3. Numerical simulations

In this section we compare a 3D and a VE model to simulate CO_2 migration in the Utsira Sand aquifer, which is a major saline aquifer in the North Sea, into which CO_2 separated from gas extracted from the overlying Sleipner field has been injected at a rate of approximately 1 Mt/year since 1996 [20, 21]. The Utsira Sand extends for more than 400 km in north-south direction and between 50 and 100 km in the east-west axis, covering an area of approximately $2.6 \cdot 10^4$ km^2 [21]. The geometry of the aquifer is irregular and complex. While the top surface is undulatory and varies smoothly in the depth range of 550-1500 m, the bottom is more complex with multiple domes of up to 100 m high and 1–2 km wide. The aquifer thickness ranges from 300 m near the CO_2 injection site to 200 m farther north (200 km from the injection site). The reservoir caprock is several hundred meters thick and comprises several units of low permeability materials (shales, glacio-marine clay, and glacial till) [21]. Geophysical logs indicate that the main reservoir has a proportion of clean sand between 0.7 and 1.0 with a small shale fraction composed by multiple thin ($\sim$1 m) layers that constitute vertical flow barriers. The interpretation of seismic surveys, performed periodically since the CO_2 injection started, indicate that such shale layers have a major impact on the CO_2 migration because an significant part of the rising CO_2 has been trapped underneath these low permeability layers forming multiple quasi-independent plumes [20, 22]. Analyses of core samples of the Utsira formation sand have estimated porosity values between 35 % and 40 % and permeability in the range 1000-3000 mD [21].

Model setup

Numerical simulations were performed using a preliminary numerical model setup by the Statoil R&D group [23] to study how CO_2 migrates once it reaches the upper-most sand layer. Thus, the model includes the section of the aquifer immediately underneath the caprock and above the upper most shale layer as shown in Figure 2. The domain covers an area of approximately 60 km^2 and has an average thickness of 25 m. The numerical grid includes 120,000 hexahedral cells with constant 50 m spacing in the horizontal directions and average 5 m spacing in the vertical direction. Estimated permeability values for the top sand layer and caprock are shown in Figure 2.In the model the horizontal components of the permeability tensor are assumed isotropic and vary between 1789 and 2018 mD, while the vertical component is assigned as equal to 1/10th of the horizontal value. Because of the relative low permeability of the caprock and the underlying shale relative to the main sand aquifer, they are modeled as impermeable boundaries. The porosity of the aquifer sand was set according to a linear correlation with the permeability and has a mean value equal to 0.36. The amount of CO_2 that reaches the top of the aquifer was simulated as a point source with specified injection rates that increase from 0 to $5 \cdot 10^6$ m^3/year during the first 32 years and then set to zero until the end of the simulation (132 years). The total amount of CO_2 injected is $5.3 \cdot 10^6$ m^3 at reservoir conditions.

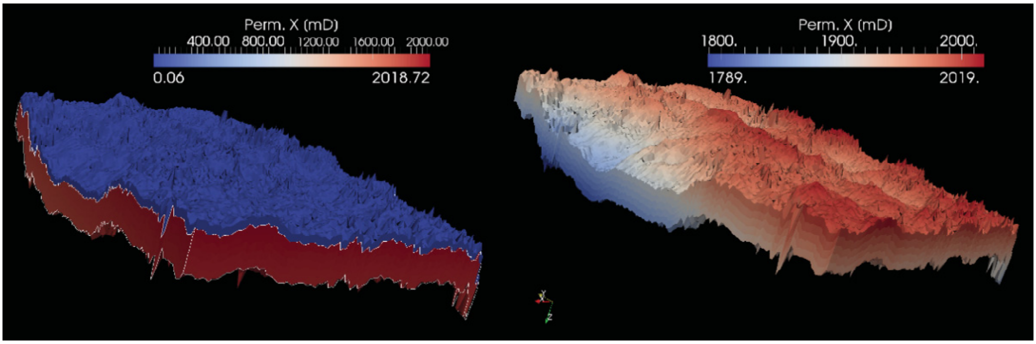

Figure 2: Estimated horizontal permeability for the upper 25 m of the Utsira Sand aquifer and lower 10 m of the caprock. There are large contrasts in permeability between the main aquifer and the caprock (left), but only moderated differences within the aquifer itself (right).

Simulation results

We present results of 3D and VE simulations carried out with the commercial ECLIPSE Reservoir simulator [24] and the VE module of the open-source Matlab Reservoir Simulation Toolbox (MRST) developed at SINTEF ICT and available at http://www.sintef.no/Projectweb/MRST/. In the following discussion we will refer to the different numerical solutions as ECLIPSE-3D, ECLIPSE-VE and MRST-VE. To test the sensitive of the 3D solution with respect to the vertical discretization, we run the ECLIPSE-3D simulations using the original grid (coarse) and a refined grid (fine) that has five times more horizontal layers than the original one. Capillary forces were not included in the simulations presented below, however, as explained above, they can be easily included in the VE formulation without introducing additional computational complexity [9, 25]. The 3D simulations