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Published in:
Journal of Petroleum Science and Engineering

Link to article, DOI:
10.1016/j.petrol.2019.106350

Publication date:
2019

Document Version
Peer reviewed version

Citation (APA):
Modeling of waterflood efficiency using outcrop-based fractured models

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Keywords: Discrete fracture modelling, improved oil recovery, recovery optimization

Abstract

We analyze the waterflood performance using an outcrop-based model, representative of North Sea fractured chalk reservoirs. To this end, we consider published data on the fracture geometry of Lägerdorf quarry in northern Germany and create a two-dimensional Discrete Fracture-Matrix (DFM) outcrop-based model, populated with the rock and fluid properties, typical for North Sea oil reservoirs. We conduct several DFM simulations to study the dependency of oil recovery factor with respect to water injection rate under uncertainty in fracture apertures and orientations, using both sea and low salinity water as injection fluids. Based on simulation results, we show that if there is a noticeable impact of fractures on the flow, the slower injection rates lead to higher recovery in terms of water pore volumes injected. The main factor influencing the recovery efficiency is whether there is a direct

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communication between the inflow and outflow boundaries via highly conductive fractures. However, if
the fractures’ apertures in the direct communication path are small enough, the capillary forces can
counterbalance the viscous displacement in fractures thus leading to better recovery. We demonstrate
that commonly used statistical measures of fractures orientation and connectivity cannot predict this
type of behavior.

1. Introduction

Declining production in mature North Sea reservoirs calls for improved methods of oil recovery which
must be both economically attractive and have low environmental impact. In this work we are
concerned with fractured chalk oil reservoirs, currently developed using waterflooding with sea water,
see e.g. (Agarwal, et al. 1999; Griffin, et al. 2007; Nijs and Damm 1993; Orman and Harrer 2017). Such
reservoirs are characterized by high permeability contrast between matrix and fractures, which often
leads to premature water breakthrough in producing wells and poor sweep efficiency. In this work, we
are concerned with the first of these challenges. More specifically, we wish to estimate how well can we
predict the recovery from a fractured reservoir once we know the statistical properties of fractures’
distribution such as fracture density, orientation, and connectivity.

In order to address this question, we rely on hydrodynamic modeling of outcrop-based models, where
the geometry of fracture network can be observed directly. Modelling of outcrop-based fracture
networks can provide insights on equivalent permeability of naturally fractured reservoirs (Bisdom, et al.
2016a and 2016b), estimate the effects of viscosity ratio on sweep efficiency and the shape of saturation
fronts (Belayneh, et al. 2006), and can assist in evaluating standard reservoir modeling approaches such
as corner-point gridding and dual-porosity models, see (Geiger and Matthäi 2014), (Gong and Rossen
2018). Besides, outcrop core flooding data can be used in selecting a relevant fluid model (Seyyedi, et al.
2018), and fractures’ statistics can be readily obtained by geometrical analysis of fracture traces, see
(Healy, et al. 2017), (Sanderson and Nixon 2015) and references therein. Thus, by comparing the
reference results from hydrodynamic simulations on outcrops with such statistical properties as fracture
density, orientation distribution, and connectivity one would be able to transfer the relationships
established on outcrops to the subsurface data.

The requirement for hydrodynamical modeling of fracture network to be considered as a reference
solution rules out many numerical methods (we refer to (Berre, et al. 2018) for a review of the methods
available in the literature). Since we wish to explicitly resolve all fracture traces mapped on an outcrop,
the industry-standard single and dual porosity/dual permeability models (Kazemi, et al. 1976), (Gilman
and Kazemi 1983) are not the suitable candidates. The matrix permeability for the North Sea chalk
reservoirs is typically low but not negligible, so one cannot employ the Discrete Fracture Network (DFN)
models, where the flow is assumed to occur in fractures only, see e.g. (Berrone, et al. 2018; Erhel, et al.
2012). Among the Discrete Fracture-Matrix (DFM) models we disregard those methods that involve
some degree of upscaling of small fractures (e.g. embedded DFM (Li and Lee 2006) and MsFVM
(Hajibeygi, et al. 2011)). Computational efficiency considerations require that we use a low-dimensional
representation of fractures. Besides, we wish to avoid any averaging across fracture-matrix cell
interfaces as in e.g. box method (Helmig 1997) or FE-FV methods (Geiger-Boschung, et al. 2007) which
can lead to excessive numerical smearing of propagating saturation fronts in highly conductive fractures
(Nick and Matthäi, Comparison of Three FE-FV Numerical Schemes for Single- and Two-Phase Flow
Simulation of Fractured Porous Media 2011). We are thus left with a family of cell-centered FV methods
Among these methods, we choose the numerical method of (Gläser, et al. 2017), which is implemented in DuMuX, an open-source simulator for transport processes in porous media (Flemisch, et al. 2011).

As an example of outcrop-based fracture network we consider the dataset, acquired from a chalk quarry in Lägerdorf, see (Koestler and Reksten 1995; Srivastava, et al. 2004). From a two-dimensional (2D) representation of Lägerdorf quarry wall, we create sector models which differ from each other by fracture density, anisotropy, and connectivity. The conforming triangular unstructured mesh is created by perturbing the fracture geometry slightly in order to improve the quality of resulting mesh elements similar to the approach of (Karimi-Fard and Durlofsky 2016; Mallison, et al. 2010). Rock properties needed for the model closure are taken from the experimental study (Graue and Bognø 1999).

We simulate sea and low salinity water flooding of the sector models and evaluate how the oil recovery is influenced by changes in injection rate under uncertainty in fracture apertures. For modeling of low-salinity waterflood we utilize an industry-standard approach (Jerauld, et al. 2006) where relative permeability and capillary pressure curves are interpolated between the low salinity and high salinity end points. The rock functions are obtained by a history match of core flooding experiments (Taheri, et al. 2019; Yousef, et al. 2011).

The paper is organized as follows. We start with a description of model construction in Section 2 and discuss meshing in Section 3. The rock and fluids model is presented in Section 4. The hydrodynamic model and the numerical implementation are described in Sections 5 and 6, respectively. Section 7 contains the simulation results of selected waterflooding scenarios. We end up with conclusions in Section 8.
2. Fracture network

For construction of an outcrop-based model we consider the fracture network, mapped on the Wall #1 of the Lägerdorf dataset (Koestler and Reksten 1995; Srivastava, et al. 2004). This network can be conveniently visualized and analyzed using FracPaQ, a MATLAB toolbox for the quantification of fracture patterns (Healy, et al. 2017). Following (Healy, et al. 2017), we estimate the fracture density at point \((x, y)\) as a number of fracture segments within a circle centered around \((x, y)\) per circle area, whereas the circle radius is chosen so that the area of interest is covered with non-intersecting circles. The fracture pattern and an estimate of fracture density for the Wall #1 of the Lägerdorf dataset is presented in Figure 1.
As discussed in (Koestler and Reksten 1995; Srivastava, et al. 2004), the fractures are closely linked to certain geological features which can be identified on the outcrop. In order to study the effects of fracture density, anisotropy, and connectivity on recovery during fluid flow simulation, we select three square subdomains (“sectors”) of equal size (10 x 10 m) which can be characterized as follows:

- **Anisotropic sector** with anisotropic distribution of fracture segments orientations;
- **Highly fractured sector** with a relatively isotropic distribution of fracture segments orientations;
- **Isolated sector** with relatively poor connectivity.

Zooms of fracture patterns for anisotropic, highly fractured, and isolated sectors are presented in Figure 2, the corresponding rose and connectivity diagrams are shown in Figure 3 and in Figure 4, respectively.

Rose diagram is a circular histogram plot which displays the frequency of fracture segments according to their respective angles. Following (Healy, et al. 2017; Sanderson and Nixon 2015), we quantify connectivity of a fracture network using a ternary plot with the 3 vertices of a triangle denoting I (“isolated nodes”), Y (“abutting nodes”) and X (“cross-cutting intersections”). For each sector, the relative number of I, Y, and X nodes of fracture traces constitute a triple which correspond to a point on the connectivity diagram. More connected networks will plot towards the lower Y-X tie of this diagram, whereas less connected networks will plot towards the I apex.

The default option in FracPaQ (Healy, et al. 2017) is to estimate the connectivity of fracture segments. Consequently, the connectivity diagram for topologically the same network depends on fractures’
discretization (i.e., number of fractures’ segments and nodes). In this work, we use connectivity of fracture traces, which is invariant with respect to fractures’ discretization.

Figure 2. Fracture patterns for anisotropic, highly fractured, and isolated sectors.

Figure 3. Rose diagrams for anisotropic, highly fractured, and isolated sectors.
Observe that both anisotropic and highly fractured sectors are characterized by high fracture density, whereas the isolated sector contains much less fractures, see Figure 1 (bottom) and Figure 2. The fracture pattern for the anisotropic sector clearly exhibits a preferential direction, whereas highly fractured and isolated sectors are characterized by much more isotropic fracture distribution, see Figure 3. All three sectors exhibit similar connectivity properties with the isolated sector being the less connected, followed by the anisotropic and highly fractured sectors.

3. Meshing

Natural fractures often occur in a form of swarms, closely aligned with such geological objects as faults or lithological layers and intersecting at acute angels (Nelson 2001). This behavior can also be observed at in fracture patterns for anisotropic, highly fractured, and isolated sectors in Figure 2. The resulting set of intersecting internal boundaries pose serious problems for robust creating of conforming unstructured meshes (Adler, et al. 2012). More specifically, the mesh elements located near fractures intersections are typically characterized by high aspect ratios which are known to be detrimental for the accuracy and convergence speed of numerical schemes (Zienkiewicz and Taylor 2000). Besides, the presence of very thin elongated mesh elements often leads to severe timestep restriction due to CFL condition (Matthäi, et al. 2010).
Fracture traces for the Lägerdorf dataset (Koestler and Reksten 1995) are represented as a set of consecutive linear segments of approximately 0.5 m length. The endpoints of the fracture segments constitute a set of Delaunay triangulation points. Additional triangulation points are inserted in order to maintain a requested mesh density. Finally, the conforming 2D meshes are created using the Bowyer–Watson triangulation algorithm implemented in Gmsh (Geuzaine and Remacle 2009).

The quality of a triangular element is assessed using the inverted scaled radius ratio indicator

\[ QI = \frac{2r}{R}, \]

where \( r \) is the inscribed and \( R \) is the circumscribed radius, respectively. The quality indicator \( QI \leq 1 \), whereas the equality sign corresponds to the best quality equilateral triangle (Pébay and Baker 2003), and smaller \( QI \) values correspond to worse quality triangles.
Figure 5 shows the distribution of $Q_I$ for a triangulation of the anisotropic sector. Observe that the worst elements are located near fractures intersections. Close inspection of fracture geometry at these locations suggests that joining of fracture traces which are located close to each other may improve the mesh quality. Joining of fracture traces is done by introducing new points at fracture intersections, and by merging the fracture nodes which lie within a prescribed tolerance from each other. For creating of perturbed fracture geometries below, we have used the threshold value of 0.05 m.
Figure 6. Comparison of rose diagrams for anisotropic, highly fractured, and isolated sectors. The original geometries are denoted with blue bars, the perturbed geometries – with red bars.

Figure 7. Comparison of connectivity diagrams for anisotropic, highly fractured, and isolated sectors. The original geometries are denoted with blue dots, the perturbed geometries – with red dots.

A comparison of rose and connectivity diagrams for the original and perturbed geometries is presented in Figure 6 and in Figure 7, respectively. Merging fracture nodes results in reducing the number of I nodes and transforming some of them into Y nodes thus leading to better connectivity, while not changing significantly the rose diagrams. The reader is referred to (Hardebol, et al. 2015) for a detailed analysis of fracture cross connections and abutments on the flow.

The effect of merging of fracture nodes on the $Q_I$ for the case of anisotropic sector is illustrated in Figure 8. Observe that merging fracture nodes lead to both decreased number of total mesh elements...
and to decreased number of low-quality elements. A quantitative evaluation of the effect of merged fracture nodes on triangulation for anisotropic, highly fractured and isolated sectors is presented in Table 1. For anisotropic and highly fractured sectors, which are both characterized by high fracture density, modifications in fracture geometries lead to about 5% decrease in the number of mesh elements and mesh nodes. However, the number of low-quality elements below the threshold of $Q_I = 0.5$ is reduced by more than 30%. The results for the isolated sector with low fracture density demonstrate the same behavior but with smaller decreases in the corresponding numbers of elements and nodes.

Figure 8. $Q_I$ distribution for triangulations of the original and perturbed fracture geometry for the anisotropic sector.
Table 1. Mesh statistics for original and perturbed fracture geometries.

<table>
<thead>
<tr>
<th>Sector</th>
<th># elements (orig/perturbed/Δ%)</th>
<th># nodes (orig/perturbed/Δ%)</th>
<th># elements with ( QI &lt; 0.5 ) (orig/perturbed/Δ%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anisotropic</td>
<td>5760 / 5503 / 4%</td>
<td>2722 / 2597 / 5%</td>
<td>143 / 98 / 31%</td>
</tr>
<tr>
<td>Highly fractured</td>
<td>6441 / 6111 / 5%</td>
<td>3031 / 2872 / 5%</td>
<td>161 / 103 / 36%</td>
</tr>
<tr>
<td>Isolated</td>
<td>4306 / 4214 / 2%</td>
<td>2068 / 2024 / 2%</td>
<td>50 / 44 / 12%</td>
</tr>
</tbody>
</table>

4. Rock and fluid properties

An important parameter for the evaluation of the flow and transport behavior of the fracture network is the variation in fracture aperture. In case of Lägerdorf, the fractures apertures range from 0 to 15 mm, which can be attributed to pressure release of the outcrop (Koestler and Reksten 1995). In this work, we consider fracture aperture as one of the unknown parameters and study the sensitivity of hydrodynamic simulations with respect to changes in apertures. We limit ourselves to the case when fracture aperture is uniform for all fracture segments and assume that fracture permeability can be calculated using the power law.

Since neither porosity nor permeability distribution is available for the Lägerdorf dataset (Koestler and Reksten 1995), we consider both matrix and fracture porosity and permeability distributions to be uniform. The specific values are taken from the core flooding study (Graue and Bognø 1999) on the outcrop material from Rørdal quarry near Aalborg in Denmark. Note that the porosity and permeability values are representative for North Sea chalk formations, see e.g. (Hjuler and Fabricius 2009).
As in (Graue and Bognø 1999), we consider the phase densities and viscosities to be constant for both oil and water phases. The values of corresponding properties are listed in Table 2.

Table 2. Rock and fluid properties used in hydrodynamical simulations.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix porosity</td>
<td>0.476</td>
</tr>
<tr>
<td>Matrix permeability</td>
<td>2.3 mD</td>
</tr>
<tr>
<td>Fracture aperture</td>
<td>0.01, 0.1, and 1 mm</td>
</tr>
<tr>
<td>Fracture porosity</td>
<td>0.476</td>
</tr>
<tr>
<td>Fracture permeability</td>
<td>8.4, 844, and 84437 D</td>
</tr>
<tr>
<td>Water density</td>
<td>1050 kg/m³</td>
</tr>
<tr>
<td>Oil density</td>
<td>730 kg/m³</td>
</tr>
<tr>
<td>Water viscosity</td>
<td>1.09 cP</td>
</tr>
<tr>
<td>Oil viscosity</td>
<td>0.92 cP</td>
</tr>
</tbody>
</table>

For the purposes of low-salinity waterflood modeling we assume that the properties of brine are identical to these of sea water, and that the water phase contains sea water (SW) and low-salinity water (LSW) components. Pure SW and LSW are characterized by their distinct set of relative permeabilities and a capillary pressure curve. In this work, we utilize a set of Brooks-Corey type relative permeabilities (Taheri, et al. 2019). We assume that the water-oil relative permeabilities for the mixture of SW and LSW can be represented as an interpolation between the corresponding relative permeability of pure SW and pure LSW. More specifically, for a given water saturation $S_w$, we compute the corresponding effective water saturations for pure SW and pure LSW according to
where the subscripts $S$ and $L$ refer to SW and LSW, $S^\kappa_{we}$ are the effective water saturations, and $S^\kappa_{wr}$ and $S^\kappa_{or}$ are residual water and oil saturations, respectively. Pure SW and LSW water-oil relative permeabilities are computed as

$$k^\kappa_{rw} = K^\kappa_w (S^\kappa_{we})^{n^\kappa_w}, \quad k^\kappa_{ro} = K^\kappa_o (1 - S^\kappa_{we})^{n^\kappa_o}. $$

Finally, the water-oil relative permeabilities when water is a mixture of SW and LSW are computed according to

$$k^\kappa_{rw} = x^S_w k^S_{rw} + (1 - x^S_w) k^L_{rw}, \quad k^\kappa_{ro} = x^S_w k^S_{ro} + (1 - x^S_w) k^L_{ro},$$

where $x^S_w$ is a molar fraction of SW in water phase. The values of water-oil relative permeability parameters are presented in Table 3.

<table>
<thead>
<tr>
<th>Water phase</th>
<th>$K_w$</th>
<th>$K_o$</th>
<th>$n_w$</th>
<th>$n_o$</th>
<th>$S_{wr}$</th>
<th>$S_{or}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure SW</td>
<td>0.394</td>
<td>0.202</td>
<td>2.053</td>
<td>2.016</td>
<td>0.103</td>
<td>0.355</td>
</tr>
<tr>
<td>Pure LSW</td>
<td>0.262</td>
<td>0.976</td>
<td>3.999</td>
<td>1.210</td>
<td>0.103</td>
<td>0.132</td>
</tr>
</tbody>
</table>

To the best of our knowledge, there are no experimental results for the capillary pressure curve for the LSW case. Therefore, for pure SW and pure LSW we use the capillary pressure curve (Graue and Bognø 1999), adjusted to the corresponding values of residual saturations. The capillary pressure curve for the case when water is a mixture of SW and LSW is computed by interpolation between the pure SW and pure LSW curves, analogously to the case of relative permeabilities curves defined above. The plots of oil-water relative permeabilities and the capillary pressure for the cases of water consisting of pure SW...
and water consisting of pure LSW are presented in Figure 9. Observe that low salinity water shifts the set of relative permeabilities towards more water-wet system.

![Relative permeability and Capillary pressure](image)

*Figure 9. Relative permeabilities and capillary pressure for the cases of water consisting of pure SW (blue lines) and water consisting of pure LSW (red lines).*

5. Hydrodynamic model

Our starting point is a compositional model without diffusion and source/sink terms (e.g. (Chen, Huan and Ma 2006), (Helmig 1997))

\[
\phi \frac{\partial \sum_{x} x_{\alpha} \xi_{\alpha} S_{\alpha}}{\partial t} + \nabla \cdot \left( \sum_{x} x_{\alpha} \xi_{\alpha} u_{\alpha} \right) = 0, \quad \alpha = w, o, \quad \kappa = S, L, O,
\]

where the subscript $\alpha = w, o$ denotes respectively water and oil phase, the superscript $\kappa = S, L, O$ refers to a SW, LSW, and oil component respectively, $\phi$ is porosity, $x_{\alpha}^{\kappa}$ is the molar fraction of component $\kappa$ in phase $\alpha$, $\xi_{\alpha}$ is the molar density of phase $\alpha$, $S_{\alpha}$ is the saturation of phase $\alpha$, $u_{\alpha}$ is the Darcy velocity of phase $\alpha$,

\[
u_{\alpha} = -\frac{k_{\alpha}}{\mu_{\alpha}} K (\nabla p_{\alpha} - \rho_{\alpha} g)
\]
with $\mu_\alpha$ being the viscosity of phase $\alpha$, $K = K I$ – the permeability tensor, $I$ – the unity tensor, $p_\alpha$ – the pressure of phase $\alpha$, $\rho_\alpha$ – the mass density of phase $\alpha$, and $g$ – the gravity acceleration. The model is augmented with the saturation constraint $S_w + S_o = 1$ and the relationship for capillary pressure, $p_c = p_o - p_w$. \(3\)

Note that the equation (1) corresponds to a single continuum model, i.e. the state variables refer to either matrix or fractures disjoint domains. These state variables are the macroscopic parameters, averaged over a representative elementary volume (REV); we assume that a range of volumes exist for an REV that satisfy meaningful size constraints, see (Bear 1972; and Bear and Bachmat 1990).

Assume that the distribution of each component $\kappa = S, L, O$ into the two phases $\alpha = w, o$ is subject to the condition of stable thermodynamic equilibrium (e.g. (Firoozabadi 1999)), \(F_w^K(p_w, T, x_{w^K}) = F_o^K(p_o, T, x_{o^K})\), \(4\)

where $F_{\kappa}^\alpha$ is the fugacity function of the component $\kappa$ in phase $\alpha$. Introducing the fugacity coefficients \(\varphi_{\kappa}^\alpha = \frac{F_{\kappa}^\alpha}{x_{\kappa}^\alpha p_{\alpha}}\), \(5\)

the equilibrium condition can be rewritten as a system of linear equations with respect to $x_{\kappa}^\alpha$, \(\varphi_w^S x_w^S p_w - \varphi_o^S x_o^S p_o = 0,\)

\(\varphi_w^L x_w^L p_w - \varphi_o^L x_o^L p_o = 0,\)

\(\varphi_w^O x_w^O p_w - \varphi_o^O x_o^O p_o = 0.\) \(6\)

We impose a condition that SW and LSW components should always stay in the water phase, and oil component should stay in the oil phase, i.e.

\[x_w^S = x_o^S = x_o^L = 0, \quad x_o^O = 1,\] \(7\)

which implies that $\varphi_w^S$, $\varphi_o^L$, and $\varphi_w^O$ can be set to an arbitrary non-zero number (e.g. to 1), and $\varphi_w^S = \varphi_o^L = \varphi_w^O = 0$. Substituting these values in the compositional model (1), we end up with the system
\[ \nabla \cdot \mathbf{u}_t = 0, \]
\[ \phi \frac{\partial S_w}{\partial t} + \nabla \cdot (f_w \mathbf{u}_t) = 0, \]
\[ \phi \frac{\partial x_w^l S_w}{\partial t} + \nabla \cdot (x_w^l f_w \mathbf{u}_t) = 0, \]  \quad (8)

where \( \mathbf{u}_t = \mathbf{u}_w + \mathbf{u}_o \) is the total velocity, \( f_w = \lambda_w / (\lambda_w + \lambda_o) \) is the fractional flow function, and \( \lambda_\alpha = k_{r\alpha} / \mu_\alpha \) is the mobility of phase \( \alpha = w, o \).

The system of equations (8) is an extension of a classical Buckley-Leverett model where the concentration of the advected tracer \( x_w^l \) influences the evaluation of the fractional flow since \( f_w = f_w(S_w, x_w^l) \). This model has been studied extensively in the context of various EOR scenarios, see (Pope 1980; Trangenstein 1988; Bedrikovetsky 1993).

### 6. Numerical implementation

The LSW model described above has been implemented into the DFM module (Gläser, et al. 2017) of the open-source numerical simulator DuMuX (Flemisch, et al. 2011), which is specialized on multiphase flow and transport in porous media\(^2\). We have used the 2D fully implicit cell-centered finite volume method of the DFM module (Gläser, et al. 2017), where the fractures are included as 1D facets of the 2D matrix mesh thus requiring conforming unstructured meshes (Alkämper, et al. 2016). The transmissibilities for the matrix-fracture interaction are obtained by integrating the governing conservation law (1) and Darcy's law (2) over a control volume with a fracture (Gläser, et al. 2017; Martin, et al. 2005). The resulting low-dimensional representation of fractures leads to better computational efficiency as compared to the equidimensional approach (where both fractures and the matrix are meshed with 2D elements) because in the former case there is no need to introduce extremely fine mesh elements.

\(^2\) The numerical implementation is publicly available at https://git.iws.uni-stuttgart.de/andrian/dumux.
across fractures. The method of (Gläser, et al. 2017) has been validated using a comparison with analytical solution and by comparing the results with the equidimensional approach (i.e., where both fractures and the matrix are meshed with 2D elements). Another variant of the cell-centered finite volume method with low-dimensional representation of fractures (Karimi-Fard, et al. 2006) has been validated using a comparison with an industry-standard simulator.

7. Simulated waterflood scenarios

We are interested in gaining insights into the following questions related to successful waterflooding of fractured chalk reservoirs in the North Sea:

1. If a preferential fracturing direction has been identified in the field, how should the injection and production wells be placed for optimal recovery?
2. What is the impact of low salinity waterflooding on oil recovery?
3. What is the optimal water injection rate?

We address these questions by considering the following simulation scenarios:

1. Waterflooding of the anisotropic sector model using sea water in the x- and y-directions, which are roughly parallel and normal to the preferential fracture orientation, respectively (cf. Figure 2 and Figure 3). This flow configuration allows for a direct estimate of the influence of anisotropy on the flow pattern, and has been used in several simulation studies on 2D outcrop models (Belayneh, et al. 2006; Geiger and Matthäi 2014; Hardebol, et al. 2015).
2. Sea water flooding of the highly fractured sector using different injection rates.
3. Sea water flooding of all sectors with different injection rates assuming different fracture apertures.
The simulations are set up by assigning the Neumann boundary conditions on the inflow edge, the Dirichlet boundary conditions on the outflow edge, and no-flow condition on the opposite edges of the corresponding sector model. The pressure at the outflow edge is kept equal to 1 bar. (The capillary pressure in the boundary conditions is set to zero so there is just one pressure which is equal to both water and oil pressures there.)

In order to study the sensitivity of hydrodynamic simulations with respect to changes in apertures, we use the aperture values of $10^{-5}$, $10^{-4}$, and $10^{-3}$ m, which cover the range of hydraulic apertures corresponding to realistic in-situ stress conditions (Bisdom, et al. 2016).

The gravity effects in simulations are neglected. Fluid and rock parameters used in simulations are specified in Table 2 and Table 3. Liquid volumes and rates in the simulations are calculated assuming a unity thickness of the domain.

The considered flow configuration can be viewed as a portion of repeating injection-producing well patterns (Craig 1993): the inflow edge of a sector model mimics an injection well, and the outflow edge – a production well. The choice of the sector size of 10 x 10 m is similar to grid block sizes used in reservoir simulation which makes it possible to apply the findings from DFM simulations to practical reservoir engineering problems. Besides, this sector size allows us to have enough fractures to be able to compute the statistical quantities such as fracture anisotropy and connectivity and to understand qualitatively their influence on recovery.
Anisotropic sector sea water flooding

In order to study the effect of fracture anisotropy on recovery factor, we simulate waterflooding with sea water (SW) in the x- and y-directions. For the x-direction waterflooding, the inflow is at the left boundary, for the y-direction – from the bottom boundary. The simulations are run using the water injection rates of \(1 \times 10^{-6}\), \(2 \times 10^{-6}\), and \(4 \times 10^{-6}\) m\(^3\)/sec.

Snapshots of oil saturations for waterflooding in the x- and y-directions using the injection rate of \(4 \times 10^{-6}\) m\(^3\)/sec and fractures apertures of \(10^{-3}\) m after 54 days of SW injection are presented in Figure 10, and the corresponding graphs of recovery vs. time and water pore volumes (PV) injected are presented in Figure 11. An analysis of the results suggests that waterflooding in y-direction is more efficient than the one in y-direction in terms of both time and pore volumes (PV) of water injected. This behaviour can be explained by arguing that in the case of waterflooding in y-direction water advances quickly in the
fracture network so that the contact area between injected water and matrix oil becomes significant and oil gets effectively swept by capillary imbibition effects.

Still, the noticeable difference in saturation distribution in Figure 10 for the cases of waterflood in x- and y-directions cannot be explained by the anisotropy effects alone. An inspection of the fracture pattern in Figure 12 reveals that a reason for this difference is related to the fact that the inflow and outflow boundaries are hydraulically better connected in case of the waterflood in x-direction as compared to the waterflood in y-direction. Indeed, the low permeability matrix barrier for the waterflood in x-direction is much smaller than the corresponding barrier for the waterflood in y-direction (cf. the areas, highlighted with red and black circles in Figure 12). Consequently, in case of the waterflood in y-direction the injected water quickly advances up to the low permeability matrix barrier, and higher recovery is achieved by combined action of viscous displacement and imbibition in the large part of the matrix.

We validate these claims by modifying the fracture network for the anisotropic sector in such a way that the fracture paths do connect the inflow and outflow boundaries for both waterfloods in x- and y-directions. We do so by prolongating the corresponding fracture traces in the red and black circles of Figure 12. The saturation distributions for this modified fracture network are presented in Figure 13. Comparing the results with that of the original fracture network in Figure 10, one notices that the saturation distributions for waterfloods in the x- and y-directions for the modified fracture network are much more similar compared to the original case in Figure 10.

A comparison of the rose and connectivity diagrams for the perturbed fracture network with merged nodes and the modified connected fracture network is presented in Figure 14.
Observe that the rose diagrams for both networks are indistinguishable from each other, and the difference in their connectivity is small (compare with the difference in connectivity for the original and perturbed networks in Figure 7).

However, despite very similar statistical properties of fractures’ distribution for the both networks, waterflood performance in x- and y-directions is remarkably different, see Figure 11. For the case of the waterflood in x-direction, the recovery efficiency graphs for the both networks are indistinguishable. However, waterflood in y-direction is significantly more efficient for the perturbed fracture network with merged nodes as compared to the modified connected fracture network. This can be explained by the fact that the low permeability barrier is much thinner in the case of the waterflood in x-direction as compared to the one for y-direction (cf. Figure 12).

Coming back to the case of the original fracture network, water injection in the direction of main fractures’ orientation might still look plausible in order to get higher efficiency in terms of volume of water injected, cf. Figure 11. However, these advantages disappear as long there is single fracture path, connecting the inflow and outflow boundaries. Current approaches which are used to statistically characterize subsurface fractures’ density, anisotropy, and connectivity (Healy, et al. 2017), (Sanderson and Nixon 2015) do not allow for an unambiguous identification of a fracture path connecting an injector with a producer. Thus, the risk of having a direct communication between injector and producer is higher than potential benefits in terms of saving on injection water volumes. Note that the above conclusions have been known in the reservoir engineering community since long time. As stated in (Craig 1993), fractures in the injector-producer direction results in early water breakthrough and in subsequent large volumes of produced water.
Figure 11. Recovery factors for waterflooding of the anisotropic sector in the x-direction (left) and y-direction (right) using the pressure drop $\Delta P = 9$ bar and fractures apertures of $10^{-3}$ m. Dotted lines correspond to a modified fracture network geometry (see text).

Figure 12. Fracture pattern for anisotropic sector (left) and its zoom (right). The red circle highlights the low permeability matrix barrier for the waterflood in x-direction, the black circle – the barrier for waterflooding in y-direction.
Figure 13. Snapshots of oil saturations for waterflooding of the anisotropic sector with modified fracture pattern (see text) in the x-direction (left) and y-direction (right) using the injection rate of $4 \cdot 10^{-6}$ m$^3$/sec and fractures apertures of $10^{-3}$ m after 54 days of SW injection.

Figure 14. Comparison of rose rose and connectivity diagrams for the perturbed fracture network with merged nodes (red) and the modified connected fracture network (green).

To summarize, characterizing a fracture network with just rose and connectivity diagrams does not tell much about hydraulic connectivity of the network. An uncertainty in the position of low permeability
thin matrix barrier can completely change the hydraulic connectivity of the network leading to drastic changes in timing of water breakthrough and overall recovery efficiency. It is thus important to properly quantify the definition of hydraulic connectivity, see (Sanderson and Nixon 2015) for a discussion.

Highly fractured sector low salinity water flooding

In order to assess the impact of low salinity waterflooding on oil recovery, we simulate waterflooding of the highly fractured sector with sea water and with low salinity water. Snapshots of oil saturations after 40 days of waterflooding of the highly fractured sector in the x-direction with SW and LSW using the injection rate of $2 \times 10^{-6} \text{ m}^3/\text{sec}$ and fractures apertures of $10^{-4} \text{ m}$ are presented in Figure 15. The corresponding graphs of recovery vs. time and water pore volumes (PV) injected as well as the water cut (WCT) vs. time are presented in Figure 16.

Since the relative permeabilities and the capillary pressure for LSW are characterized by much smaller irreducible oil saturation as compared to SW (see Table 3), it is not surprising that LSW yields significantly better recovery factor than SW, especially at later simulation times.
Figure 15. Snapshots of oil saturations after 40 days of waterflooding of the highly fractured sector in the x-direction with SW (left) and LSW (right) using the injection rate of $2 \cdot 10^{-6}$ m$^3$/sec and fractures apertures of $10^{-4}$ m.

It is interesting to note that the SW injection yields much earlier water breakthrough as compared to the LSW injection, see Figure 16 (right). In order to analyse this behaviour, we consider a one-dimensional (1D) model problem which retains certain aspects of the original waterflooding of the highly fractured sector. More specifically, we simulate waterflooding in a 10-meter long 1D domain with SW and LSW with the same saturation boundary conditions as in the waterflooding of the highly fractured sector. For the purposes of fair comparison between SW and LSW in both cases we assign the same value total...
velocity \( u_t = u_o + u_w = 10^{-8} \) m/s. The model is closed by providing rock and fluids properties from Table 2 and Table 3, respectively. Since the most oil recovery comes from the matrix, the porosity and permeability of the 1D domain are taken equal to their respective values for the matrix in Table 2. One important distinction between the 1D model setup and the original waterflooding of the highly fractured sector is that in we neglect capillary effects for the case of the 1D simulation. We argue that the SW and LSW capillary pressure curves in Figure 9 are similar for low values of water saturation. Therefore, the capillary effects for SW and LSW flooding are of the same order of magnitude at early times of the simulations, and the recovery efficiency at these times is largely governed by viscous displacement effects.

Under the above-mentioned assumptions, the solutions to the 1D version of the LSW model (LSW) can be obtained analytically (Pope 1980; Trangenstein 1988; Bedrikovetsky 1993; Jerauld, et al. 2006). The snapshots of water saturation at an intermediate time of 1736 days together with the corresponding fractional flow diagram for the 1D model problem is presented in Figure 17.

Figure 17. Snapshots of water saturation after of 1736 days of SW and LSW injection (left) and the corresponding fractional flow diagram (right) for the 1D model problem. Letters denote key states defining the solution (see text).
The saturation distribution for the SW flooding in Figure 17 (left) exhibits a typical shape of the classical Buckley-Leverett solution. The rarefaction wave AB ending with a shock BC connects the states A and D with residual oil and water saturations at the left and at the right, respectively. In the fractional flow diagram in Figure 17 (right), this solution is represented by a portion of water fractional flow curve AB followed by a chord BC.

The shape of the LSW solution differs from the SW solution in the following two aspects. Firstly, the rarefaction wave EF is almost a constant line in Figure 17 (left), which manifests itself in the fact that the points E and F are almost completely superimposed on top of each other. Such a shape is due to the form of relative permeability curves in Figure 9. Secondly, there is a new wave in the LSW solution as compared to the SW solution – the contact discontinuity FG. This discontinuity separates the SW initially contained in the domain (recall that we assume the brine properties are identical to sea water properties) from the injected LSW. As shown in (Pope 1980; Trangenstein 1988), the speed of this discontinuity can be calculated from the slope of the line, connecting point F with the origin of the coordinates system. The line GH in Figure 17 (left) and the overlapping points G and H in Figure 17 (right) represent a single state. Finally, this state H is connected to the state with the residual water saturation via the shock HI.

For the specific values of parameters in Table 3 which defined SW and LSW relative permeabilities, and for specific saturation boundary conditions used in the simulations the slope of the chord BC is higher than that of the chord HI so that the shock BC is faster than HI.
Faster moving oil front in case of SW flooding results in a faster water breakthrough as compared to the LSW flooding. After the discontinuity between SW from LSW arrives at the outflow boundary, LSW flooding gradually becomes more efficient since LSW’s residual oil saturation is lower than that of SW.

Impact of various injection rates on oil recovery

In order to assess the impact of different injection rates on oil recovery under uncertainty in fractures apertures, we simulate waterflooding of the anisotropic, highly fractured, and isolated sectors with sea water with different injection rates and various fractures apertures. The simulations are run using the water injection rates of $1 \cdot 10^{-6}$, $2 \cdot 10^{-6}$, and $4 \cdot 10^{-6}$ m$^3$/sec at the left boundary. The pressure at the right outflow boundary is kept equal to 1 bar. The simulations are run for constant fractures apertures of $10^{-5}$, $10^{-4}$ and $10^{-3}$ m.

The graphs of recovery factor (RF) vs. time and vs. the number of water pore volumes (PV) injected for the anisotropic sector for different injection rates are presented in Figure 18.
In all cases a higher injection rate results in faster recovery, see Figure 18 (top). Note that the time needed to achieve a certain level of recovery for a given rate is inversely proportional to the value of fractures’ aperture.

The dependency of the recovery factor as a function of water PVs injected is presented in Figure 18 (bottom). Observe that in case of the aperture of $10^{-5}$ m all injection rates yield the same recovery factor. This behavior can be explained by examining the flow patterns for the corresponding simulation runs. Figure 19 (left) shows a snapshot of oil saturation after 150 days of sea water flooding of the anisotropic sector using the injection rate of $1 \cdot 10^6$ m$^3$/sec and the fractures apertures of $10^{-5}$ m. For comparison, an analogous snapshot is presented in Figure 19 (right) for the case of the fractures apertures of $10^{-4}$ m. Observe a dramatic influence which fractures aperture exerts on the flow pattern.
When the aperture is too low ($10^{-5}$ m in this case), the fractures do not contribute substantially to the flow and the displacement is essentially occurring only in the matrix, see Figure 19 (left).

Figure 19. Snapshots of oil saturations after 150 days of sea water flooding of the anisotropic sector using the injection rate of $1 \cdot 10^{-6}$ m$^3$/sec. Left: using the fractures apertures of $10^{-5}$ m. Right: using the fractures apertures of $10^{-4}$ m.
As soon as there is a noticeable impact of fractures on the flow, the slower injection rates lead to higher recovery, see Figure 18 (bottom). For small fracture apertures this effect is less pronounced as compared to large apertures. The higher the aperture, the more injected water is flowing through the system leading to poorer recovery in terms of water PVs injected. If the apertures are small enough, injected water has more time to get imbibed in the matrix thus leading to higher sweep efficiency and, consequently, higher recovery.

The dependency of recovery on time and PVs injected for the highly fractured sector are presented in Figure 20. Note that in the highly fractured case there is a direct communication between in the inflow and outflow boundaries via fractures. However, the capillary forces balance the fast advancement of injected water in fractures, so the results for the highly fractured and anisotropic sectors with the
aperture of $10^{-5}$ m are virtually indistinguishable from each other, and the results for the aperture of $10^{-4}$ m are qualitatively similar. The situation is different for the case of the aperture of $10^{-3}$ m, where the recovery is less efficient in terms of time and water PVs injected.

![Recovery factors vs. time and PVs injected for the sea water flooding of isolated sector using different injection rates and fractures apertures. Blue lines correspond to the injection rate of 1·$10^{-6}$, green – to the rate of 2·$10^{-6}$, and red – to the rate of 4·$10^{-6}$ m$^3$/sec.](image)

The recovery factors vs. time and PVs injected for the sea water flooding of isolated sector using different injection rates for the fractures aperture of $10^{-4}$ and $10^{-3}$ m are shown in Figure 21 (we do not present the results for the aperture of $10^{-5}$ m since they are identical with the corresponding results for the anisotropic and highly fractured sectors in Figure 18 and Figure 20, respectively). This similarity is remarkable because the isolated and anisotropic sectors are quite different from each other in terms of fracture density, fracture orientation, and connectivity (cf. Figure 1, Figure 2, Figure 3, and Figure 4). As
we have seen above, as soon as there is no direct communication between the inflow and outflow boundaries (which is the case for both anisotropic and isolated sectors), the recovery rate is determined by the degree of hydraulic connectivity in the direction of the pressure gradient. As discussed above, the conventional definition of connectivity (Healy, et al. 2017), (Sanderson and Nixon 2015) and the references therein does not allow for proper quantification of hydraulic connectivity. Nick and Bisdom 2018 also showed that anisotropy of the permeability is impossible to extract from the fracture patterns itself.

It should be noted that the recovery dependency on injection rate has been a subject of multiple experimental, analytical and numerical studies since 1960s, see e.g. (Mattax and Kyte 1962; Kleppe and Morse 1974; Bourbiaux and Kalaydjians 1990; Pooladi-Darvish and Firoozabadi 2000; Karimaie and Torsæter 2007). However, identification of an optimal injection rate seems to be problematic due to complex oil-brine-rock interactions, the fracture geometry, and pore structure of the rock (Morrow and Mason 2001).

8. Conclusions

In this work, we describe the steps towards building a numerical DFM model of a fractured chalk outcrop and simulate sea and low salinity water flooding of selected subdomains of the outcrop, which are characterized by different fracture density, orientation, and connectivity. The two-phase three-components model for low salinity waterflooding has been implemented in an open source simulator (Flemisch, et al. 2011).

Our observations and results can be summarized as follows:
1. Automatic creation of an unstructured mesh, conforming to fractures, can lead to poor quality mesh elements near fracture intersections. We put forward a heuristic approach in which we perturb the geometric positions of fracture traces so that the connectivity of the fracture network does not change significantly, but the number of low-quality elements below certain threshold is reduced by more than 30%;

2. The main factor influencing the recovery efficiency is whether there is a direct communication between the inflow and outflow boundaries via highly conductive fractures. If this is the case, getting a reasonable recovery factor requires injecting of large volumes of water. However, if the fractures’ apertures in the direct communication path are small enough, the capillary forces can counterbalance the viscous displacement in fractures thus leading to better recovery;

3. If there is no direct communication between the inflow and outflow boundaries via highly conductive fractures, the sensitivity analysis of the recovery factor based on fracture density, anisotropy, and connectivity is dubious because of the statistical nature of these measures. In fact, the presence of a single thin low permeability barrier in a crucial part of the fracture network can completely change the flow pattern;

4. If the network is hydraulically connected in two perpendicular directions, then flooding in direction normal to primary fractures’ orientation is more efficient than the one along fractures’ orientation;

5. As soon as there is a noticeable impact of fractures on the flow, the slower injection rates lead to higher recovery. For small fracture apertures this effect is less pronounced as compared to large apertures;

6. Low salinity waterflooding yields higher ultimate recovery than sea water flooding provided the former is characterized by low residual oil than the latter;
7. Sea water flooding yields faster water breakthrough as compared to low salinity water flooding. This behavior can be explained by considering an analytical solution for the one-dimensional Buckley-Leverett problem with a tracer.

9. Acknowledgments

This work has been supported by the Advanced Waterflooding program at the Danish Hydrocarbon Research and Technology Centre. The authors are grateful to Dr. Andreas G. Koestler for providing the Lägerdorf quarry data.

10. References


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1. Perturbing of fracture geometry reduces the number of low-quality elements by 30%;
2. Flooding normal to fractures direction is more efficient than along the fractures;
3. Slower injection lead to higher recovery in terms of water pore volumes injected;
4. Sea water flooding yields faster water breakthrough than low salinity flooding.