average spacing of 3.9m in the complete model versus 3.8m in the sub-models.

As with the sub-models, we model the aperture distribution as a function of stress in the complete model, and calculate fluid pressure in N-S and E-W directions (Figure 12b,c). The large contrast between N-S and E-W fluid pressures observed in the sub-models is also seen in the complete Alima model (Figure 12b,c). The increased permeability in N-S direction is mainly the result of a few flow pathways along hydraulically open fractures (Figure 12c), similar to what was observed in the sub-models.

The sub-models underestimate the permeability of the complete Alima model for both heterogeneous and averaged apertures with an average error of 10% (Figure 12d-f). The permeability values in these figures are the average of N-S and E-W permeability. The underestimation is largest for the models with the highest permeability (i.e. N-S compression), while for E-W compression and elastoplastic models, the underestimation is small. Under N-S compression, the increase in permeability is controlled by a limited number of flow pathways. These pathways are partly outside the sub-models, resulting in an underestimation.

6. Discussion

6.1. Fracture aperture versus geometry

The amount of shear displacement and the resulting hydraulic aperture distributions in the presented models are partially driven by the orientation of the fracture with respect to the
For maximum hydraulic aperture, Barton-Bandis predicts that fractures should ideally strike at a small angle (i.e. close to 15°) with respect to $\sigma_1$ (Figure 4c). As a result, model Alima3, which has the largest spacing and smallest fracture intersection count, but ideally oriented fractures for large hydraulic apertures, has a larger equivalent permeability than the other models. Figures similar to Figure 4c may be useful for defining the relation between fracture orientation and hydraulic aperture. When in-situ stress data are available, and the mechanical rock properties are relatively homogeneous, such that fracture attributes are only influenced by stress, the impact of fracture orientation can be implemented into DFN modeling workflows to define a hydraulic aperture distribution without the need of geomechanical modeling of aperture.

In the studied models, the fracture orientation and the associated hydraulic aperture distribution have a stronger impact on equivalent permeability than length or spacing. Spacing does not significantly impact equivalent permeability, even though we have defined spacing as a function of length using equation (6). We do find that for constant spacing, equivalent permeability is higher for a fracture system consisting of few large fractures rather than many small fractures. This distinction is however not made by equation (6).

In terms of fracture network connectivity, the number of pathways in both horizontal directions has no direct impact on permeability, as these pathways are not necessarily hydraulically open under the given stress conditions. Percolation studies often assume a non-permeable matrix, i.e. disconnected fractures do not contribute to flow. This yields a binary response in permeability, where breaking up a fracture network by removing a single fracture may yield a large change in permeability (i.e. the percolation threshold) (Long and Witherspoon, 1985; Berkowitz and Balberg, 1993). We do not find this effect in our permeability analysis, where 10mD matrix flow is included and fracture aperture is relatively small. Other studies that take into account coupled fracture-matrix flow find that even with
matrix permeability, connectivity has a larger impact than aperture (Philip et al., 2005; Olson et al., 2009). However, the contrast between matrix and fracture permeability is large in most of these models, resulting in an equivalent permeability that is effectively only controlled by fracture permeability (Matthäi and Belayneh, 2004). For low matrix permeability (i.e. less than 10mD), fracture network connectivity is controlling for fluid flow, while for a more permeable matrix, absolute apertures define flow (Bisdom et al., submitted). Furthermore, since the Barton-Bandis model also includes segments with zero hydraulic aperture, it also impacts connectivity.

6.2. **Upscaling aperture and permeability**

In contrast to other studies (Paluszny and Matthäi, 2010; Nick et al., 2011), the permeability of our models with average weighted aperture is smaller than those with the heterogeneous aperture distribution. This difference is likely related to the type of aperture modeling, as we consider aperture under compression with a low fluid pressure, yielding values smaller than 0.3mm. These apertures do result in a fracture permeability as defined by the cubic law that ranges up to 800 Darcy for the base case models in Figure 7, but the total change in equivalent permeability of the entire network is relatively small.

Another possible cause for the underestimation is that we apply the averaging method for the entire hydraulic aperture distribution ranging from $3 \times 10^{-4}$ m to $4 \times 10^{-8}$ m, whereas earlier work only contains hydraulically open fractures with a hydraulic aperture larger than $1 \times 10^{-6}$ m (Nick et al., 2011).

6.3. **Predictive value of 2-D flow models for 3-D fractured reservoirs**

The studied models are limited to fracture lengths in 2-D, representing a horizontal section through a bed-perpendicular fracture network, capturing the horizontal equivalent permeabilities, without considering vertical permeability. The studied models can be used to
define horizontal permeability in layers with bed-confined fractures or highly persistent fractures, where the 2-D horizontal slice is representative for the entire vertical section. Gravity and overburden stress is not taken into account, but in thin sub-horizontal layers, gravity has no impact when assuming fully saturated single-phase flow.

In 3-D bed-perpendicular fracture systems, the stress-induced variations in aperture predicted by Barton-Bandis may become relatively insignificant compared to mesoscopic rotation of fractured rock segments resulting from slip along bedding planes (e.g. Lei et al., 2015). Slip along bedding planes may also result in increased opening of fractures that is not described by the Barton-Bandis model. This process is observed through microseismic for hydraulic fractures, but may also affect natural fractures (Gu et al., 2008).

In natural fracture networks, where fractures commonly have scattered orientations resulting in highly-connected networks, the consideration of 3-D connectivity significantly increases permeability magnitude and anisotropy (de Dreuzy et al., 2012). At the fracture scale, these 3-D models show that heterogeneous aperture along single fractures results in flow bottlenecks that decrease permeability, which is also observed in our 2-D models.

**Conclusions**

We have presented an integrated workflow that applies the Barton-Bandis method to model stress-sensitive normal and hydraulic aperture in fracture networks to generate heterogeneous aperture distributions even along single fractures. The impact of heterogeneous aperture on flow is quantified in terms of equivalent permeability, modeling the fractures with heterogeneous apertures explicitly in a permeable matrix.

We show that this workflow can be used to study equivalent permeability in complex fracture networks, using deterministic fracture patterns from outcrops to obtain realistic geometries. The studied networks have relatively simple geometries compared to what is
commonly observed in outcrops, but this permits for studying in detail the impact of each
individual geometrical attribute on the aperture distribution along single fractures and on
permeability. However, the presented workflow can be applied to larger multi-scale discrete
fracture networks (Bisdom et al., in press).

Our main findings are:

i. The Barton-Bandis model predicts that the hydraulic aperture of fractures with
minor amounts of shear under compression is highly heterogeneous, even within
single fractures. This results in a disconnected fracture network where a small
fraction of the network contributes significantly to the equivalent permeability. In
our models, the angle between \( \sigma_1 \) and the fracture strike is the controlling factor
for hydraulic aperture and subsequent fracture network permeability. Fractures that
strike slightly oblique to \( \sigma_1 \) experience both dilation and a small amount of shear
displacement, creating poorly interlocking fractures with a relatively large
hydraulic aperture.

ii. In the studied models, fracture block size and spacing have a relatively small
impact on equivalent permeability. When considering both fracture and matrix
flow, the role of percolating clusters of fractures is negligible, as is the impact of
fracture connectivity. From the four sub-models studied, the model with the lowest
fracture density and lowest connectivity, showed the highest equivalent
permeability as most fractures were oriented ideally with respect to \( \sigma_1 \).

iii. Upscaling of the heterogeneous aperture distribution to a single averaged aperture
may provide the same equivalent permeability as the heterogeneous model when
there is no large contrast between flow in different directions. Averaging and
upscaling equivalent permeability of small-scale fracture models can provide an
accurate description of permeability when flow is relatively homogeneous, i.e. most fractures contribute to flow. Otherwise, the small-scale models may underestimate equivalent permeability.

The stress-based aperture and permeability modeling workflow, with heterogeneous apertures along single fractures, may provide more representative heterogeneous aperture distributions for describing small-scale permeability in non-reactive reservoir rocks (i.e. within a grid cell), from which the resulting permeability may be assigned to grid cells in reservoir-scale fracture flow models.

Acknowledgements
This work is part of the PhD research of the first author, sponsored by TOTAL S.A.. The fieldwork data in this study has been acquired in collaboration with S. Bouaziz, A. Hammami, and S. Makni (ENIS Sfax), R. Vaughan (VU University) and T. Thorgilsdottir (TU Delft). Data has been digitized and processed using DigiFract (N. Hardebol, TU Delft) and SKUA/Gocad (Paradigm), supported with research plugins (Gocad Research Group). The fracture dataset for this paper is available in CAD format through dx.doi.org/10.4121/uuid:6d096e88-14e0-4d6e-aeca-a0b9f7b3ea56. Petrophysical analysis of rock samples has been done by S. Toby (VU University). The authors would like to thank S. Geiger and P. Corbett (Heriot Watt University) for providing inspiration for the manuscript, and N. Hardebol (Delft University of Technology), W. van der Zee and M. Holland (Baker Hughes) for their advice regarding geomechanical modeling. We thank the guest editor, O. Lacombe, and the reviewers (anonymous and P. Gillespie) for their thorough and detailed reviews, which significantly improved this manuscript.
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### Table 1 Overview of parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
<th>Constant</th>
</tr>
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<tr>
<td>JRC</td>
<td>Joint Roughness Coefficient</td>
<td>-</td>
<td>15.0</td>
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<td>JCS</td>
<td>Joint Compressive Strength</td>
<td>MPa</td>
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<tr>
<td>$E_0$</td>
<td>Initial ‘unstressed’ aperture</td>
<td>mm</td>
<td>0.3</td>
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<tr>
<td>$E_n$</td>
<td>Normal aperture</td>
<td>mm</td>
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</tr>
<tr>
<td>$u_s$</td>
<td>shear displacement</td>
<td>mm</td>
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</tr>
<tr>
<td>$u_{peak}$</td>
<td>Peak shear displacement</td>
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<td></td>
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<td>block size</td>
<td>m</td>
<td></td>
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<td>$e$ and $\bar{e}$</td>
<td>hydraulic aperture (and averaged hydraulic aperture)</td>
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<tr>
<td>$v_{\text{m}}$</td>
<td>maximum closure</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>$K_{\text{ij}}$</td>
<td>initial stiffness</td>
<td>MPa/mm</td>
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<tr>
<td>$E$</td>
<td>Young’s Modulus</td>
<td>GPa</td>
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</tr>
<tr>
<td>$\nu$</td>
<td>Poisson’s ratio</td>
<td>-</td>
<td></td>
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<tr>
<td>$\sigma_n$, $\sigma_2$ and $\sigma_3$</td>
<td>Normal, maximum and minimum horizontal stress</td>
<td>MPa</td>
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<tr>
<td>$\delta_{ij}$</td>
<td>Kronecker delta</td>
<td>-</td>
<td></td>
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<tr>
<td>$\varepsilon$</td>
<td>strain</td>
<td>-</td>
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<tr>
<td>$\beta$</td>
<td>angle between fracture strike and $\sigma_1$</td>
<td>°</td>
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<tr>
<td>$\tau$</td>
<td>shear stress</td>
<td>MPa</td>
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<tr>
<td>c</td>
<td>cohesion</td>
<td>MPa</td>
<td></td>
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<tr>
<td>$\phi$</td>
<td>internal friction angle</td>
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<td>Darcy flow</td>
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<td>$k$, $k_{\text{eq}}$, $k_m$, $k_f$</td>
<td>Permeability (equivalent, matrix, fracture)</td>
<td>m$^2$ or mD</td>
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<tr>
<td>s</td>
<td>2D fracture spacing</td>
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<tr>
<td>A</td>
<td>fractured rock area</td>
<td>m$^2$</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>Total length of fractures</td>
<td>m</td>
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</tr>
<tr>
<td>$d_0$</td>
<td>dimension parallel to main fracture trend</td>
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<tr>
<td>$l_e$</td>
<td>element length</td>
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### Table 2 Summary of fracture geometry

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<th>ALIMA2</th>
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<th>ALIMA4</th>
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<tr>
<td># fset 1</td>
<td>19</td>
<td>20</td>
<td>9</td>
<td>22</td>
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<tr>
<td>spacing fset 1 [m]</td>
<td>6.8</td>
<td>604</td>
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<tr>
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<tr>
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<td>34</td>
<td>52</td>
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<tr>
<td>spacing fset 2 [m]</td>
<td>5.6</td>
<td>7.2</td>
<td>8.8</td>
<td>5.1</td>
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<tr>
<td>length fset 2 [m]</td>
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<td>9.0</td>
<td>8.8</td>
<td>5.1</td>
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<tr>
<td># total</td>
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<td></td>
<td>3.3</td>
<td>3.6</td>
<td>4.9</td>
<td>3.5</td>
</tr>
<tr>
<td>------------------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>spacing [m]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>average length [m]</td>
<td>9.5</td>
<td>11.6</td>
<td>10.1</td>
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<td># intersections</td>
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<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>E-W pathways</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
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**Figure 1** Overview of the parameters used to calculate the normal and hydraulic apertures: a) the initial aperture which is laterally consistent and a function of fracture roughness and strength; b) Following the application of in-situ stress, the fracture experiences limited shear displacement and partial closure.
Figure 2 Modeling fractures as seams in a Finite Element mesh: a) triangular mesh with 2 intersecting fracture seams (thick black line elements). Nodes along these line elements are duplicated to create seams; b) resulting deformed mesh after (exaggerated) opening of the two seams, showing normal opening ($E_n$), shear displacement ($\Delta u_s$) and local normal stress ($\sigma_n$), as well as how often each fracture node is duplicated to create the seams.
Figure 3 Set-up of the numerical mechanical models with a single fracture. Maximum horizontal compression $\sigma_1$ is applied in the $y$-direction, which exerts a Poisson’s stress $\sigma_3$ in the $x$-direction. The rock matrix is fully elastic with a Young’s Modulus of 50 GPa and a Poisson’s ratio of 0.3.
Figure 4 Relation between normal opening ($E_n$) and hydraulic aperture ($e$) for a fracture that is striking parallel to the direction of $\sigma_1$, compared to that of a fracture striking at 30°: a) normal aperture; b) hydraulic aperture; c) average normal and hydraulic aperture as a function of orientation.
Figure 5 Regional setting of the Alima anticline in the Gafsa basin in central Tunisia: a) Structural setting of the Gafsa basin, adapted from Bouaziz et al. (2002); b) The E-W striking Alima fold (backdrop from Bing maps, September 2014); c) Stratigraphic chart of the Late Cretaceous to present-day compiled from Bouaziz et al. (2002) and Zouaghi et al. (2009).
Figure 6 Original outcrop model with interpreted fractures, from which the 4 Alima sub-models are extracted: a) Digitized outcrop model of the steeply dipping pavement in the Alima anticline with the position of the four outcrop windows; b) Lower hemisphere stereoplot of the 345 fracture orientations (red) and bedding (blue); c) Stereoplot with back-rotated fracture orientations; d) The four fracture models.
Figure 7 Equivalent permeability in N-S (black bars) and E-W directions (gray bars) for each outcrop model as a function of maximum horizontal stress oriented in: a) N-S direction; b) E-W direction. The $k_f$ value indicated for each plot is the average fracture permeability calculated using the cubic law; c) fracture spacing distribution with the average for each sub-model; d) fracture length and blocksize distributions for each sub-model, with the average length indicated in each plot.
Figure 8 Fracture orientation per model, highlighting in black all fractures that strike at an angle of 10 to 30° with respect to the direction of maximum horizontal stress. The corresponding hydraulic aperture distribution is plotted under each model, with the percentage of hydraulically open vs. closed fracture segments.
Figure 9 Equivalent permeability in N-S direction (black curves) and E-W direction (gray curves) for each sub-model as a function of increasing stress: a) Maximum horizontal stress in N-S direction; b) Maximum horizontal stress in E-W direction.
Figure 10 Equivalent permeability in N-S direction (black curves) and E-W direction (gray curves) as a function of a changing Young’s modulus (a-c) and a changing Poisson’s ratio (plots d-f). Figures a, c-d and f are modeled with $\sigma_1$ oriented N-S, while (b) and (e) are modeled with $\sigma_1$ oriented E-W. Models corresponding to a-b and d-e are fully elastic, with their base case scenario properties listed in the legend, and c and f are modeled using an elastoplastic rock.
Figure 11 N-S (black curves) and E-W (grey curves) equivalent permeability for all four Alima models, calculated using an average aperture. For comparison with heterogeneous aperture, the thick black and gray curves show the N-S and E-W heterogeneous aperture averaged for all sub-models; a) N-S compression; b) E-W compression; c) elastoplastic rheology under N-S compression.
Figure 12 Permeability of the Alima sub-models compared to the full model: a) hydraulic aperture distribution in the Alima model, with the areas of the sub-models indicated for reference; b) E-W fluid pressure for Alima, white lines indicate pressure contours; c) N-S fluid pressure. Arrows indicate fluid velocity (small grey arrows indicate low velocity, large black arrows areas with high velocity); d-f) permeability comparison between the average permeability of the sub-models and the full model, calculated using the heterogeneous and constant averaged aperture distributions.