DERIVING SINGLE-PHASE EFFECTIVE FLOW PROPERTIES IN COMPLEX TIDAL SANDSTONE RESERVOIRS

By

Rui Hou

A report submitted in partial fulfillment of the requirements for the MSc and/or the DIC.

September 2012
Declaration of own work

I declare that this thesis

**Deriving single-phase effective flow properties in complex tidal sandstone reservoirs**

is entirely my own work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

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Deriving single-phase effective flow properties in complex tidal sandstone reservoirs

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M. D. Jackson, G. Hampson, B. Y. G. Massart

Abstract

Heterolithic tidal sandstone reservoirs have a significant potential on hydrocarbon reserves and characterized by complex interbedded sedimentary features like flaser, wavy, and thin lenticular architectures. However, the reservoir properties are difficult to predict due to the presence of millimetric- to centimetric-scale intercalations of sandstone and mudstone.

The aim of this project is to derive the reservoir property (effective permeability) with generic 3m × 3m × 1m models of sandy tidal bar deposits, constructed using outcrop data from the Dir Abu Lifa Member in Egypt. The models are significantly larger than the typical core-plug data, but smaller than the typical reservoir grid blocks. A single injector-producer pair completed in the middle of buffer zone was employed to estimate the effective permeability with the mud drape coverage range from 0% to 100%. The effective permeability in all three directions is highly variable with mud drape coverage. Over the mud drape coverage range, permeability along dip direction ($K_{nx}$) reduces to 7% of its initial values, while permeability along strike direction ($K_{ny}$) decreases by 54%. Vertical permeability ($K_{nz}$) drops more dramatically with increased mud drape coverage than it in horizontal directions over the same range, due to laterally extensive mud drapes. The ratio $K_{nx}/K_{nh}$ is dominated by the values of $K_{nz}$, which gives a 99% reduction for the very muddy cases.

Experimental design was employed in this project to indicate the impacts of sedimentological heterogeneities on heterolithic tidal sandstones models. The heterogeneities such as mud patches major axis, percentage of foreset parts compared to toset parts (foreset ratio) and distribution of foreset parts compared to toset parts (progradation angle) are indicated to be the significant controls on the effective permeability in X and Y (horizontal) directions for heterolithic tidal sandstone models at the scale of 3m × 3m × 1m.

1. Introduction

Heterolithic tidal sandstone reservoirs are of increasing economic significance, in offshore Norway but also world-wide (i.e. Alaska, Canada, Venezuela and Russia) (Martinius et al., 2005). These reservoirs are made up of complex interbedded sedimentary features like small-scale flaser, wavy, and lenticular architectures (e.g. Martinius et al. 2001). These millimetric- to centimetric-scale intercalations of silt and mudstone vary highly both laterally and vertically and reflect the variations in the energy present in tide-dominated or influenced depositional environments (e.g. Reineck and Wunderlich, 1968; Dalrymple, 1992). The cyclicity of the tidal depositional processes is due to the succession of the flood and ebb current, alternated with periods of slack water. During these periods, small mud particles are deposited from suspension and generate mud drapes (Nio and Yang, 2001). These heterolithic intervals lead to complex three-dimensional (3-D) architecture (Jackson et al., 1999) so that the reservoir properties, such as porosity, permeability, capillary pressure and mobile oil saturation, are difficult to predict (e.g. Norris and Lewis, 1991; Martinius et al., 2001). Additionally, the mud drapes can act as barriers to fluid flow (Ringrose et al., 2005). Experience in mid-Norway has indicated that better reservoir description and modelling can improve the field performance, leading to significant economic benefits (e.g. Martinius et al., 2005). Consequently, reasonable modelling methods should be employed to capture the small-scale, significant elements in sandstone-mudstone system (e.g. Jones et al., 1995). For heterolithic tidal sandstone reservoirs, the small-scale intercalations of sandstone and mudstone are difficult to model them for flow simulations using conventional modelling methods (Jackson et al., 2003).

Permeability variations in hydrocarbon reservoir models are typically represented on a block-centred grid using values obtained from core-plugs, wireline-log data or well test data. This approach is difficult to apply to tidal sandstone models due to the important variation of properties with length scale. Core data (mm-cm scale) are sampled without the variability of facies and well test data (100m-km scale) are averaged over various different facies. None of these measurements are directly applicable for typical simulation grid-blocks (10’s – 100’s of metres). Consequently, upscaling permeability is difficult to yield representative effective values which represent the permeability structure (Renard and de Marsily, 1997). Attempts have been made to resolve the problems by incorporating two-dimensional (2-D) outcrop data (e.g. Oost and Baas, 1994), using three-
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dimensional (3-D) models constructed from large rock specimens with different sizes (Jackson et al., 2003; Jackson et al., 2005). These previous studies have shown a better understanding of the impact on tidal sandstone heterogeneities and quantified the effect of properties such as the sandstone connectivity on the effective permeability and displacement efficiency in tidal sandstone reservoirs (Jackson et al., 2003; Jackson et al., 2005; Brandsaeter et al., 2005). According to the results from previous studies at various scales, both individual and averaged effective permeability values vary as a function of sample volume in which permeability data obtained from core-plugs will not be representative at the scale of a reservoir model grid-block regardless of the number of measurements taken (Jackson et al., 2003). In addition, the reservoir properties (sandstone connectivity, effective permeability and displacement efficiency) of heterolithic tidal facies from 2-D data are commonly underestimated or even overlooked when applied to 3-D simulation models (Jackson et al., 2005).

The aim of this project is to use high resolution, small-scale models of tide-dominated intervals constructed in an ongoing project, and numerical simulations of single flow through these models, to determine effective permeability values for application in reservoir model grid blocks. The scale of the 3-D simulation models is significantly larger than typical core-plug data and the volume of the models performed are potentially closer to the representative elementary volume (REV) as introduced by Bear (1972). The REV corresponds to a specific sample volume at which oscillations due to heterogeneities become homogenized and lead to a statistical representative value (Norris and Lewis, 1991; Jackson et al., 2003). For multi-scale heterogeneities reservoirs, the REV represents the minimum volume sampled which should provide the data for upscaling. In this project, high resolution 3-D models (3m × 3m × 1m) of sandy tidal deposits were constructed for flow simulations (Massart et al., 2011). The spatial distribution of mud drapes in the sandy tidal bar cross-bed sets and variability of heterogeneities are captured in these models. The 3-D models are constructed using the Dir Abu Lifa Member, Egypt as an analogue to represent the tide-influenced heterolithic sandstone layers of Jurassic Are, Tilje and Ile formations in the Linnorm Field in mid-Norway.

The objectives of this project are two-fold. The first is to quantify the impact of the proportion of mud drapes along the sandy tidal bar cross-bed sets on the effective permeability in x, y (horizontal), and z (vertical) directions. The second is to use experimental design to identify the key sedimentological heterogeneities (variations of six geological input parameters) that control effective permeability in all three directions. This project is of importance to provide economic benefits for the Linnorm development by presenting a better understanding of fluid flow behaviours in tidal sandstone reservoirs.

2. Models of Heterolithic Tidal Sandstone

2.1. Geological setting

The Linnorm field, previously known as the Onyx field, was discovered in 2005 and comprises an approximated 23.7 billion cubic meter of gas and 0.6 million cubic meter of condensate. It is located in the Halten Terrace, offshore mid-Norway where several other fields have been discovered (Figure 1A), and is expected to start production under PL 255 by Norske Shell.

Figure 1: Geology of Linnorm field A) Map presenting hydrocarbon fields in the Halten Terrace. The red dot points out the Linnorm field. B) Are, Tilje and Ile formations are shown in the general lithostratigraphy of the mid-Norwegian continental shelf. C) Geoseismic structural cross-section (A-A’ in Figure 1A) through the southern Halten Terrace indicating the typical structural closures of reservoirs (Martinius et al. 2005).
The hydrocarbons in this field were proven in Are, Tilje and Ile formations of Early to Middle Jurassic age (Figure 1B), trapped within fault blocks, with the Upper Jurassic and Base Cretaceous unconformities forming the main closures (Figure 1C). All three formations were deposited in tidal or fluvio-deltaic and estuarine environments (Martinius et al. 2005). It is inadequate to characterize the Linnorm field with limited data available (only core and well data). Therefore, the Dir Abu Lifa member outcrop analogue of the Late Eocene deposits of the Fayoum Depression in the Western Desert, Egypt, was used in constructing the model performed in this project, in order to develop a better comprehension of the depositional environment, the distribution of facies and the reservoir properties.

2.2. Model construction

The 3-D models used in this project are small-scale, high resolution sections of sandy tidal bar deposits constructed using surface-based modelling methods adapted for flow simulation (White and Barton, 1999; Jackson & Muggeridge, 2000; Jackson et al., 2005; Sech et al., 2009; Jackson et al., 2009). The rock volume modelled was subdivided into smaller-scale volumes, which were defined by top and base boundary surfaces. These smaller volumes are called ‘elemental volumes’ in which heterogeneity surfaces have the same geometry and length-scale (Massart et al., 2011). High-resolution photographs and measurements of the outcrop parameters were collected to generate the dataset used constructing the models (Figure 2). 3-D template surfaces for each heterolithic sedimentary feature were defined by a 3-D parametric function, extracted from outcrop analogue or subsurface core data (i.e. toeset thickness and dip angle). The mudstone was distributed as elliptical patches in 3-D along the heterogeneity surfaces using the same methodology used in previous study (Jackson & Muggeridge, 2000). A mudstone frequency function was used to characterize the position and dimensions of the mudstone patches (Massart et al., 2011). The mudstone patches were added along the 3-D template surfaces until reaching the required proportion of mudstone, which linked to the mudstone distribution function extracted from outcrop analogue observation. The model was constructed from elemental volumes and sandy tidal bars were created by stacking multiple dune cross-bed sets.

To ensure the models were suitable for 3-D reconstruction and gridding input, the following rules are applied (Jackson et al., 2005):

1. All surfaces and zones are continuous across the model.
2. No matter where a sandstone or mudstone pinches out, it is still defined but designated zero thickness (the upper and lower bounding surfaces coincide).
3. Surfaces must not cross.
4. All surfaces must be vertically monotonic (no overhanging surfaces).
2.3. Gridding for simulation

In order to preserve the complex 3-D sedimentary architecture of the sandstone and mudstone layers, corner point grids suitable for flow simulation were constructed from the model of sandy tidal bar deposits, in which the geological heterogeneity variations were captured by variations in grid architecture. Complex reservoir geological architectures and reservoir description, such as reservoir boundaries, faults, heterogeneities, horizontal wells and flow patterns, can be represented by the corner point (distorted) grids (Waldsley, 1980; Goldthorpe and Chow, 1985). Rectangular Cartesian grids are widely used, but are unsuitable for characterizing high resolution models due to their limitations of presenting faults and heterogeneities inaccurately (Ding and Lemonier, 1995). In contrast with conventional Cartesian grid, the use of corner point gridding effectively avoids numerous, small-sized grid cells that flow simulation become computationally expensive and improves the accuracy. The methodology employed by White and Barton (1999), developed and applied for 3-D heterolithic tidal structures by Jackson et al. (2003) and Jackson et al. (2005) conducted to build the corner point grids in this project.

The grid constructed has vertical pillars with a constant spacing (5 cm) in i and j dimensions. In the k dimension, the irregular grid was built due to the numerous dipping surfaces and pinch-outs, which could lead to numerical errors for flow simulations. The geometry of upper and lower layers is dominated by the geometry of the surfaces, and the distribution of the intermediate layers is proportionate. Wherever sandstone or mudstone layers pinch out, the boundary surfaces coincide and intermediate cells are assigned to zero thickness. These cells are set to be inactive, in order to minimize the number of cells required to represent the models for simulations, and bridged using non-neighbour connections, so they are not treated as barriers to flow (Jackson and others, 1999). The model dimensions are 3m x 3m x 1m for all flow simulations and the thickness of mud drape surface is controlled by the constant thickness of grid blocks which is 0.35 cm.

Although corner point grids are more efficient than rectangular Cartesian grids for flow simulation, grid artefacts can be introduced in the solution to flow equations across non-orthogonal faces. For the case of high resolution non-orthogonal grids, large errors can be introduced using corner point grids for flow simulations (Wu and Parashkevov, 2005). Previous studies (e.g. Ding and Lemonier, 1995; Peaceman, 1996) have represented the limitations, especially the impact of non-orthogonality on simulation results accuracy, however, errors introduced by non-orthogonality cannot be predicted accurately whatever methods employed (Bagheri and Settari, 2003).

2.3.1. Gridding for sensitivity analysis

The models constructed to estimate the impact of sedimentological heterogeneities on the effective permeability were varied with six different parameters (Appendix B). Each model was simulated with different mud drape coverage (0%, 25% and 100% in foreset parts and 1.25%, 25% and 100% in toeset parts) along X and Y directions, respectively. The sandy and muddy models with these heterogeneities (Table 1) were constructed first from the outcrop observations (Figure 4), and then seven models with different input parameters were constructed for sensitivity analysis. A two-level fractional-factorial design (e.g. White et al., 2001; Choi et al., 2011) was employed for each case in which each heterogeneity can take low and high cases that are chosen to reflect the range of sensitivity analysis.

<table>
<thead>
<tr>
<th>Table 1 Ranges of six geological input parameters</th>
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<tbody>
<tr>
<td>Signification</td>
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<tr>
<td>Toeset dip angle</td>
</tr>
<tr>
<td>Foreset thickness (mean value)</td>
</tr>
<tr>
<td>Foreset ratio</td>
</tr>
<tr>
<td>Progradation angle</td>
</tr>
<tr>
<td>Mud patches size</td>
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<tr>
<td>Narrowness of cross-bed sets</td>
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</table>

The mean value of foreset thickness was calculated for all models using log-normal distribution with same standard deviation in which the maximum value was 15 cm and the minimum value was 0.5 cm. Progradation angle was used for estimating the effect of distribution of Foreset parts compared to Toeset parts on effective permeability. The narrowness of cross-bed sets can be divided into two subclasses by primary descriptions of shape: two-dimensional (2D) and three-dimensional (3D) dunes. 2D dunes have fairly regular spacing, heights and lengths, with straight or slightly sinuous crestlines. However, 3D dunes have irregular spacing, heights and lengths, with highly sinuous or discontinuous crestlines (Ashley, 1990). Percentage of Foreset parts compared to Toeset parts was presented as foreset ratio, which was the ratio of foreset parts volume to the model volume and calculated via three dip oriented cross-sections (approximation) for 3D dunes cases and on one dip oriented cross-section (correct) for 2D dunes cases. The mud drape thickness was calculated using uniform distribution.
3. Flow Simulation Methodology

The simulations were designed to estimate effective permeability in the principal axes of the permeability tensor (X corresponding to the dip direction, Y corresponding to the strike direction and Z corresponding to vertical direction) and imitate the setup of conventional core experiments to measure permeability. Schlumberger’s ECLIPSE© 100 software was used to perform the simulations to estimate the effective permeability and ReliaSoft’s DOE++ software tool was employed to perform the experimental design for sensitivity analysis.

A set of models were built with percentage of probabilistic mud drape coverage along each foreset surface ranging from 0 to 100% and along each toesset surface ranging from 0 to 100% at 0% mud drape coverage in foreset surfaces. The lower extreme represents the case in which there are no mud drapes presenting at all and corresponds to the models fully filled with sandstone in which the simulation is affected by the grid architecture. For all flow simulations, the injector was controlled by constant flow rate and the producer was controlled by bottom hole pressure. Numerical simulations for reservoir studies commonly consider many cases, scenarios and realizations (White and Royer, 2003), which leads to an expensive estimate of the effect of all possible parameters on reservoir behaviour. However, experimental design (Box et al., 1978; Jones et al., 1995) can estimate the effect of input factors on reservoir behaviour with a relatively small number of reservoir-simulation models (White et al., 2001). The methodology used for estimating the effect of heterogeneities on the effective permeability in the Linnorm field was similar to the one used by (Choi et al., 2011).

3.1. Model Structure

To calculate effective permeability in X (dip) and Y (strike) directions, buffer zones were deliberately created at the faces in the end of each direction with very high permeability and a single injector-producer well pair, which is completed in the middle of the buffer zone at each face, was used in order to ensure the negligible spread in values of water phase potential across the inlet and outlet buffer zones (Figure 5). The value of the buffer zones permeability assigned to $54 \times 10^{-6}$ mD is obtained by treating them as open fractures of three centimetre width based on combination of viscous force equations and Darcy’s law (Talabi, 2011).

Figure 5: Illustration of water phase potential at the inlet layer A) The histogram of water phase potentials without buffer zone. Water phase potentials are distributed along the inlet face heterogeneities. B) The histogram of water phase potentials with buffer zone. The values of water phase potential are uniform.
Simulation in Z direction employed a similar approach with horizontal flow models. Two extra layers with uniform thickness (2 cm) were constructed at the top and bottom of the models. These two extra layers were used as the buffer zones for vertical flow models, making the dimensions of models slightly larger.

3.2. Rock and fluid properties

Two sets of permeability were used in the models for each facies: sandstone and mudstone. All sandstone cells were 77 mD, which provided the same uniform isotropic permeability values. Permeability in mudstone cells were assigned to 0.0001 mD, instead of zero permeability, in the grid blocks along the mud drape surface in order to speed up the simulations and tests (Appendix C) were performed to show the same results as zero permeability. The mud drapes in all the models are modelled with the same thickness, 3.5 mm. All cells are assigned to the same uniform porosity value, 0.31. To calculate the effective permeability, the models were saturated with incompressible water with the viscosity 0.31 cP and formation volume factor of 1.0 cc/std cc.

3.3. Simulation strategy

The strategy employed in this project is similar to the one that used by Warren and Price (1961). The models were water-saturated in order to ensure no oil production and simulated by injecting water into grid blocks in the inlet buffer zone and producing from grid blocks in the outlet buffer zone until reaching the steady state when injecting rate and producing rate balance and constant field pressure were achieved (Figure 6). The tests (Appendix C) indicated that the effective permeability calculated is independent of injecting rate and switching the injector and the producer. Therefore, the injecting water flow rate performed for simulations was assigned to 100 cm$^3$/hr for horizontal flow model and 300 cm$^3$/hr for vertical flow model in order to have the same water injecting rate per cross section area for both models.

![Figure 6: Illustration of steady state for flow simulations. A) Steady state was reached at 18 seconds for horizontal flow simulation models. B) After 18 seconds, the vertical flow simulation models reached the steady state.](image)

The tracer-saturated flow was simulated between a pair of opposing faces in y direction and assumed no flow across the other faces. The injected tracer had an initial concentration of 1 over one boundary and tracer diffusion remained zero. Tracer simulations provide a reasonable observation for flow path and are similar to the study to characterize displacement efficiency in heterolithic tidal sandstone (Jackson et al., 2005).

3.4. Numerical Permeability calculations

Flow simulation results from each model were used to calculate the effective permeability ($K_{eff}$) for each of the x, y (horizontal), and z (vertical) directions. Darcy’s law was employed for each calculation with the same assumption and boundary conditions such as, incompressible fluid, single phase and one-directional flow. The equation simplifies to

$$K_{eff} = \frac{Q_{wm} \mu_w L_m}{\Delta \theta_{wm} A_m}$$

The water phase potential ($\Delta \theta_{wm}$) is the pressure of water in each buffer zone, corrected to remove the effect of hydrostatic pressure. The cross section area ($A_m$) is depended on the direction of fluid flow and the length ($L_m$) is over which the pressure values drop. The viscosity of water ($\mu_w$) is constant for all flow simulations. It is applicable to normalize the effective permeability ($K_{eff}$) for the each case with the homogenous case permeability ($K_{eff,s}$) for that specific direction so that the effect of increased mud drapes coverage in foreset parts and toset parts was quantified with being independent of the dimensional permeability values ($K_{eff}$). The effective permeability was expressed in term of a dimensionless permeability.
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\( K_{nm} \) for the given direction. The subscript \( m \) in equations refers to the direction of flow.

\[
K_{nm} = \frac{K_{eff,m}}{K_{eff,m}}
\]  

(2)

3.5. Quality checks

Homogenous orthogonal grids (60 x 60 x 50) with the same dimensions as highly non-orthogonal model were constructed to verify the methodology used in this project. Tracer and effective permeability results obtained from this grid were compared with the high resolution model. The estimated effective permeability obtained from this grid was approximately equal to input permeability. The errors introduced from corner point grids are described in section 4.

4. Results

4.1. Correlation with Net-to-Gross

The values of net-to-gross (NTG), correlated with the corresponding proportion of mud drape coverage, are illustrated in Figure 7. As expected, net-to-gross values reduce with increased proportion of mud drape coverage. For all simulations models with variations of mud drape coverage in foreset parts (Figure 7A), the values of NTG drop down up to 40% of their initial values over the range. For all simulations models with variations of mud drape coverage in toeset parts (Figure 7B), the values of NTG drop down up to 56% of their initial values over the range.

Figure 7: Illustrations of sandstone proportion varying with fractional mud drape coverage. A) Net-to-gross for all simulation models with variations of mud drape coverage in foreset parts. B) Net-to-gross for all simulation models with variations of mud drape coverage in toeset parts. The name of simulation models are described in Appendix B.

The sandstone connectivity within variations of mud drape coverage in both foreset parts and toeset parts for heterolithic tidal sandstones is highly variable, depending on the reservoir features (small-scale flasers, wavy, and thin lenticular architectures) and consistent with the outcrop observations. For the same formation architecture, the values of NTG obtained may be different (Jackson et al., 2005).
4.2. Grid quality checks

The errors associated with the non-orthogonal corner point grid blocks cannot be neglected in this project (Table 2). The permeability values calculated from homogeneous corner point models constructed to quantify the effect of mud drape coverage on effective permeability are on average 14% different from the input isotropic permeability. The error is highly dependent on flow direction: the effective permeability in horizontal directions (X and Y) is under-estimated, whereas the vertical effective permeability is over-estimated for non-orthogonal models. The permeability in X direction leads to a serious error, compared to it in Y direction, in which the ‘element volume’ surfaces are mainly dipping in X direction. Tests on the corner point grid blocks indicate the error in each direction remains the same regardless of the number of wells, the location of wells and injecting flow rate (Appendix C).

Table 2. Measurements of error introduced by flow simulations in all three directions

<table>
<thead>
<tr>
<th></th>
<th>Value (mD)</th>
<th>Error (%)</th>
</tr>
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<tbody>
<tr>
<td>Input Isotropic Permeability</td>
<td>77</td>
<td>-</td>
</tr>
<tr>
<td>Permeability from homogeneous orthogonal model (X, Y, and Z)</td>
<td>77.6</td>
<td>-</td>
</tr>
<tr>
<td>X-Permeability (Kx) from homogeneous corner point model</td>
<td>58.1</td>
<td>25</td>
</tr>
<tr>
<td>Y-Permeability (Ky) from homogeneous corner point model</td>
<td>76.3</td>
<td>1</td>
</tr>
<tr>
<td>Z-Permeability (Kz) from homogeneous corner point model</td>
<td>89.1</td>
<td>16</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>14</td>
</tr>
</tbody>
</table>

Figure 8: Volume injection slices through models by injected tracer-saturated water. Tracer Concentration is indicated by colour scale. A), B) and C) show results from a Cartesian grid which is fully homogenous orthogonal. D), E) and F) show the same results from a corner point non-orthogonal grid which is as well fully homogenous and the grid artefact is pointed out.
The results of injecting tracer-saturated water are observed visually along the strike direction (Figure 8) to show the injected fluid path through the models. The differences between Cartesian grids and corner point grids are indicated with same dimensions and conditions. Grid artefact is indicated where cell faces are non-orthogonal to the flow as well as the pinch-outs occur (Figure 8E and 8F). The observations for effects of heterogeneity surfaces are affected by the presence of grid artefact in the simulations. Additionally, this tracer injected method as a means of observing the flow path can be used to estimate the displacement efficiency (Jackson et al., 2005), which was not considered in this project. Further work to quantify the sweep efficiency is warranted.

4.3. Impact of fractional mud drape coverage on permeability

The normalized permeability variations as a function of net-to-gross in X, Y, and Z direction as well as \( \frac{K_v}{K_h} \) ratio with NTG are shown in Figure 9A. The same normalized results are represented on semi-log scale (figure 9B) in order to obtain log-linear relationships. The errors in X, Y, and Z direction as well as \( \frac{K_v}{K_h} \) ratio (described in section 4.2) are also presented in the Figure 9A, respectively. All permeability values reduce with increased proportion of mud drape coverage. Figure 9A shows the normalized horizontal permeability in X direction \( (K_{nx}) \) and in Y direction varies from 0.07 to 1 and from 0.53 to 1, respectively, whiles the normalized vertical permeability \( (K_{ny}) \) and \( \frac{K_v}{K_h} \) ratio varies from 0.005 to 1 and 0.016 to 1, respectively.

![Figure 9: Simulation results. A) presents the normalized effective permeability in X, Y, and Z directions and \( \frac{K_v}{K_h} \) ratio. Corresponding error bars are shown as well for model 1, which has 60 x 60 x 1624 grid blocks. B) indicates the same results on semi-log scale and regression lines.](image-url)
4.4. Identification of sedimentological heterogeneities control on flow

The results used to identify effect of six heterogeneous parameters on normalized effective permeability for X and Y (horizontal) directions are presented in Figure 10 and Figure 11. Each distribution represents the results of percentage change in effective permeability in X \( (K_{nx}) \) and Y \( (K_{ny}) \) directions for six different heterogeneities, which are analogous to observations.

![Graph A](image-a.png)

**Figure 10:** Percentage change of normalized effective permeability in X and Y directions. Each simulation model was performed with 6 different mud drape coverage cases: 100%, 25% and 0% mud drape coverage in foreset parts with constant mud drape in toeset, and 100%, 25% and 1.25% mud drape coverage in toeset parts without any mud in foreset parts. A) shows the results in X direction and B) shows the results in Y direction. Label T means mud drape coverage in toeset parts and F means mud drape coverage in foreset parts.

The percentage changes in \( K_{nx} \) (Figure 10A) for these heterogeneities vary with mud drape coverage. Results of mud patches major axis lead to the biggest change (6.6%) in \( K_{nx} \), while the values of 2D/3D dunes show the smallest change (2.0%) in \( K_{nx} \). Figure 10B indicates the variation in percentage change in \( K_{ny} \) as a function of mud drape coverage for these heterogeneities. The biggest change (5.6%) is presented by the results of foreset ratio, while the values of foreset thickness show the smallest change (1.1%). The same results are shown in Tomado charts (Figure 11) used to check the sensitivity of six different heterogeneities on effective permeability in X \( (K_{nx}) \) and Y \( (K_{ny}) \) directions.
5. Discussions

5.1. Accuracy

The direction dependent errors (Table 2) are commonly encountered with corner point grid blocks. Once the grid block face is not orthogonal to the flow direction, an error will be introduced for most commercial simulators, which are highly applicable for orthogonal grid blocks. Many methods have been proposed to diminish this error, however, for the highly non-orthogonal grid blocks, only a consideration of all components of the potential gradient at block faces will reduce the errors (Aziz, 1993). All the potential gradient components may be considered using the multipoint flux approximation (MPFA), which provides a correct discretization of the flow equations for non-orthogonal grids as well as for general orientation of the principal directions of the permeability tensor (Aavatsmark et al., 2007). The concept of MPFA is that the simulation grid is split into interaction regions and flux calculations for the interface are performed within any two cells. The parameters in the calculations are split as well between the interaction regions (Aavatsmark et al., 1996). The multipoint flux approximation is achieved from the weighted sum of the potential values in grid cells of interaction region (Aavatsmark et al., 1998). A whole class of MPFA methods is used for 3-D quadrilateral grids and the O-method and the L-method are commonly applicable for numerical solutions with insignificant differences for both methods. The errors estimated from non-orthogonal grids can be reduced by these methods.

5.2. Impact of fractional mud drape coverage on permeability

In Figure 9, the normalized effective permeability values in Y ($K_{ny}$) direction are approximately the same with them in X ($K_{nx}$) direction, yet start to diverge at a NTG of about 0.94. Over the range of NTG from 0.95 to 0.74 (mud drape coverage in foreset parts models), $K_{nx}$ drops much faster than $K_{ny}$ and eventually become about 8 times smaller than $K_{ny}$ at the maximum mud drape coverage (minimum NTG) making the interbedded system effectively anisotropic. The drop of $K_{nx}$ is large in which an up to 95% reduction occurs over the range, while $K_{ny}$ encounters a relatively small drop with reduction to 53% of its initial value. The normalized effective permeability in vertical ($K_{nz}$) direction drops much more dramatically than horizontal permeability over the range from 0.9 to 1 and eventually becomes ‘constant’ as NTG decreases to about 0.9, due to laterally extensive mud drapes. About 99% reduction for $K_{nz}$ is indicated over the range of NTG from 0.744 to 1. The development of
heterolithic tidal sandstone reservoirs as used here may be highly affected by this heterogeneity-induced anisotropy. The normalized horizontal permeability \( K_{nh} \) was achieved by taking the geometric average of \( K_{nx} \) and \( K_{ny} \) for each mud drape coverage case and the ratio of the vertical permeability \( K_{nz} \) to \( K_{nh} \) is presented as a function of mud drape coverage (NTG) as well. The \( K_v/K_h \) ratio is dominated by \( K_{nz} \) because of the more significantly impact of mud drape coverage on \( K_{nz} \) than \( K_{nh} \) and follows the same trend as \( K_{nz} \) with a 99% reduction over the range.

The normalized permeability in all three directions as well as \( K_v/K_h \) ratio is fit to the equivalent exponential equations (Figure 9B) for the model used in this project. The goodness of fit (R²) is within 0.99 for all equations.

\[
k_{nx} = 10^{-12.416(NTG)^2+26.264(NTG)−13.826} \hspace{1cm} (5)
\]

\[
k_{ny} = 10^{1.5936(NTG)^2−1.7218(NTG)+0.1309} \hspace{1cm} (6)
\]

\[
k_{nv} = k_{nz} = 10^{10383.23(NTG)^3−16496.1(NTG)^4+283467(NTG)^3−243052(NTG)^2+103983(NTG)−17760} \hspace{1cm} (7)
\]

\[
k_v/K_h = 10^{46697(NTG)^3−157568(NTG)^4+270105(NTG)^3−231053(NTG)^2+98627(NTG)−16808} \hspace{1cm} (8)
\]

These results here are similar with ones (Figure 12) estimated by Ringrose et al. (2005). They proposed a method to estimate the vertical permeability in heterolithic tidal deltaic sandstones using a 0.1m \( \times \) 0.5m \( \times \) 0.5m SBED model, which was used to simulate small-scale bedding structures. A set of bedding planes was migrated by using vectors to mimic the depositional process. The observations of the anisotropic development in the horizontal plane with small sandstone volumes and the approximately log-linear relationship between effective permeability and NTG at high sandstone proportions were indicated in their study as well. The similarity in variations of effective permeability in all three directions with NTG cannot indicate whether the volume of the model (9,000,000 cm^3) in this project or Ringrose et al. (2005) (25,000 cm^3) reaches the representative elementary volume (REV) for flow simulation. Further study is warranted to estimate the REV for heterolithic tidal sandstones models.

The direction as well as sandstone fraction dependent variations have the potential implications for the tidal sandstone field development, especially for sandy tidal bar deposits dominated reservoirs such as the Linnorm field. This project shows the sedimentary architecture of these heterogeneities leads to more barriers to flow along dip direction (X) yielding an effectively isotropic system. The achieved correlation for effective permeability with NTG proposes a method to calculate effective permeability by estimating the value of NTG from tidal sandstone reservoirs. The method using NTG to estimate the flow properties for the interbedded system must be cautioned, because NTG is not a fixed reservoir property, but also a function of scale where it is measured (Ringrose, 2008). This implies that the indications from NTG in this project are required the modifications to obtain a proper understanding of the variation of NTG with scale for the model constructed. The effective permeability function of NTG estimated in this project is not representative for all scale of simulation models in which no results show the volume of the model here reaches the REV. Numerical models with variety of sample volume should be constructed to derive the REV.

5.3. Identification of sedimentological heterogeneities control on flow

Figure 10 shows that the results of percentage change in both \( K_{nx} \) and \( K_{ny} \) are fluctuated over the range of mud drape coverage. In figure 10A, results of mud drape major axis have positive impacts on \( K_{nx} \) in that could over-estimate the calculated effective permeability, whereas results of progradation angle show negative effects on \( K_{nz} \) in that could under-estimate the calculated effective permeability. Generally, results of foreset ratio have positive impacts on \( K_{nx} \) over the range, however, show negative effects on \( K_{nz} \) in sandy (less than 25% mud drape coverage in toeset parts) or muddy (greater than 30% mud drape coverage in
foreset parts) cases. In figure 10B, the impacts of foreset ratio, mud patches size and 2D/3D dunes are positive on $K_{ny}$. However, results of toset dip angle and progradation angle show negative effects on $K_{ny}$.

The tornado charts (Figure 11) indicate the key controls of sedimentological heterogeneities in heterolithic sandstone reservoirs of the Linnorm field in tidal-influenced environment on the effective permeability in $X$ and $Y$ (horizontal) directions over the range of mud drape coverage: 1) Mud patches size. 2) Percentage of Foreset parts compared to Toeset parts (foreset ratio). 3) Distribution of Foreset parts compared to Toeset parts (progradation angle) and the average percentage changes on horizontal permeability are approximate 3% over the range. These three key sedimentological heterogeneities are on the significant control of mud drape coverage in foreset parts, which produce more obstruction to flow along dip and strike directions compared to toset parts. Caution must be exercised in constructing simulation models for heterolithic tidal sandstone reservoirs with these heterogeneities, which will provide significant uncertainties for flow simulation.

6. CONCLUSIONS

- The effective permeability in all three directions is highly variable with mud drape coverage. With reduced NTG, $K_{nx}$ reduces to 7% of its initial values, while $K_{ny}$ decreases by 54%. $K_{nz}$ drops more dramatically with increased mud drape coverage than it in horizontal directions over the same range, due to laterally extensive mud drapes. The ratio $K_{nx}/K_{ny}$ is dominated by the values of $K_{nz}$, which gives a 99% reduction for the very muddy cases.
- The key controls of sedimentological heterogeneities on the horizontal effective permeability are mud patches size, foreset ratio and progradation angle over the range of mud drape coverage at the scale of 3m x 3m x 1m model in this project.
- Flow simulations for heterolithic tidal sandstone reservoirs are mainly controlled by the mud drape coverage in foreset parts, as producing barriers to flow.

7. RECOMMENDATIONS

- This project only considered the single-phase flow, so the effects of multi-phases flow on the relative effective permeability as well as reservoir recovery are warranted by extending the methodology employed here.
- The errors generated from the corner point grids in this project may be reduced by using MPFA method as discussed in section 4.1. MPFA method would provide more reliable and applicable results for heterolithic tidal sandstone reservoir characterizations. The commercial simulator Schlumbergers ECLPSE 300 has been installed with the O-method and the U-method and an ongoing project will be employed to verify the application of this software tool to characterize reservoir properties.
- There are various heterogeneities observed from the outcrop and the simulations performed here only considered the sandy tidal bars. The interactions of heterogeneities are highly recommended to be investigated to the effect on the flow behaviour.
- It is not clear that the sample volume used in this project reached the representative elementary volume (REV). Therefore, the research to investigate REV is warranted.

Nomenclature

**Notation**

- NTG: Net to gross
- MPFA: Multipoint flux approximation
- REV: Representative elementary volume
- $d$: foreset thickness
- $e$: toset thickness
- $Q$: flowrate
- $K$: permeability
- $\Delta L$: the length over which the pressure drop
- $A$: cross section area perpendicular to flow direction
- $R^2$: goodness of fit
- $k_v/k_h$: ratio of vertical to horizontal permeability
- $i$: grid block number in the x direction
- $j$: grid block number in the y direction
- $k$: grid block number in the z direction

**Greek letters**

- $\mu$: viscosity
- $\Delta \theta$: potential
- $\alpha$: mean dip angle
Subscripts

\(w\) water phase
\(\text{eff}\) indicates an effective value
\(m\) indicates the direction of flow
\(\text{eff}_s\) indicates an effective value for a homogenous model
\(n\) indicates normalized value
\(x\) indicates value obtained in \(x\) direction
\(y\) indicates value obtained in \(y\) direction
\(z\) indicates value obtained in \(z\) direction
\(v\) indicates value estimated in the vertical direction
\(h\) indicates value estimated in the horizontal direction
References


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Renard Ph. and de Marsily G., (1997) Calculating equivalent permeability a review Advances in water resources 20 253-278


White, C. D., and Barton, M. D., (1999) Comparison of the recovery behavior of contrasting reservoir analogues in the Ferron Sandstone using outcrop studies and numerical simulation *Report of investigations* n°249, Bureau of Economic Geology, the University of Texas at Austin


APPENDIX A – CRITICAL LITERATURE REVIEW

<table>
<thead>
<tr>
<th>Paper No.</th>
<th>Year</th>
<th>Title</th>
<th>Authors</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAPG BULLETIN No.4</td>
<td>2005</td>
<td>Three-dimensional reservoir characterization and flow simulation of heterolithic tidal sandstones</td>
<td>Matthew D. Jackson, Shuji Yoshida, Ann H. Muggeridge, and Howard D. Johnson</td>
<td>Use 3-D reconstructed models to characterize the reservoir properties (sandstone connectivity, effective permeability, and displacement efficiency) of heterolithic tidal sandstones and evaluate their impact on fluid flow.</td>
</tr>
<tr>
<td>Mathematical Geology Vol.35 No. 5</td>
<td>2003</td>
<td>Upscaling Permeability Measurements Within Complex Heterolithic Tidal Sandstones</td>
<td>Matthew D. Jackson, Ann H. Muggeridge, Shuji Yoshida, and Howard D. Johnson</td>
<td>Investigate the effect of sample volume on the effective single-phase permeability of heterolithic tidal sandstones, and find that both individual and averaged effective permeability values vary as a function of sample volume.</td>
</tr>
<tr>
<td>Petroleum Geoscience Vol. 11</td>
<td>2005</td>
<td>Vertical permeability estimation in heterolithic tidal deltaic sandstones</td>
<td>Philip Ringrose, Kjetil Nordahl, and Renjun Wen</td>
<td>Effective vertical permeability is mainly a function of mudstone fraction with different characteristics above and below the percolation threshold.</td>
</tr>
<tr>
<td>SPE 29933</td>
<td>1995</td>
<td>Use of Corner Point Geometry in Reservoir Simulation</td>
<td>Y. Ding and P. Lemonnier</td>
<td>Characterize corner point geometry and its application range from different control volume type approximations.</td>
</tr>
<tr>
<td>Mathematical Geosciences 40: 753–771</td>
<td>2008</td>
<td>Identifying the Representative Elementary Volume for Permeability in Heterolithic Deposits Using Numerical Rock Models</td>
<td>Kjetil Nordahl Philip S. Ringrose</td>
<td>Propose a measurement, using numerical experiments on heterogeneous system, to determine the Representative Elementary Volume (REV) for permeability at the lithofacies scale.</td>
</tr>
</tbody>
</table>
AAPG Bulletin (2005) 89

Three-dimensional reservoir characterization and flow simulation of heterolithic tidal sandstones

Authors:
Jackson, M. D., Muggeridge, A. H., Yoshida, S., and Johnson, H. D

Contribution:
Use 3-D reconstructed models to characterized the reservoir properties (sandstone connectivity, effective permeability, and displacement efficiency) of heterolithic tidal sandstones and evaluate their impact on fluid flow

Objective of the paper:
1. To present a methodology for reconstructing the complex, three-dimensional (3-D) architecture of the sandstone-mudstone intercalations within heterolithic tidal intervals directly from outcrop data.
2. To calculate the connectivity of sands, effective permeability, and displacement efficiency of each rock specimen model.
3. To compare sand body connectivity in 2-D and 3-D to determine the applicability of 2D models in estimate reservoir properties in heterolithic tidal sandstones.
4. To explain why intervals of low resistivity and low contrast pay in the tidal environment usual produce large hydrocarbon volumes despite low net to gross.

Methodology used:
This paper used two rock specimens: one is high net-to-gross heterolithic interval and the other is low net-to-gross heterolithic interval. Sandstone connectivity was calculated from 2-D and 3-D models for each specimen. Effective permeability was calculated using the sealed side pressure solver method of Warren and Price (1961). Displacement efficiency was characterized using streamline simulation techniques (Batycky et al. 1997).

Conclusions reached:
1. The continuity and connectivity of sandstone and mudstone layers are the key control on effective permeability and displacement efficiency in heterolithic tidal intervals.
2. If sandstone layers are connected, the facies interval is likely to be productive.
3. Sandstone connectivity is the key control on the transition between productive and nonproductive rock.
4. Measurements of sandstone connectivity in 2-D underestimate the true 3-D value.
5. Core-plug measurements of permeability are unlikely to yield representative values at the scale of a reservoir model because the connectivity and continuity of sandstone and mudstone layers variation with length scale.
6. The productivity of low to moderate net-to-gross intervals in heterolithic tidal sandstones is underestimated or even overlooked.

Comments:
Provide a good understanding of how to characterize the reservoir properties in heterolithic tidal sandstones.
Mathematical Geology (2003), Vol. 35

Upscaling permeability measurements within complex heterolithic tidal sandstones

Authors:
Jackson, M. D., Muggeridge, A. H., Yoshida, S., and Johnson, H. D

Contribution:
Investigate the effect of sample volume on the effective single-phase permeability of heterolithic tidal sandstones, and find that both individual and averaged effective permeability values vary as a function of sample volume.

Objective of the paper:
To investigate the effect of sample volume on the effective single-phase permeability in heterolithic tidal reservoir and determine whether the core-plug measurements of permeability are likely to be representative at the grid-block scale.

Methodology used:
Simulating single-phase incompressible flow in 3-dimensional samples reconstructed directly from large rock specimens, using serial sectioning techniques together with surface mapping software (Jackson and others, 1999).

Conclusions reached:
Both individual and averaged, core-plug permeability measurements will not properly represent complex heterolithic tidal facies in reservoir-scale models. The most suitable averaging scheme for horizontal permeability investigated to be harmonic mean, while for vertical permeability appeared to be arithmetic mean. Also, the REV averaging method is valid only if distinct, separable length scales present.

Comments:
The suitable schemes for averaging permeability investigated will not clearly produce representative values at the grid-block scale, because the sample volume used here are still significantly smaller than typical geological reservoir model.

Vertical Permeability Estimation of Heterolithic Tidal Deltaic Sandstones

Authors:
Ringrose, P. S., Nordhal, K., and Wen, R

Contribution:
Effective vertical permeability is mainly a function of mudstone fraction with different characteristics above and below the percolation threshold.

Methodology used:
The method proposed here represents the geometrical arrangement of sedimentary of bedding by migrating a set of bedding surfaces in a manner that mimics observed geometries. The sealed-side method was used to evaluate effective permeability.

Conclusions reached:
A general function can be fitted to stochastic simulations of effective permeability of a large number of sedimentary bedding models provides a very promising predictive tool for reservoir characterization especially valuable for vertical permeability.

Comments:
Provide a good understanding of estimate effective vertical permeability.
Use of Corner Point Geometry in Reservoir Simulation

Authors:
Y. Ding and P. Lemonnier

Contribution:
Characterize corner point geometry and its application range from different control volume type approximations.

Methodology used:
Compare several different numerical methods suitable for corner point geometry modeling (distorted grids).

Conclusions reached:
The flow correction scheme is likely to be more accurate than the pressure correction scheme, especially for multi-phase flow simulations. Some approaches were proposed to resolve problems of corner point geometry in 3-D reservoir simulator in practice.

Comments:
Provide a good understanding of corner point geometry modeling method and its problems in practice.
SPE 22692 (1991)

The Geological modelling of Effective Permeability in Complex Heterolithic Facies

Authors:
R. J. Norris and J.J.M. Lewis

Contribution:
Provide a new methodology for quantifying single-phase fluid flow behaviour in heterolithic facies by defining effective permeability at REAs

Methodology used:
A new approach described in detail provided to define REVs and REA graph was constructed to define effective permeability

Conclusions reached:
Conventional geostatistical approaches are inappropriate for defining spatial permeability variation. Effective permeability varies as a function of sand connectivity.

Comments:
Provide a good understanding of REV methodology and its impact on effective permeability.
Identifying the Representative Elementary Volume for Permeability in Heterolithic Deposits Using Numerical Rock Models

Authors: Kjetil Nordahl and Philip S. Ringrose

Contribution: Propose a measurement, using numerical experiments on heterogeneous system, to determine the Representative Elementary Volume (REV) for permeability at the lithofacies scale for single phase flow.

Methodology used: Flow simulation was performed using realistic 3D lithofacies models constructed by a numerical modelling tool SBED™.

Conclusions reached: The variability for each realisation is consistent with the REV theory, in that large permeability variations at small scale are reduced as the sample volume increases. The estimated REV varies as a function of lithofacies type and is also different for vertical and horizontal permeability. According to the results, the traditional averages of core plugs in upscaling will generally underestimate vertical permeability and overestimate horizontal permeability.

Comments: The effects of fluid phase interactions need to be taken into account for multi-phase flow.

Reservoir challenges of heterolithic tidal sandstone reservoirs in the Halten Terrace, mid-Norway

Authors:
A. W. Martinius, P. S. Ringrose, C. Brostrøm, C. Elfenbein, A. Næss and J. E. Ringås

Contribution:
Present a summary of challenges of heterolithic tidal sandstone reservoirs in the Halten Terrace, mid-Norway for three different types of reservoirs: shallow, deep and very deep.

Objective of the paper:
This paper demonstrated the state of integrated reservoir description and uncertainty modelling of geological parameters and solutions may be applicable to other similar heterolithic tidal environment.

Methodology used:
Illustrate the challenges of three different types of reservoir and their corresponding solutions to guide further field development in this region.

Conclusions reached:
The work on structural uncertainty modelling in heterolithic reservoirs includes the analysis of horizon geometry, fault geometry and fault seal parameters. A range of approaches for improved characterization of heterolithic tidal sandstone reservoirs have been developed out to tackle those challenges, e.g. a new methodology and software tool (HAVANA) developed for fault analysis study.

Comments:
Provide a good understanding of challenges of heterolithic tidal sandstone reservoirs and their solutions.
Canadian Society of Petroleum Geologist, Memoir 16 (1991)

Diagnostic attributes of clastic tidal deposits: a review

Authors:
Nio, S. and Yang, C

Contribution:
Introduce a comprehensive summary of geologic setting and rock types of tidal small-scale heterogeneities models.

Methodology used:
Geological surveys

Conclusions reached:
The presence of different orders of cyclicities and their correlation with different orders of tidal cyclicities are only criteria for recognizing tidal dominance in shallow marine clastic deposits.

Comments:
Provide a comprehensive description of heterolithic tidal heterogeneity

Predicting the impact of sedimentological heterogeneity on gas-oil and water-oil displacements fluvio-deltaic Pereriv Suite Reservoir, Azeri-Chirag-Gunashli Oilfield

Authors:
Choi, K., Jackson, M. D., Hampson, J. G., Jones, A. D. W., and Reynolds, A. D.

Contribution:
Present the experimental design method for identifying the significant impact of sedimentological heterogeneities on reservoir simulations.

Methodology used:
A two-level fractional-factorial design was used for experimental design

Conclusions reached:
The sedimentological heterogeneities will affect oil recovery only if sandbod connectivity and flow path tortuosity in mobility- or gravity-stable displacements or vertical segregation in mobility-unstable displacement are controlled by them.

Comments:
Provide a comprehensive description of experimental design for reservoir simulations.


APPENDIX B – Models construction for experimental design

Table B1 shows the dimensions of each simulation model and its corresponding variations in heterogeneities. 0 means the value from the low case and 1 means the value from the high case. Figure B1 shows the cross section for each simulation model.

![Figure B1 cross section of each simulation model](image-url)
Table B Simulations models for experimental design

<table>
<thead>
<tr>
<th>model</th>
<th>Number of cells</th>
<th>Toeset dip angle</th>
<th>Foreset thickness (mean value)</th>
<th>Foreset ratio</th>
<th>Progradation angle</th>
<th>Mud patches major axis</th>
<th>2D/3D dunes</th>
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### APPENDIX C – Effective permeability calculation on homogenous model

**Table C. Simulation input data and calculation results for homogenous model in x direction**

<table>
<thead>
<tr>
<th>Number of wells</th>
<th>Input Flow rate (total)</th>
<th>Length of flow path</th>
<th>Cross-sectional Area</th>
<th>Input Viscosity</th>
<th>Potential difference</th>
<th>Input Permeability</th>
<th>Effective permeability</th>
<th>Error compared to input permeability</th>
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<td>mD</td>
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<td>0.008978</td>
<td>77</td>
<td>57.54847</td>
<td>25%</td>
</tr>
<tr>
<td>1</td>
<td>3000</td>
<td>300</td>
<td>30000</td>
<td>0.31</td>
<td>0.044480</td>
<td>77</td>
<td>58.07854</td>
<td>25%</td>
</tr>
<tr>
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<td>3000</td>
<td>300</td>
<td>30000</td>
<td>0.31</td>
<td>0.044491</td>
<td>77</td>
<td>58.06418</td>
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</tr>
<tr>
<td>30</td>
<td>3000</td>
<td>300</td>
<td>30000</td>
<td>0.31</td>
<td>0.044501</td>
<td>77</td>
<td>58.05113</td>
<td>25%</td>
</tr>
</tbody>
</table>

**Inverse the positions of injectors and producers**

| 30               | 3000                    | 300                 | 30000               | 0.31           | 0.044496            | 77                 | 58.05765              | 25%                                  |

**Effect of input mudstone permeability values on simulation**

<table>
<thead>
<tr>
<th>Input mudstone permeability</th>
<th>Input Flow rate (total)</th>
<th>Length of flow path</th>
<th>Cross-sectional Area</th>
<th>Input Viscosity</th>
<th>Potential difference</th>
<th>Input Permeability</th>
<th>Effective permeability</th>
<th>Error compared to input permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>mD</td>
<td>cm³/hr</td>
<td>cm</td>
<td>cm²</td>
<td></td>
<td>atm</td>
<td>mD</td>
<td>mD</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>100</td>
<td>300</td>
<td>30000</td>
<td>0.31</td>
<td>0.001478</td>
<td>77</td>
<td>57.45671</td>
<td>25%</td>
</tr>
<tr>
<td>0.0001</td>
<td>100</td>
<td>300</td>
<td>30000</td>
<td>0.31</td>
<td>0.001498</td>
<td>77</td>
<td>57.49941</td>
<td>25%</td>
</tr>
</tbody>
</table>