Simulation of proposed Gassum Fm. CO_2 storage sites onshore and nearshore Denmark

*Update 3**

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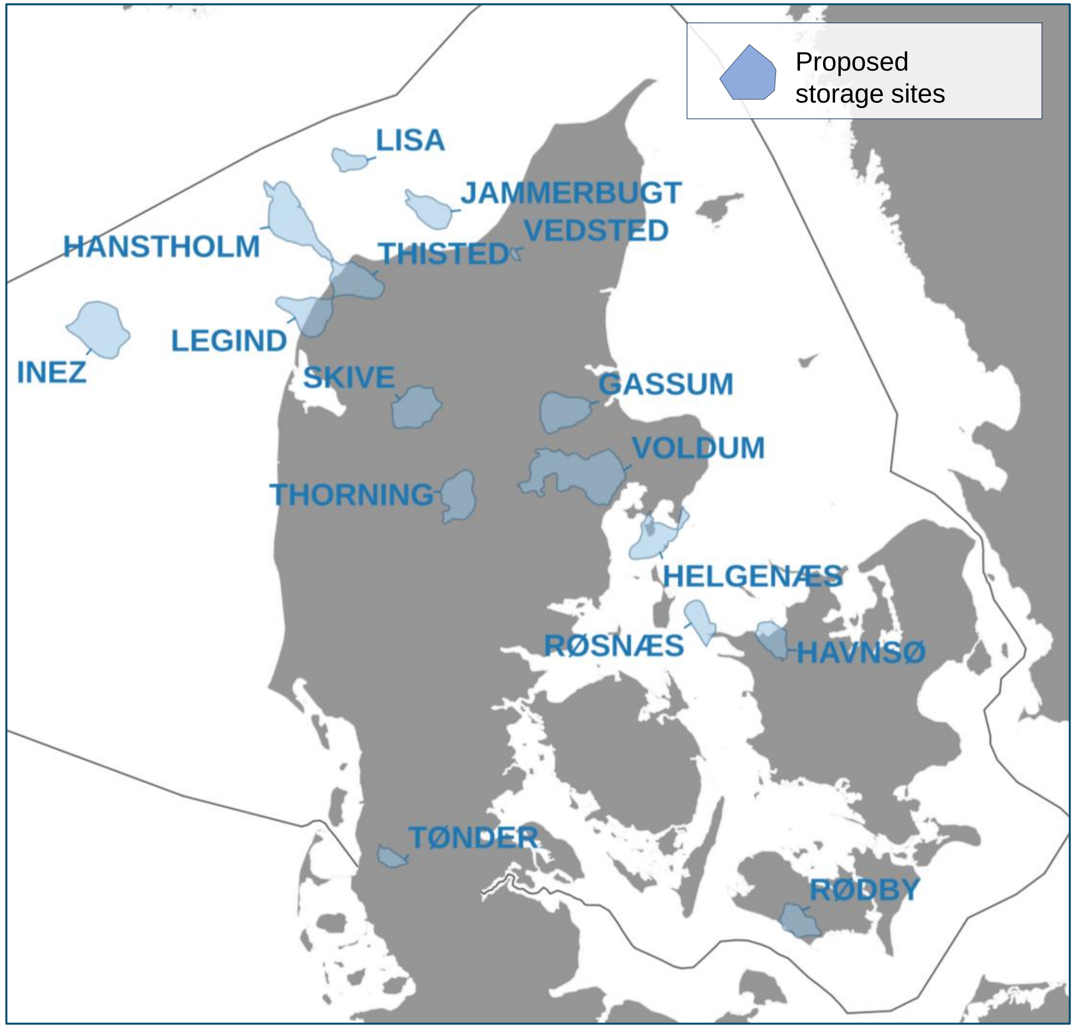
- Updated to include new GEUS structural maps and sedimentological interpretation over Havnsø and Jammerbugt
- Permeability degradation model recalibrated to new information

Executive summary - Scope

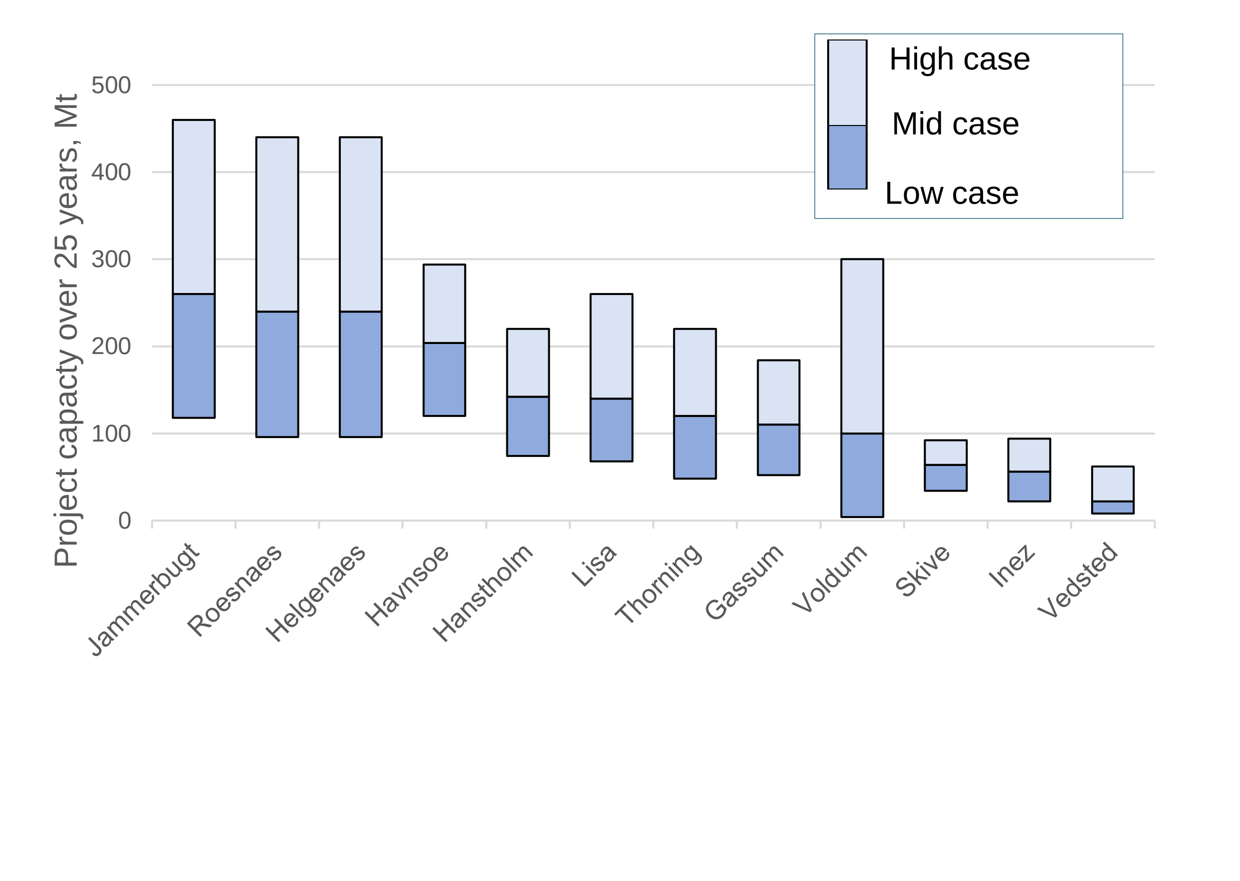
- The Danish onshore and nearshore has a number of subsurface saline aquifers, in particular the Gassum Fm., that have attracted interest from storage developers and emitters as potential CO_2 storage sites.
- GEUS has performed some excellent work defining the geology and quantifying the available pore-space in identified structures, but there are no published studies that assess the impact of the surrounding aquifer on the quantity of CO_2 that can be injected over a typical project lifetime, here taken as 25 years.
- This study addresses this gap for those storage sites using the Gassum Fm. as their primary aquifer
- Importantly, the assessment focused on **dynamic aquifer performance**, considering the influence of aquifer permeability on fluid movement, injection rates and project lifetime storage capacity by simulating the whole aquifer performance.
- With a first licence round completed and significant investments by both state and private bodies ongoing, this screening study should provide further constraint on potential storage volumes and indicate where appraisal investment could be best allocated.



Executive Summary - Results

- This dynamic aquifer simulation assessment demonstrates the importance of considering aquifer quality and connection, and has identified lower risk, higher capacity sites
- For most of the screened sites, Havnsø being an exception, aquifer quality is likely to be the controlling factor for injection capacity over a project lifetime, assumed to be 25 years.
- Where sites are well connected to a thick, high permeability aquifer, as particularly appears to be the case at Havnsø, but also in Røsnæs, Helgenæs and Jammerbugt, the project lifetime storage capacity ranks with the largest North Sea stores.
- Stores in areas of poorer aquifer quality are likely to be aquifer constrained and have a high risk of poor injection performance that can only be partially mitigated by additional wells. Nonetheless the estimated capacities are sufficient to store significant volumes of CO_2.
- It should be noted that the capacities have been calculated independently and that due to pressure interference, combined injection capacities will be less than the sum of the individual capacities. This will particularly be the case for the Havnsø, Røsnæs and Helgenæs structures, possibly to include Gassum.
- Onshore sites will benefit from lower costs likely making them the most cost-effective in Europe from a storage perspective.

Assessed storage capacity ranges for evaluated projects.



Report Contents

- Executive summary
- Simulation methodology
- Individual site summaries
- References

Simulation methology

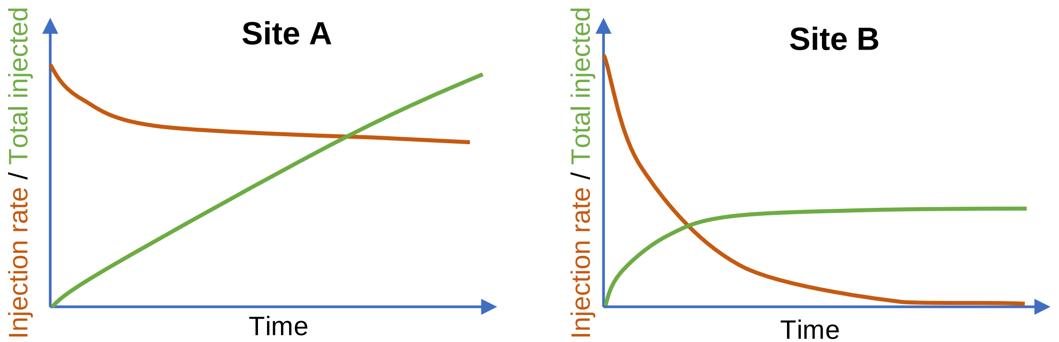
Scope of study

Aims of screening study

- Experience shows that the practical capacity of a CO_2 storage site is often limited by the quality (thickness, permeability and connectivity) of the aquifer connected to the injection point, rather than the total pore volume of the trap.
- GEUS [1, 13] have provided an excellent assessment of the pore space of identified traps. However, no dynamic aquifer assessment appears to have been published for the Danish onshore & nearshore and leading to concern that decisions might be being made without a full appreciation of the importance of the wider aquifer quality.
- A dynamic simulation was performed using an aquifer model built from publicly available data to test the factors controlling capacity for the selected sites in the Gassum Fm.
- The screening is not designed to provide definitive capacity estimates, rather to illustrate the importance of assessing the dynamic performance of the aquifer and to assess which proposed sites may be limited by aquifer or by trap capacity.
- It also makes no attempt to address containment risk through seal breach, fault leakage, fault reactivation or other mechanisms.

Impact of aquifer size and quality on storage capacity

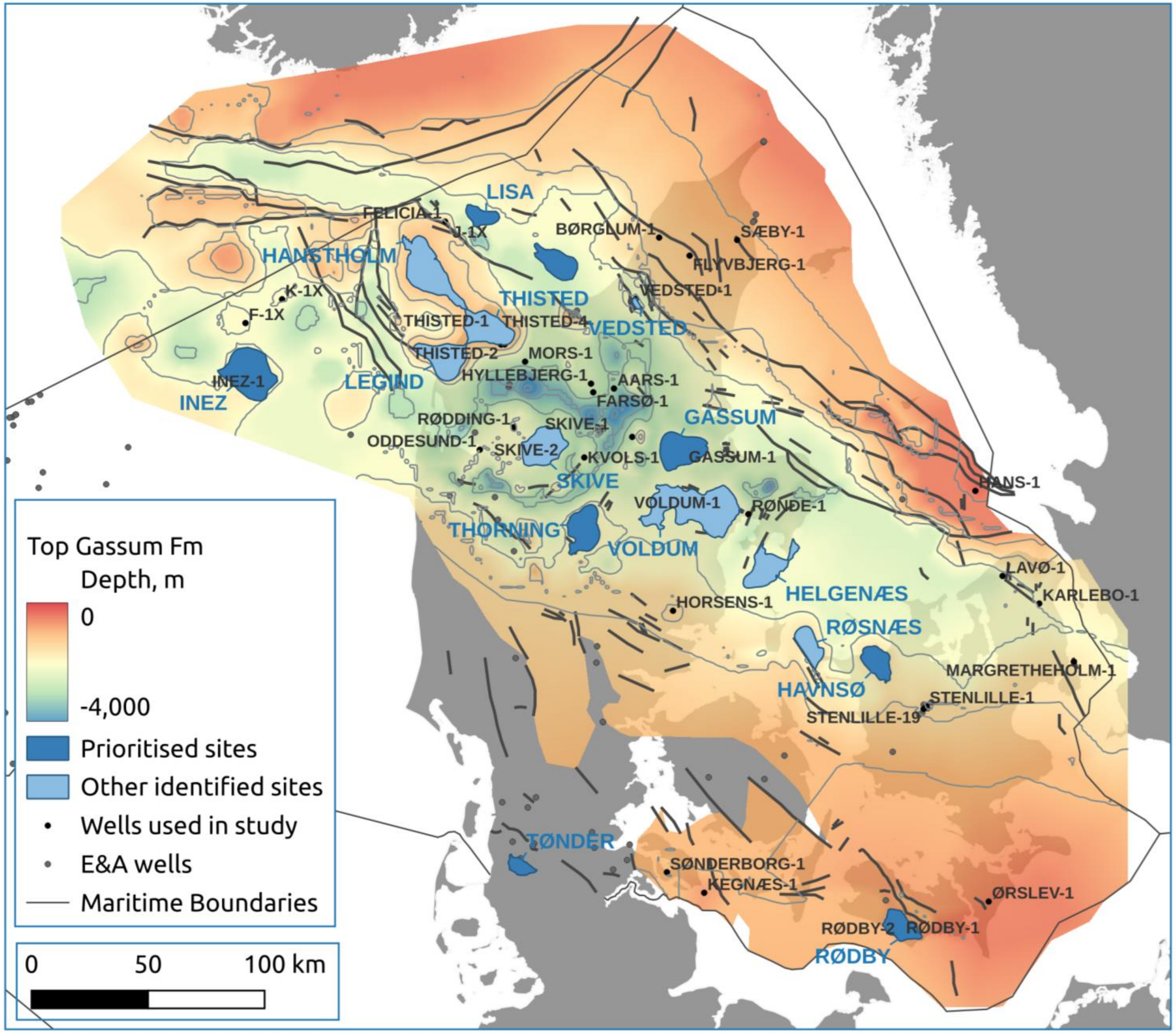
- To store CO_2 in a subsurface saline aquifer, we need to be able to inject the required quantity into the aquifer over a project lifetime.
- To inject the CO_2, space must be made by moving the aquifer brine out of the way. This can be achieved by either removing brine from the aquifer, or by compressing the brine by increasing the aquifer pressure by the CO_2 injection.
- Unfortunately, brine is rather incompressible and the degree of pressurisation is limited by the strength of the sealing units, such that we expect only approximately 0.5% volume reduction through pressure increase. So, for every 1 m^3 of CO_2 injected we need to compress and move 200 m^3 of brine.
- The ultimate quantity of CO_2 that can be injected will thus be limited by the volume of the connected aquifer
- The rate at which it can be injected and hence the total injection volume over a finite project lifetime will be limited by the aquifer size, but also its permeability, which controls the flow rate of the brine.



Examples of injection performance at sites with differing aquifer quality. Total injected volume is in green, with injection rate in orange. Site A has a large, high-quality aquifer that can support injection, whereas site B has an aquifer of limited size, effectively a sealed box, with the injection rate rapidly tailing off and the injection volume plateauing

Structural maps

- Grids of the Top Gassum Fm. depth and thickness were constructed from published maps [1,2,3,13] and released well data, and formed the basis of the aquifer model construction.
- It should be noted that the underlying seismic data is sparse and of varying vintage and quality, reducing the accuracy of the mapping.
- In particular, faulting at the crest of the structures is poorly resolved and it is possible that such faulting could reduce the effectiveness of the overlying Fjerritslev primary seal.
- Likewise, faulting will create barriers to flow for both CO_2 and aquifer brine, and it is expected that such faulting is more prevalent than currently mapped.
- The well data is biased to the structural highs, making depth conversion of the low areas difficult. As will be discussed, the low permeability in the structural lows act as a major control on dynamic storage capacity.
- Given the points above, further data gathering is required and is indeed underway. However, until the new datasets are available and can be incorporated, the structure map above is considered fit-for-purpose for an aquifer model.



Petrophysics

38 wells with logs over the Gassum Fm. were evaluated.

As the wells were drilled from 1946 (Gassum-1) to 2010 (Sønderborg-2) and for differing purposes, the type and quality of the logs differs markedly, leaving considerable uncertainty in poorer quality wells.

Børgium-1 and Stenlille-19 wells show examples of differing quality.

VSh

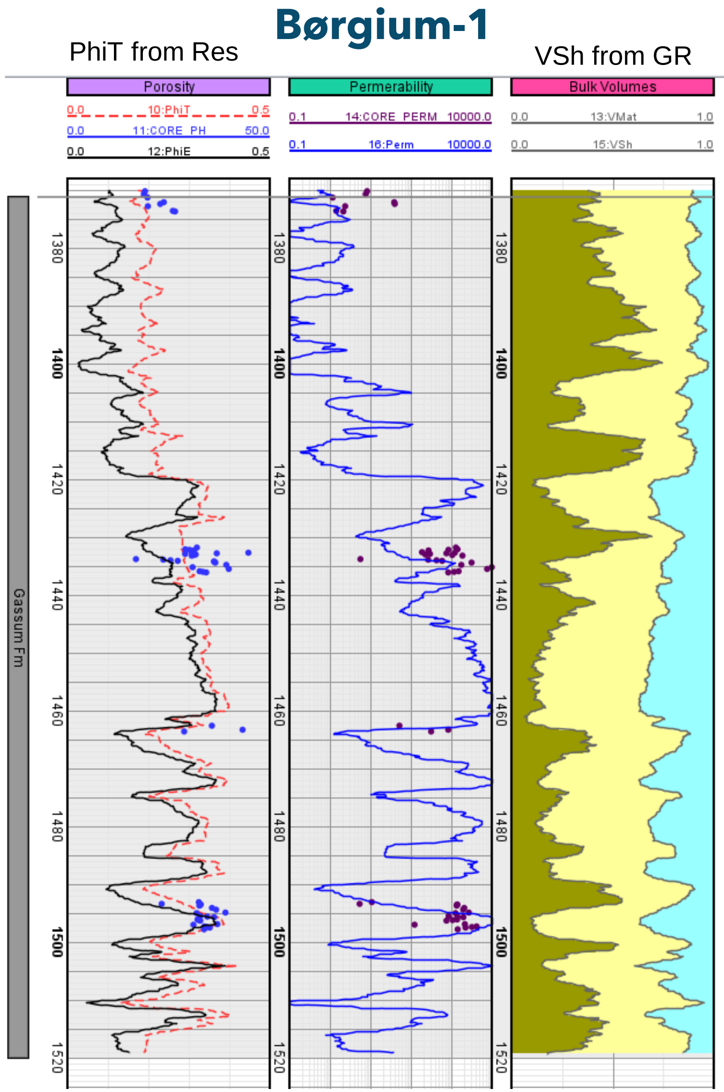
- Estimated from Gamma ray logs or where these were not available, SP logs, with calibration against Neutron-Density in wells where available.

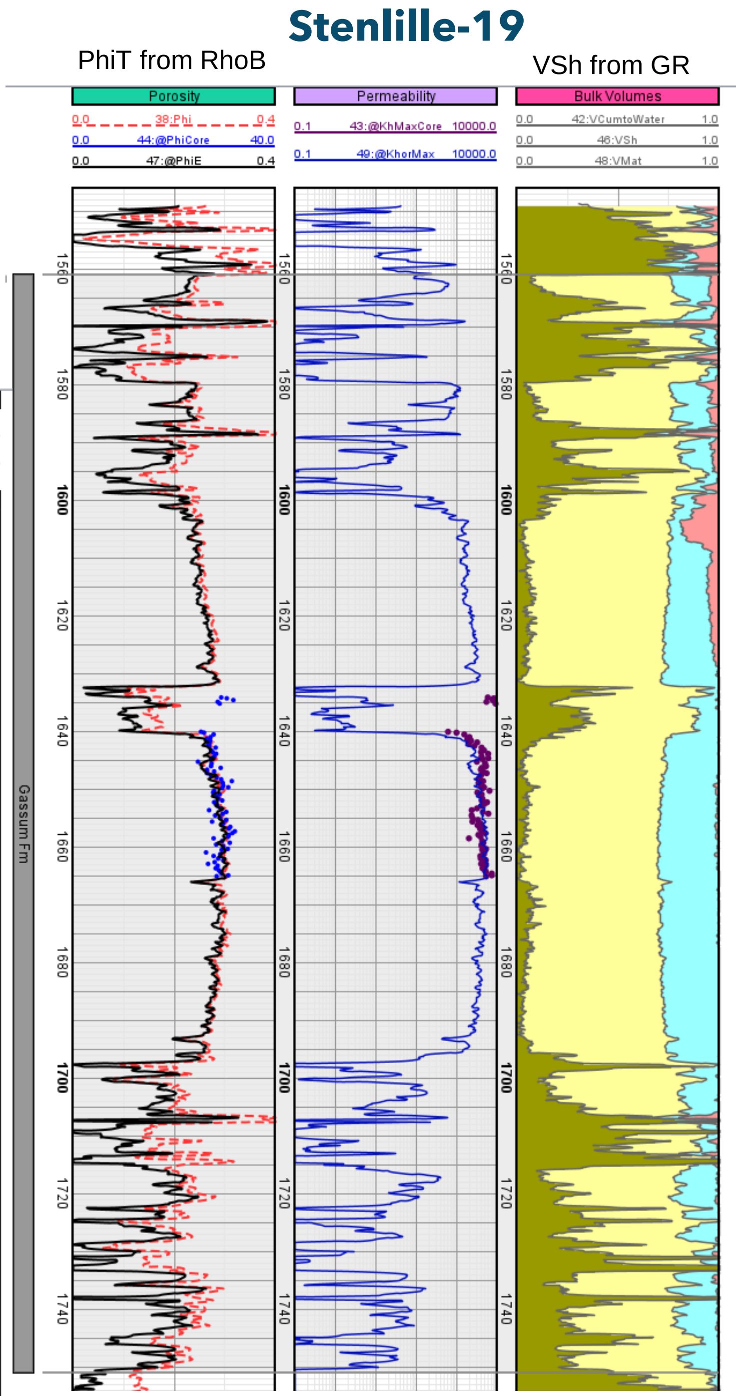
Porosity

- Total porosity estimated from density logs where available and sonic or resistivity where not;
- Log estimates were calibrated against core if available;
- Effective porosity calculated using by incorporating VSh.

Permeability

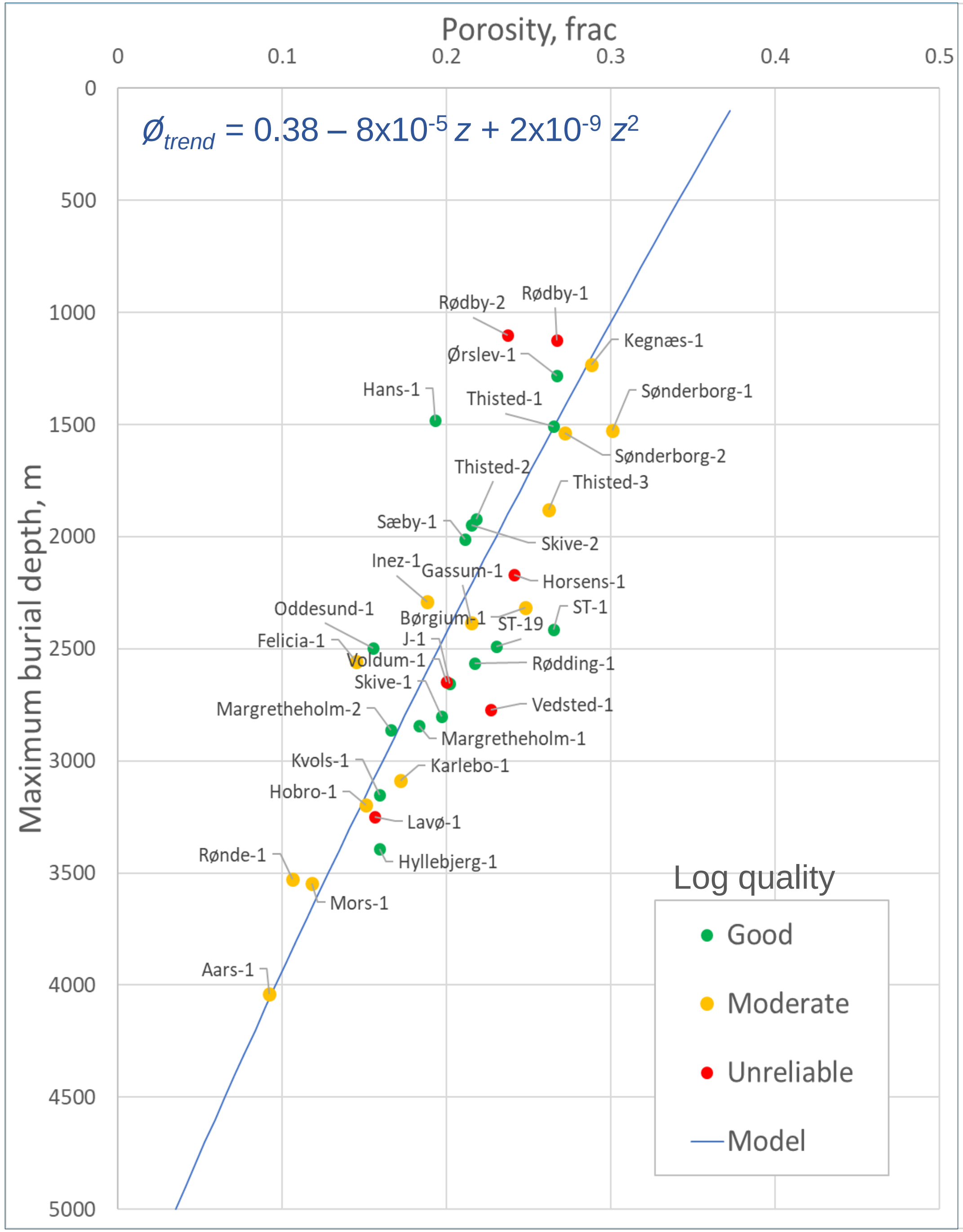
- Calculated by power law relationship with PhiE, scaled by VSh relationship (proxy for sand grain size) – see Slide 10.





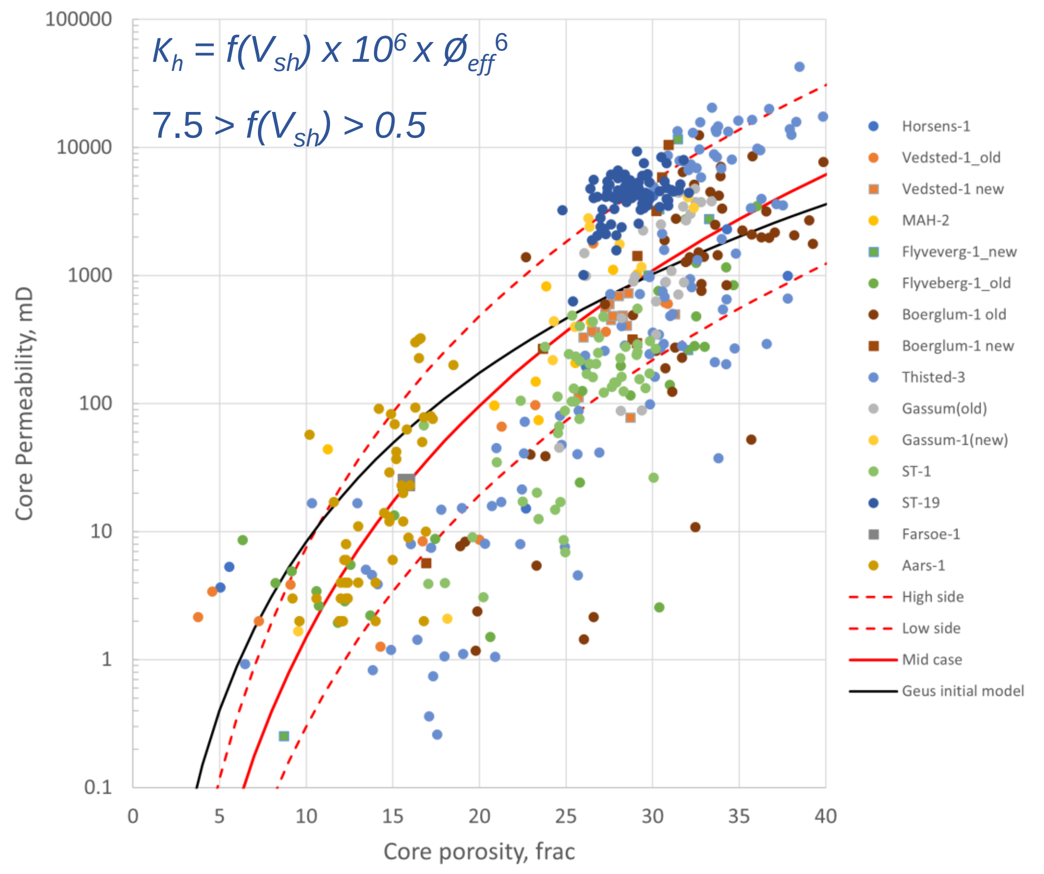
Aquifer porosity

- The quality of the aquifer, as described by its thickness, net-to-gross, porosity and permeability, controls its ability to support brine movement away from the injection site.
- Plotting net aquifer porosity (VSh cut-off only) against maximum burial depth illustrates that there is a general trend of decreasing porosity with burial depth with 5 porosity units lost for each additional 1000 m of burial depth.
- There is considerable scatter on the plot due to variations in the depositional setting, with variations in grain-size, sorting and clay content. For example, Stenlille has anomalously good quality aquifer, whereas poorer aquifer facies was encountered e.g. at Hans-1 and Voldum-1. This variation has been tentatively explained by proposing a sediment entry point at the south-eastern end of the basin [4,5,6].
- It should also be noted that porosity is expected to depend on maximum burial depth rather than the current depth, with onshore Denmark having experienced 400 – 800 m of Tertiary uplift, resulting in the aquifers currently being shallower than their maximum burial depth. A map of uplift was constructed from [7] and used to correct current depth to maximum burial depth
- The top Gassum structure map, uplift map, porosity-depth trend and well logs were used to produce maps of net-to-gross and porosity for individual aquifer layers across the Gassum Fm fairway.



Permeability

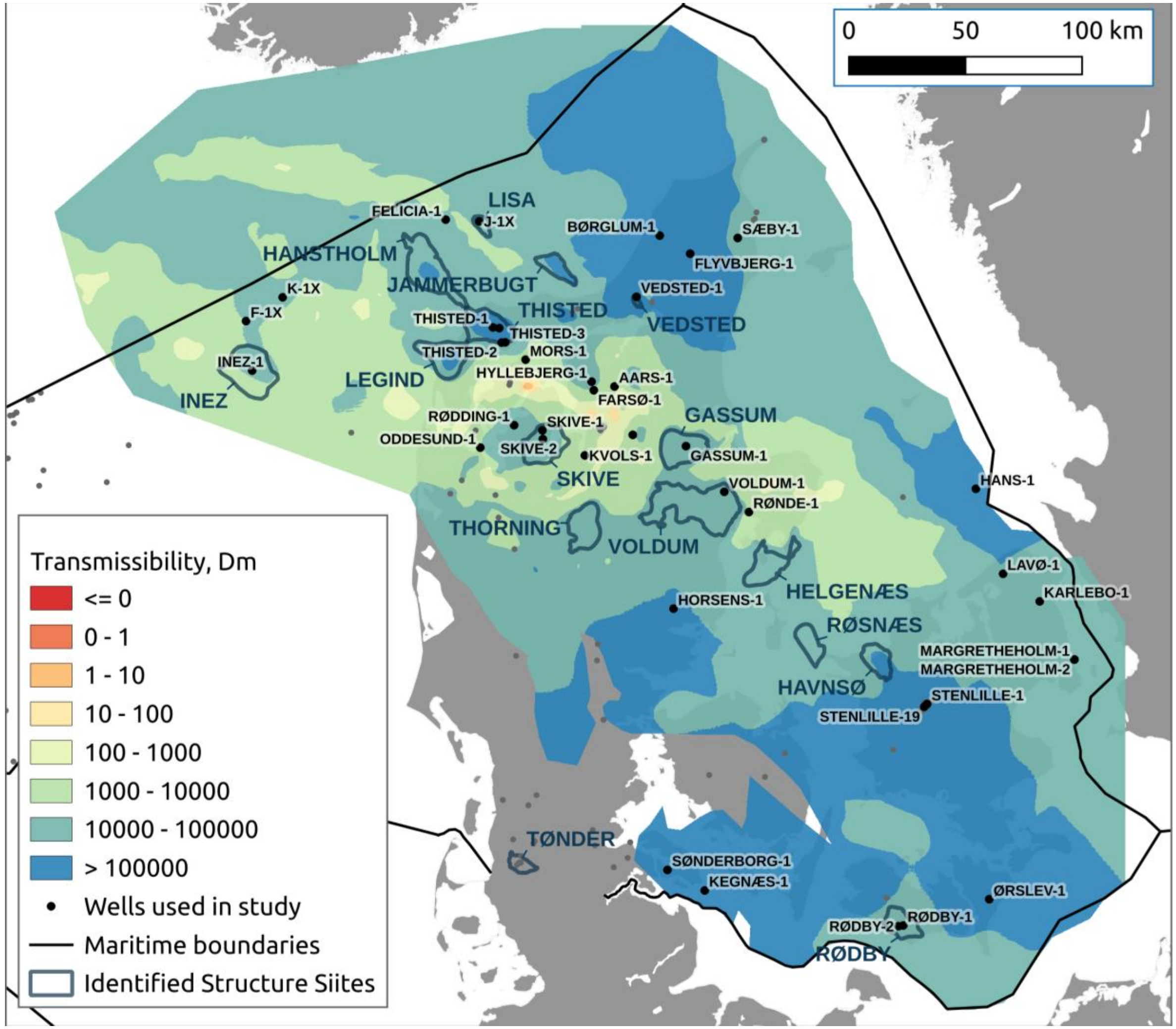
- Permeability is the most critical parameter for aquifer performance
- While porosity loss is approximately linear with depth, permeability is generally related to porosity by a power law relationship so reduces with depth considerably more rapidly. Hence, storage sites surrounded by deep aquifer will have much worse performance than those where the aquifer shallows away from the site
- A porosity/permeability transform was created on the available core analysis data.
- There is considerable scatter in the dataset with different units following different trends, with an order of magnitude difference in permeability from the same porosity, this variation occuring both vertically and laterally.
- A published analysis of the core data [8] indicates that the primary factor controlling the porosity-permeability trends is the grain size and sorting. Based on this analysis, we have used the Vsh as a proxy for sand quality and used it to build a calibrated model for permeability
- The relationship enables the generation of upscaled permeability maps for the aquifer layers in the model.
- It should be noted that the dataset is biased, with most wells drilled towards crestal locations rather than the deeper flank settings that will control aquifer performance. Collection of such data should be an appraisal objective.



Permeability v porosity from core measurements in the Gassum Fm.

Kh map

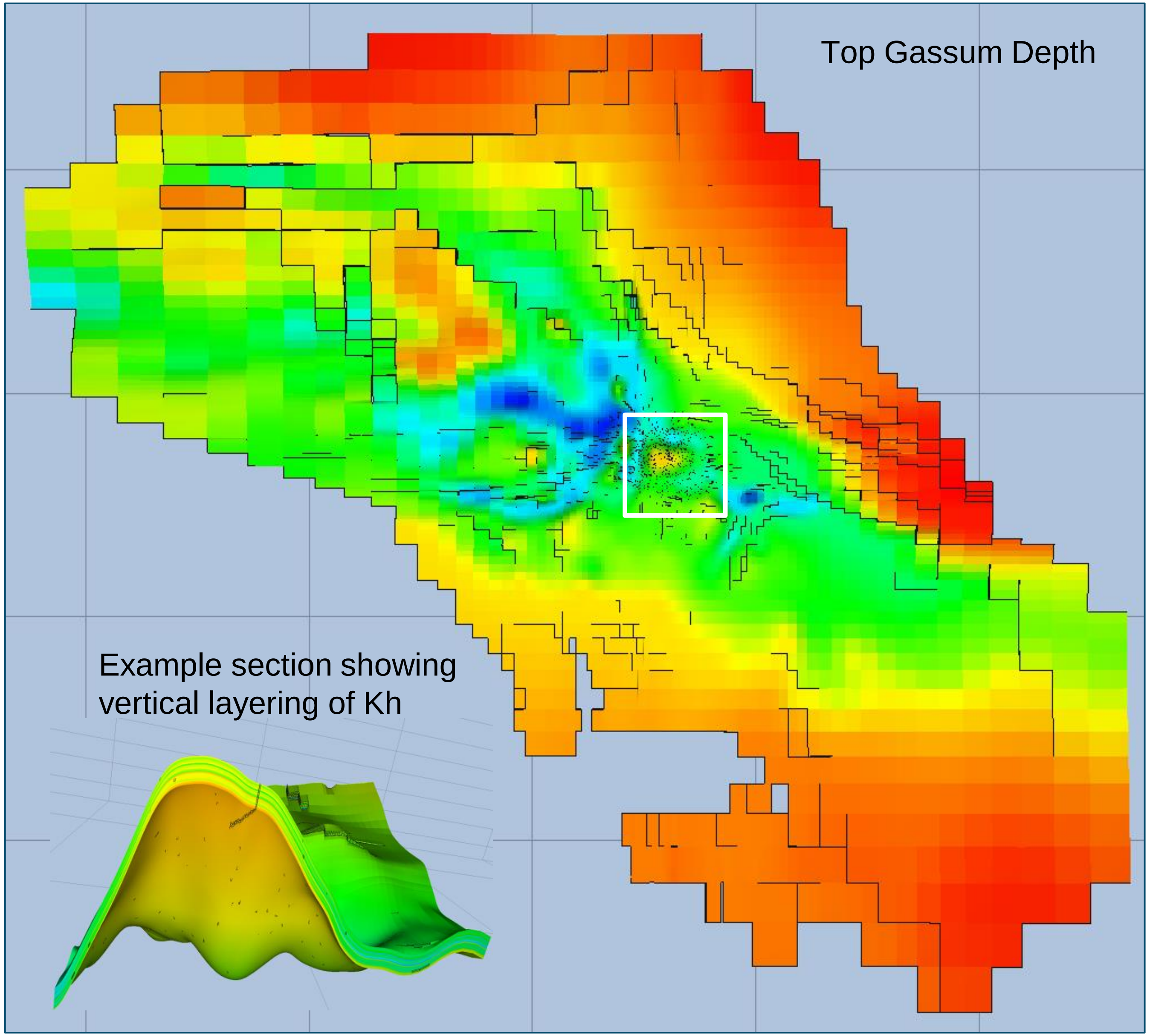
- The results of the aquifer quality mapping can be compiled into a Permeability Thickness (Kh) map, calculated by summing the average net permeability times net thickness for each layer.
- Kh is the primary control on both the injectivity of the injection wells and the ability of the aquifer to move brine away from the injection wells to make room for the CO_2. As such the Kh map provides some immediate observations on the potential of the different proposed sites.
- Havnsø and, to lesser extents Røsnæs and Helgenæs, are expected to have excellent to good Kh on their crests and to be well connected to the very high Kh region in the south of the aquifer.
- Hanstholm has an excellent crestal Kh, and a good Kh in the surrounding aquifer, though separated from the wider aquifer by faults.
- Lisa and Jammerbugt have good crestal Kh, but are separated from the aquifer by large faults which offset the Gassum Formation, constraining the injection capacity
- Gassum, Voldum, Thorning and Skive, while having good Kh on their crests, are surrounded by low Kh aquifer, limiting their capacity.
- The offshore Inez, while connected to aquifer, has relatively low Kh.
- The Vedsted structure is surrounded by good Kh aquifer, and if the structure is not separated from the aquifer by faults, the capacity may be limited by the small trap volume rather than aquifer.



Permeability thickness map for the Gassum Fm.

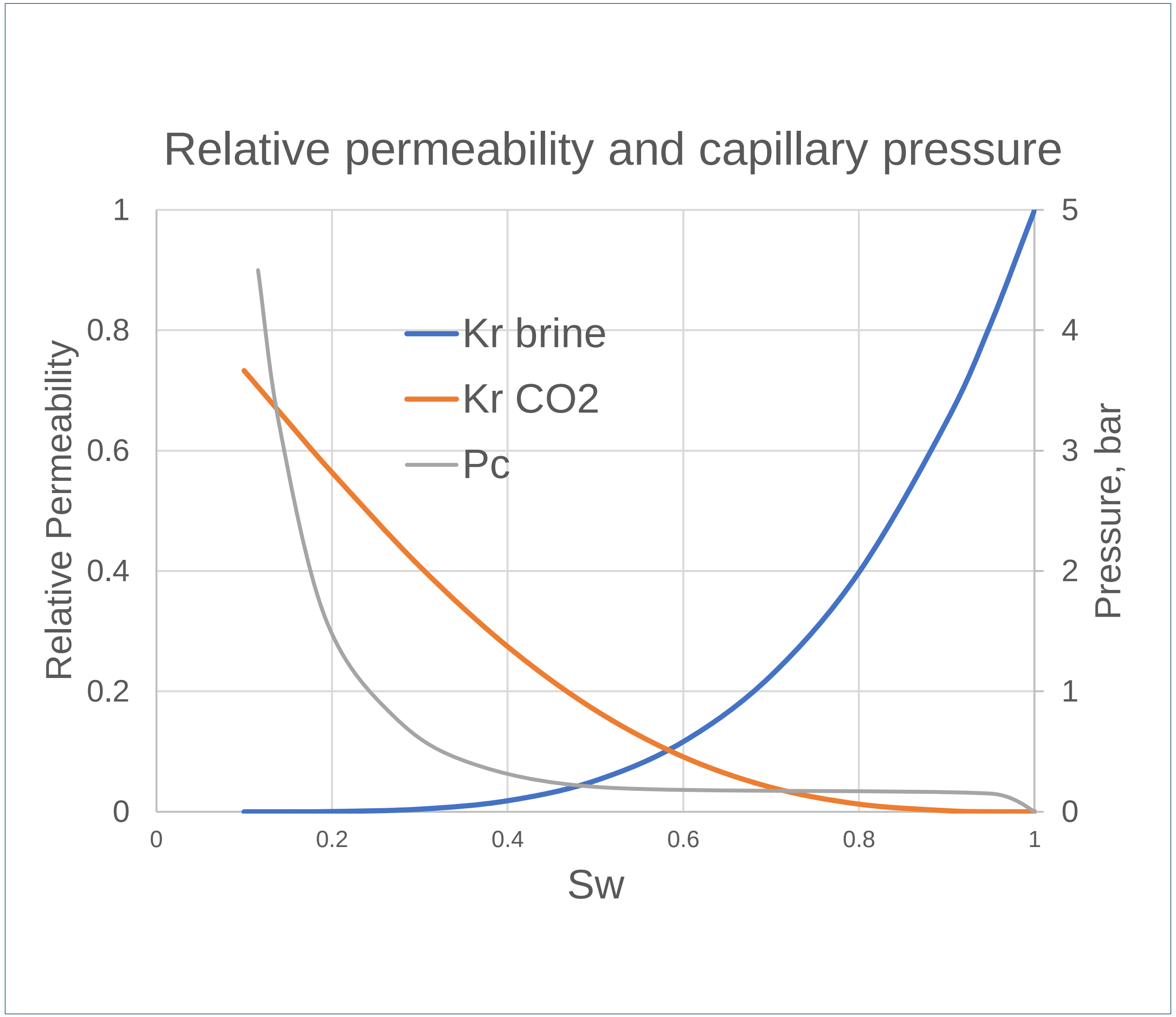
Aquifer model construction

- A static model was built for the full aquifer extent to ensure that the displacement of brine away from the injection points was properly modelled without having to introduce boundary conditions.
- An expending cartesian grid was employed to enable a computationally feasible grid size, with a sufficiently small cell size over the areas where CO_2 injection and migration is expected. A central 100 m grid spacing, expanding gradually to 20,000 m was designed for each structure modelled.
- The mapped Gassum Fm. aquifer thickness was divided into 20 layers based on a proportional slicing.
- The properties in the layers (net-to-gross, porosity, horizontal permeability) were populated from the well data, together with the porosity-depth and porosity-permeability trends as discussed previously, and using appropriate upscaling. Kv/Kh was upscaled for each layer, interpolated and used to calculate vertical permeability from horizontal.
- Faults from the available publications [1,2,3] were incorporated into the model and were assumed to act as barriers to flow. In practice there are likely to be more faults and hence more baffles and barriers than currently modelled.



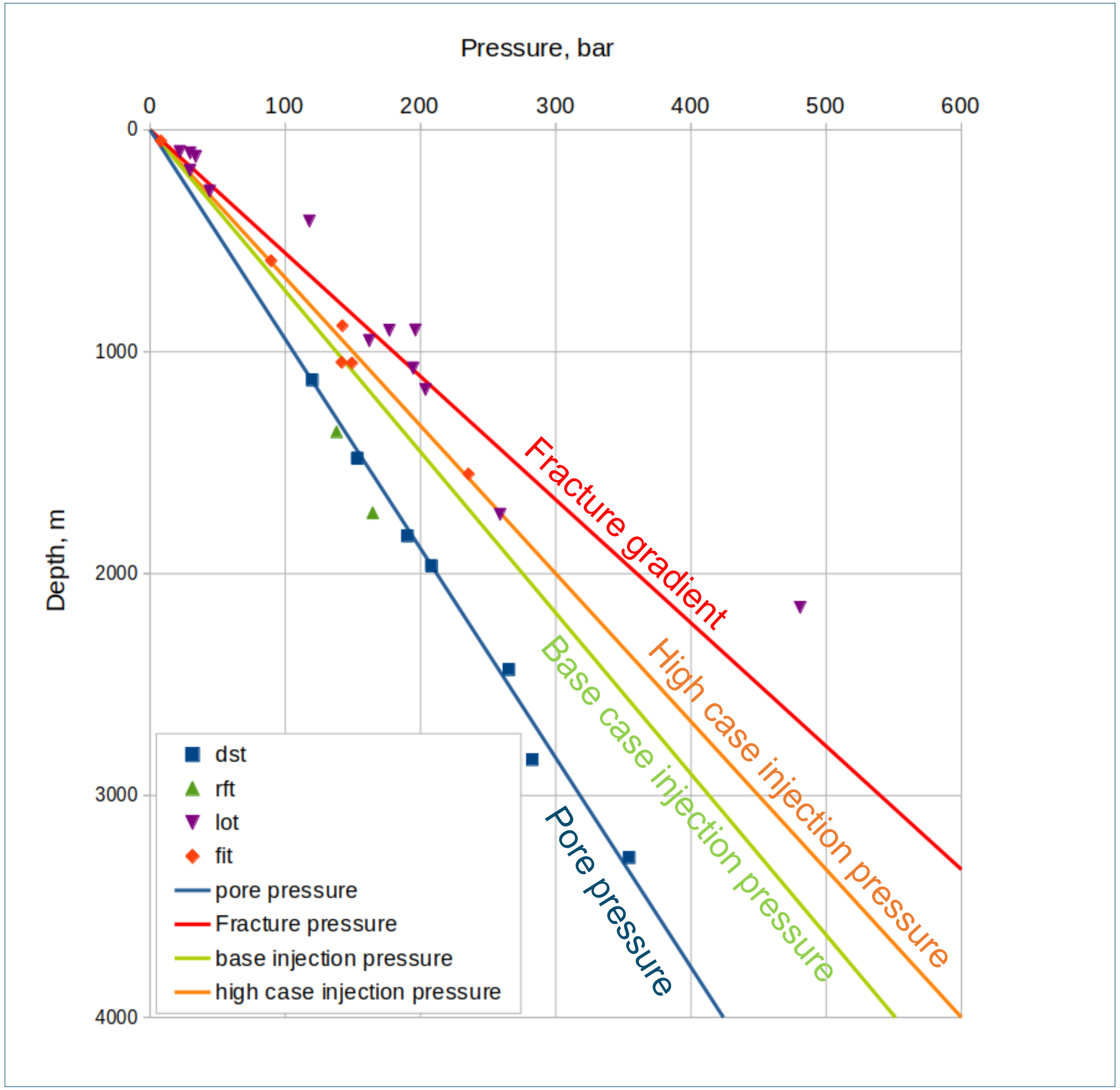
Relative permeability

- There is limited data available to constrain the capillary and relative permeability curves to describe two-phase flow in the simulation.
- Brine-air capillary curves are available from the SCAL analysis performed on the Stenlille-1 Gassum Fm core and this was used to define the Pc curve, with appropriate correction to CO_2-brine and upscaling.
- CO_2 – brine relative permeability data is not available for the Gassum Fm. Hence upscaled curves based on Sleipner data [9] were employed. As the Utsira aquifer at Sleipner is a similar quality to the Gassum Fm. aquifer over the proposed storage sites, this is considered a reasonable approximation.
- In practice, the simulations show that the capacities of almost all Gassum Fm. structures are limited by the ability of the aquifer to dissipate pressure away from the injection site, which is controlled by single-phase flow of brine and is not influenced by the relative permeability curves.
- However, if trap capacity or plume migration becomes a matter of concern, a more detailed review of the two-phase flow parameters and possibly a fine scale simulation would be beneficial.



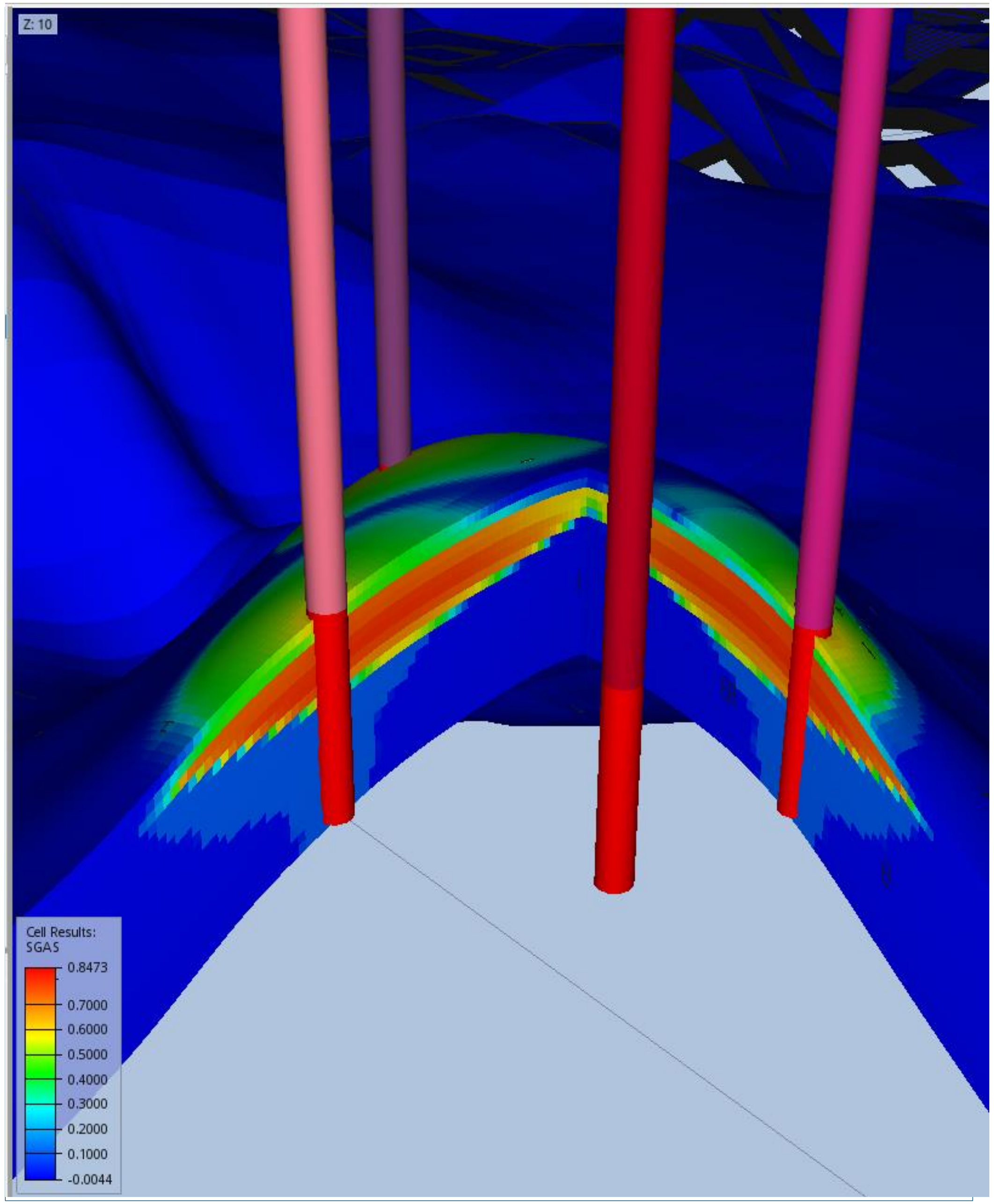
Pressure and temperature

- Pressure data is relatively sparse due to the age of the wells and the lack of hydrocarbons, but sufficient data is available to draw reasonable conclusions on the pore pressure and injection pressure limits.
- The available DST and RFT data supports an assumption of hydrostatic pressures with a gradient of 0.106 bar/m. This gradient is consistent with the measured brine densities of the Gassum Fm. pore fluids, discounted for less saline pore fluids in the overburden section.
- There is scatter around this gradient, but it is unclear whether this is due to measurement error or is an indication of significant pressure compartmentalisation.
- The available leak-off tests (LOT) indicate a fracture gradient of 0.18 bar/m, but an anomalous reading at Karlebo-1 gives a gradient of 0.15 bar/m. This latter figure is used to constrain the high case maximum injection pressure.
- For the base case, a maximum injection pressure equal to 1.3 times the original pore pressure (0.138 bar/m) is used, a conservative approach justified by the uncertainty on crestal seal capacities and legacy well penetrations.
- A temperature gradient of 28^{O}C/km Is assumed based on [3]. There will be lateral temperature variations, especially when overlying salt domes, but results are relatively insensitive to temperature.



Simulation

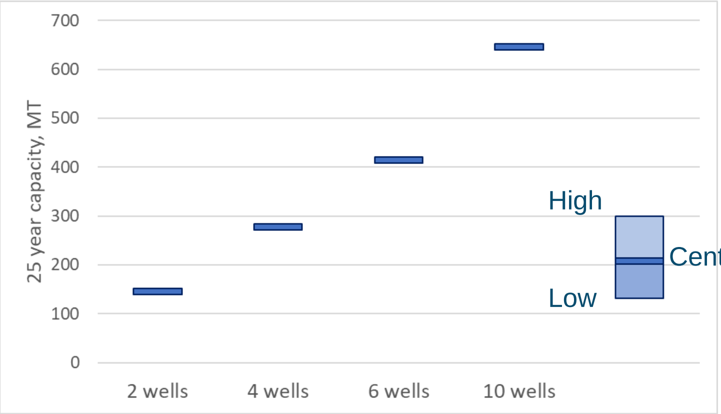
- Simulation was performed using the OPM Flow simulator [10], employing the inbuilt CO2store functionality [11], which incorporates the Span and Wagner CO2 PVT [12].
- Simulations were performed at each proposed Gassum Fm. storage site to assess the maximum quantity of CO2 than could be injected into and contained within structure, given constraints on maximum aquifer pressure at the injection site and any surrounding weak points.
- Simulations were performed for increasing number of injectors until additional wells failed to add significant capacity
- The aquifer pressure constraint was imposed using a bottom hole pressure (BHP) limitation, with an additional maximum well rate based on a reasonable maximum tubing head pressure (THP) of 100 – 120 bar, assuming a 5 in injection tubing completion.
- With a base case number of wells established, low case and high case sensitivities were performed with the horizontal permeabilities scaled by 0.33 and 2 respectively. Other sensitivities were assessed, including a high case injection pressure increasing from 0.18 to 0.15 bar/m, but in all cases, the aquifer permeability was the most sensitive parameter.
- Simulations were performed for 25 years injection and a period of relaxation. Additional runs were performed to assess plume movement over several millennia post closure, but as with one exception, all sites were underfilled after 25 years injection, this was of limited interest.



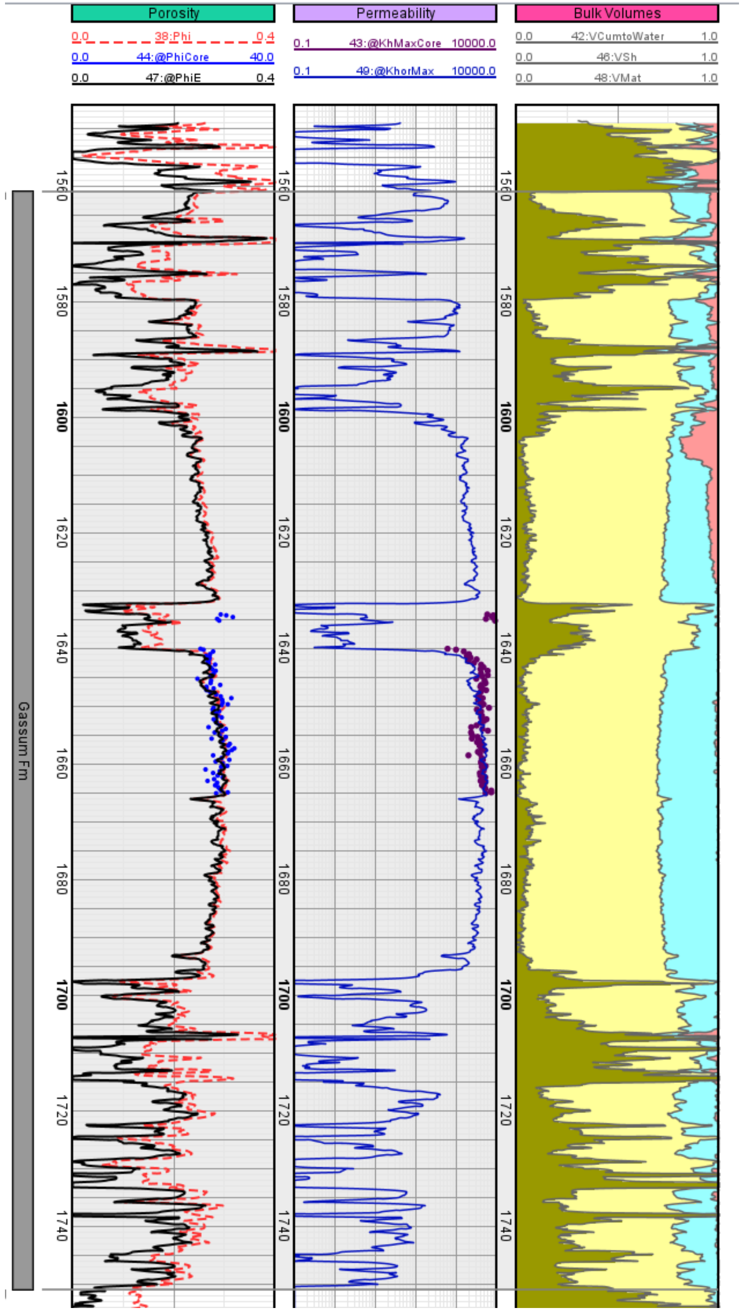
Summaries for Gassum Fm. Sites anticipated in licence round

Havnsø

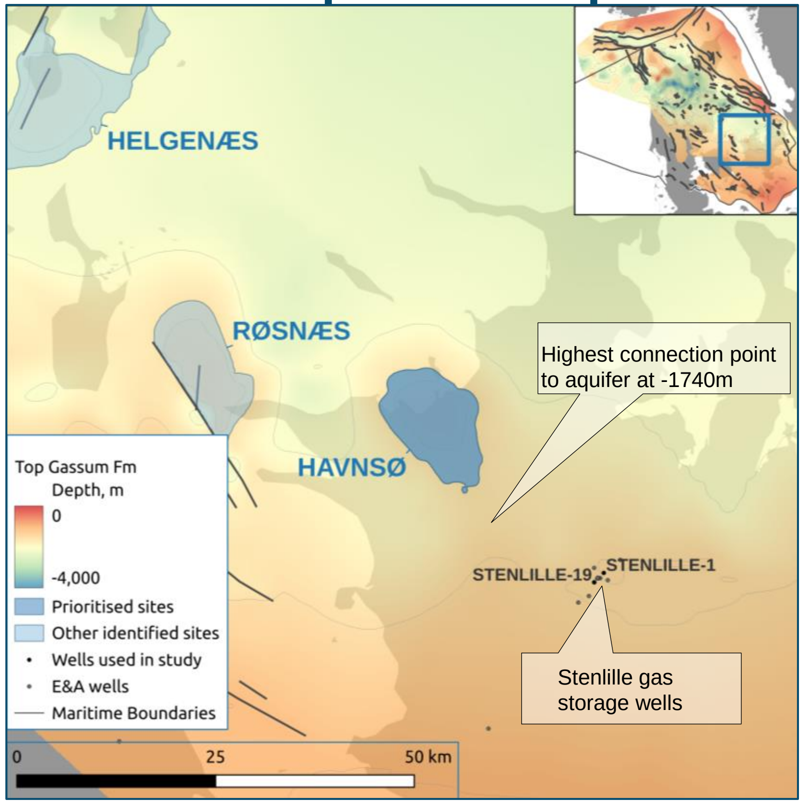
- The Havnsø structure is a low relief anticline connected to the high Kh aquifer to the south by a shallow saddle.
- Wells at the Stenlille gas storage site, 25 km to the SE, show excellent quality sands with multi-Darcy permeabilities, although only the lowstand units are expected to extend over Havnsø [13].
- Simulation shows that the permeability-thickness over the structure allows injection rates more than sufficient to fill the trap within 25 years.
- Havnsø is therefore likely to be trap constrained and 4 wells are modelled as sufficient for injection capacity. Capacity estimates below are based on GEUS pore-space estimates and using average CO_2 saturations of 0.5 – 0.7

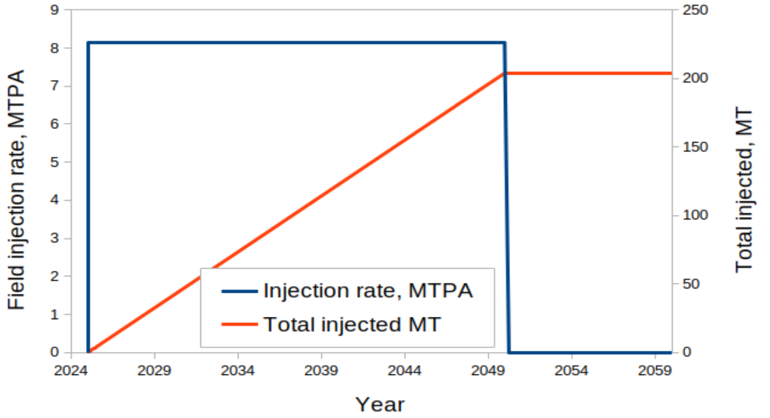


Stenlille-19



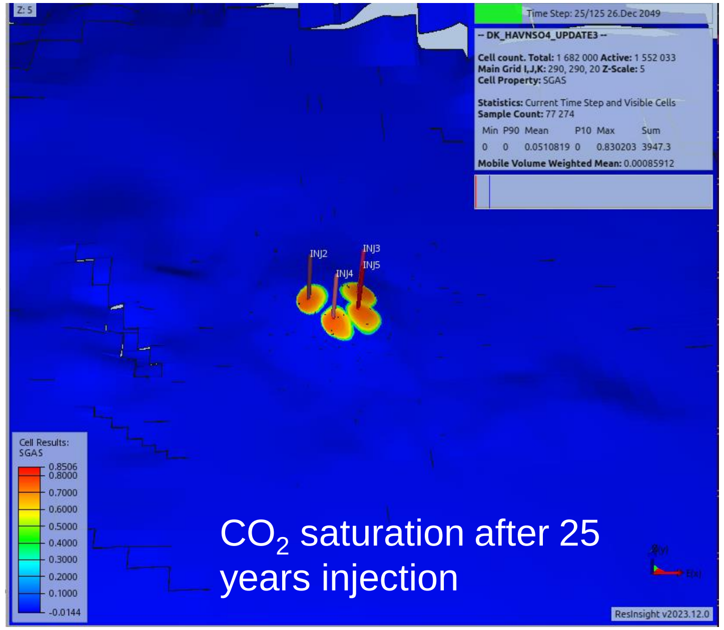
Top Gassum depth

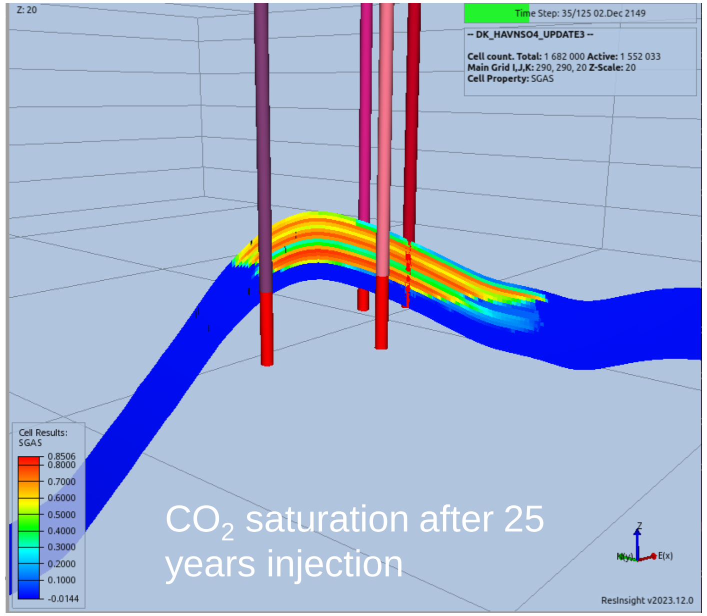


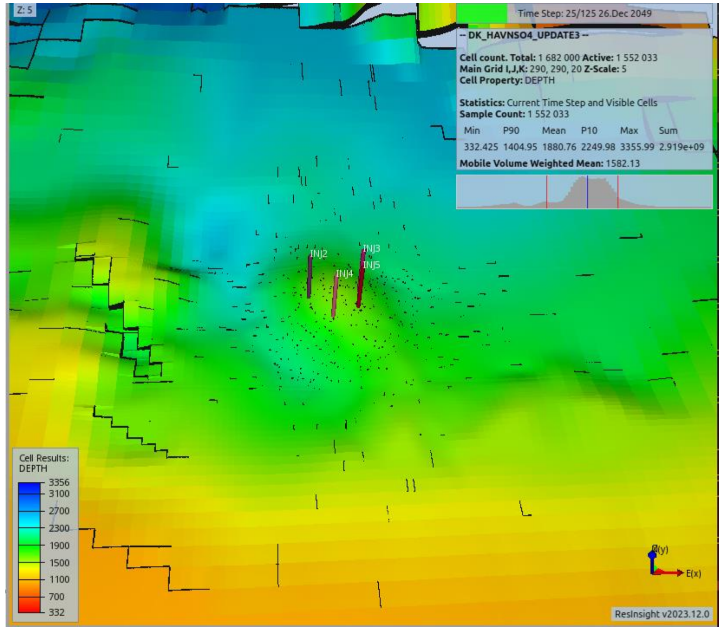


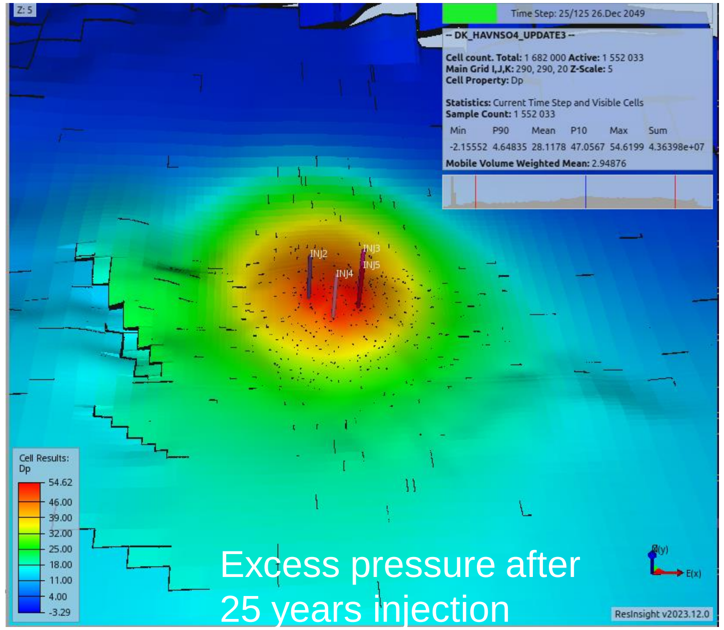
Havnsø

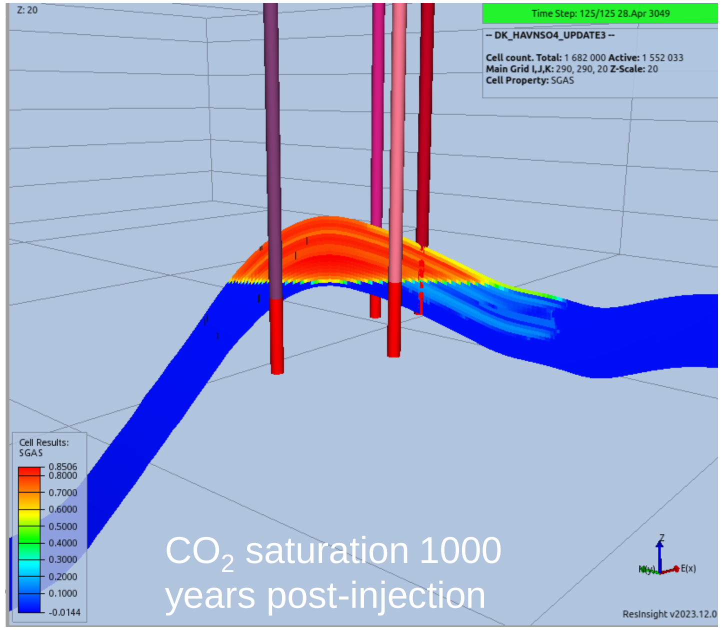
- Havnsø benefits from a good aquifer at the injection point and a strong connection to the excellent quality regional aquifer to the south. This can be seen by the broad extent of the aquifer pressure increase, which enables large volumes of CO_2 to be injected.
- Given the excellent connected aquifer, capacity is primarily limited by the pore space in closure and the saturation of CO_2 that is achieved in the net sands, but also Kv/Kh & injector placement. Core analysis will be required to fully assess the S_{CO2}, but it is likely to be in the range of 0.6 – 0.8.





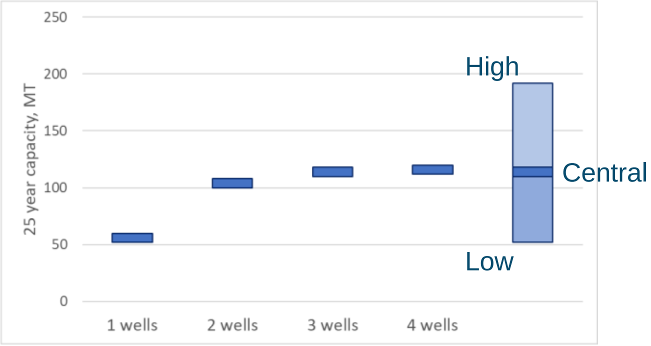




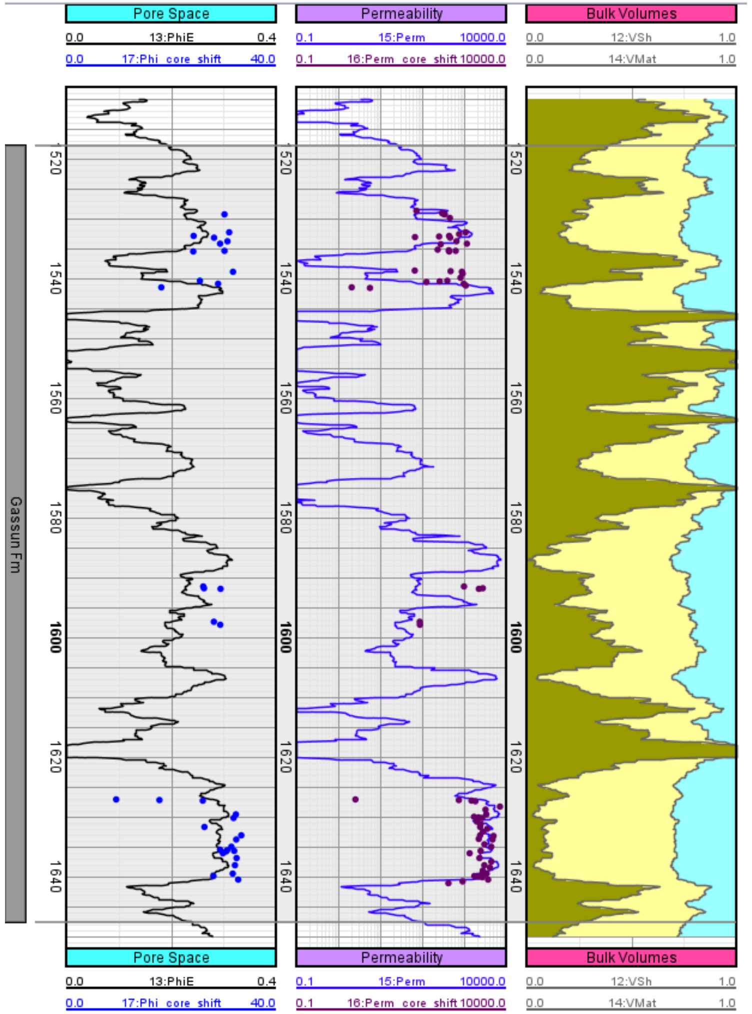


Gassum

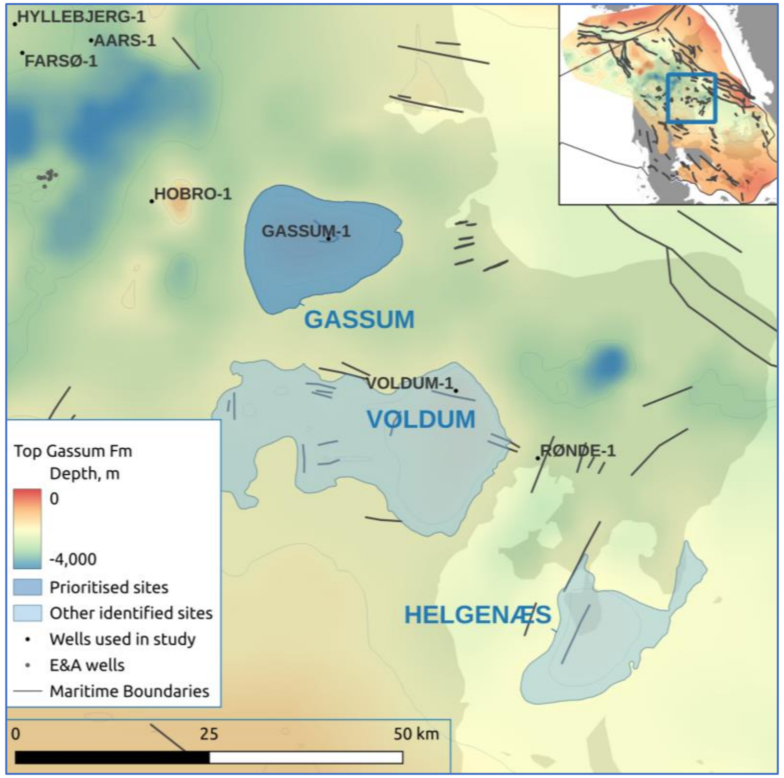
- The Gassum structure is a high relief salt cored anticline separated from the wider aquifer by a rim syncline with a saddle to the south.
- The aquifer quality is well constrained by the Gassum-1 well on the crest, which had 73 m of net sand with an average porosity of 25% and good to excellent permeabilities.
- Simulation shows that the excellent aquifer quality on the crest can support high initial injection rates which then decline to 3 - 4 Mtpa due to reduction in aquifer quality in syncline connecting to the wider aquifer.
- 2 - 3 wells are modelled as being sufficient to meet the injection capacity, with additional injectors having only a minor increment.

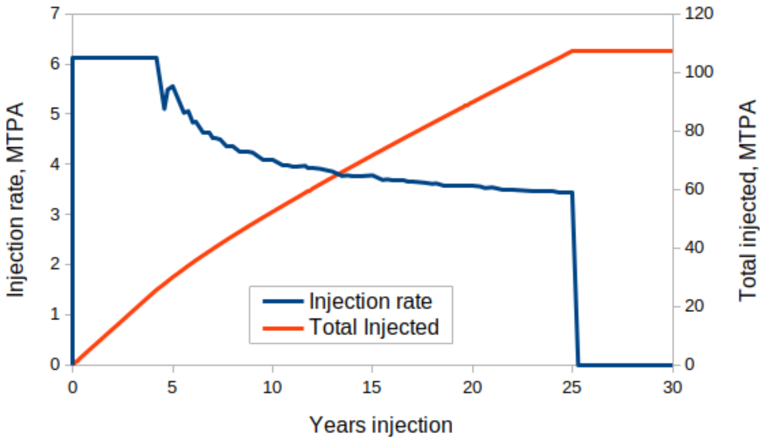


Gassum-1



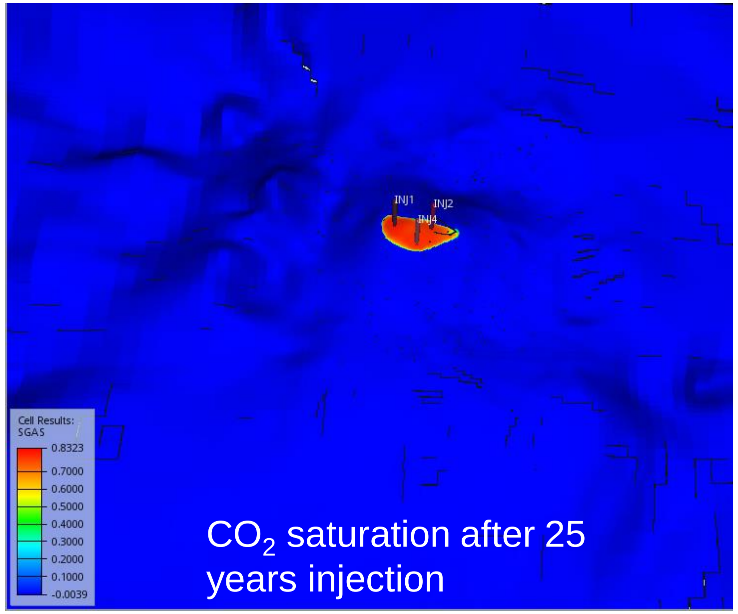
Top Gassum depth

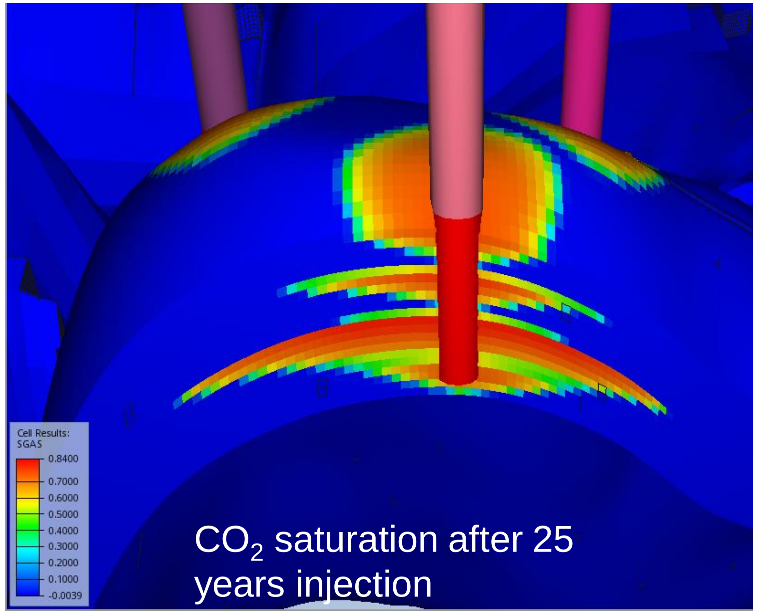


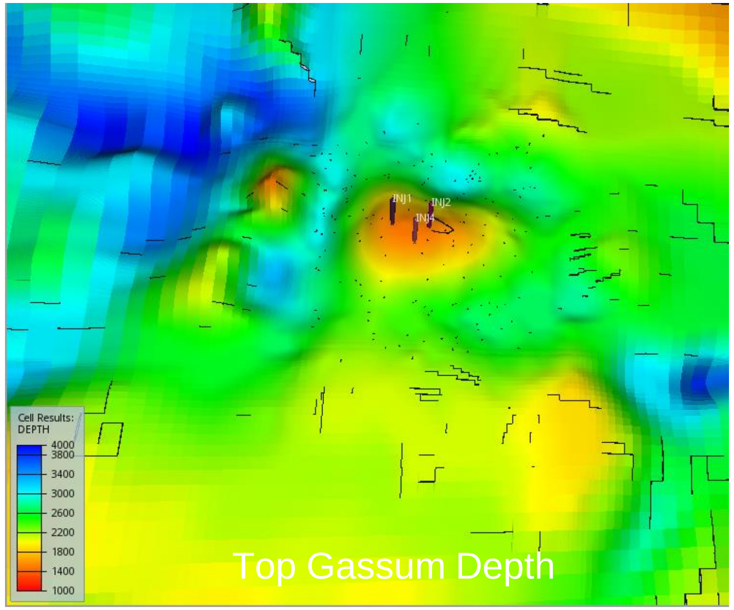


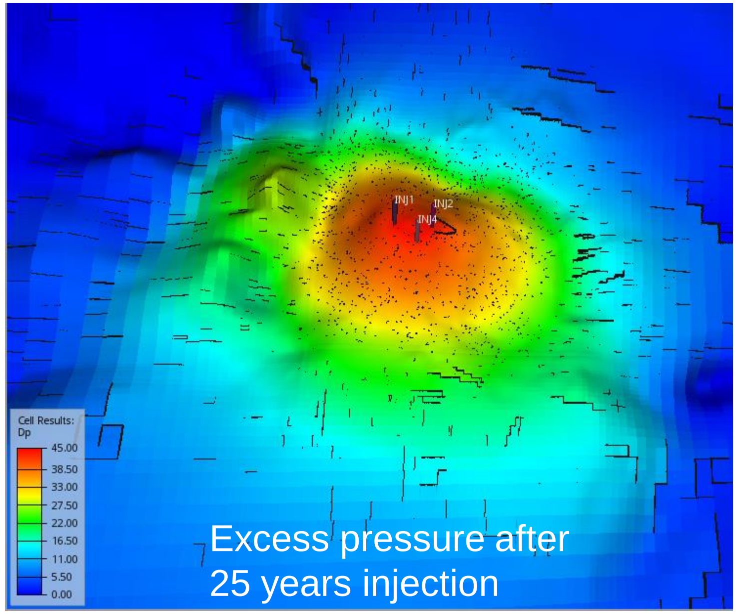
Gassum

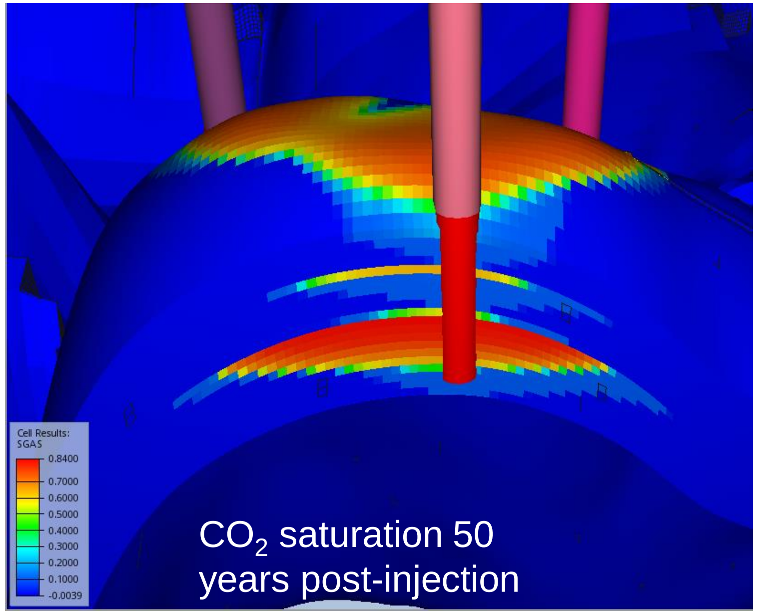
- The excess pressure map shows that the dissipation of injection pressure into the aquifer creates a broad area of elevated pressure that extends further to the south due to the better aquifer quality in this direction. This could influence other projects using the Gassum aquifer, such as the Aarhus geothermal project.
- The saturation plots at end of injection and after 50 years show the vertical flow barriers from the aquifer layering influencing CO_2 distribution. Over the following millennia, the CO_2 relaxes fully to form a single column under the Top Gassum seal.







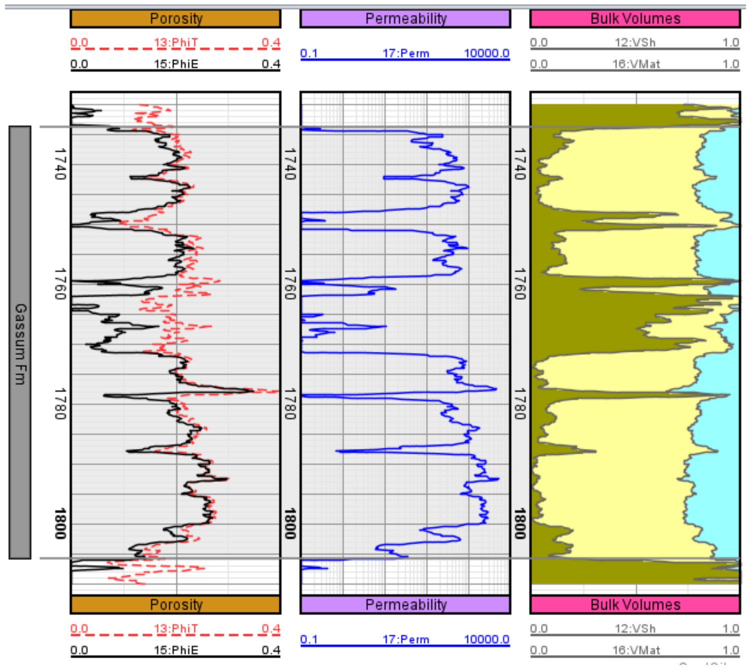




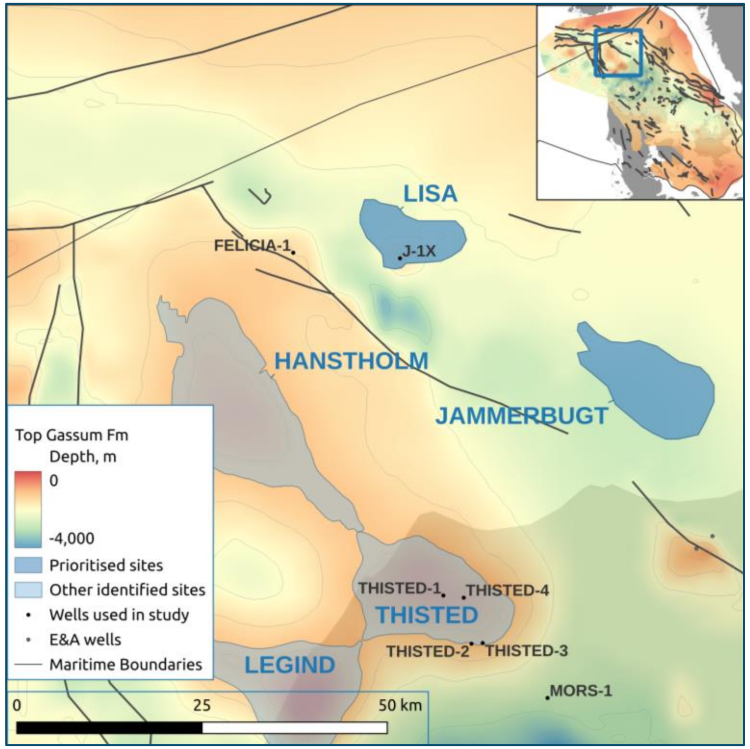
Lisa

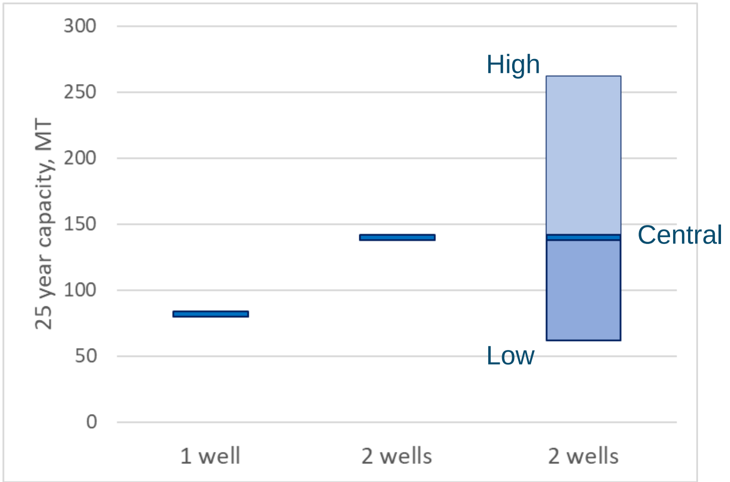
- The Lisa structure consists of a small anticline to the east of a major fault that marks the eastern limit of the Hanstholm/ Thisted high. While separated from the high Kh aquifer to the west by this fault, it appears to be well connected to the high Kh aquifer to the north with the aquifer to the east and south, modelled as having only moderate Kh.
- The J-1 well, drilled on the structure encountered 57 m of net sand with average porosity of 20% and permeabilities estimated to average around 1 Darcy.
- Simulation shows that long term injection rates of circa 5.5 Mtpa can be achieved resulting in total injection of 60 – 240 Mt.
- The capacity would be reduced if aquifer pressures were increased by injection into nearby structures, particularly Jammerbugt.
- 2 wells are modelled as being just sufficient to meet the injection capacity.

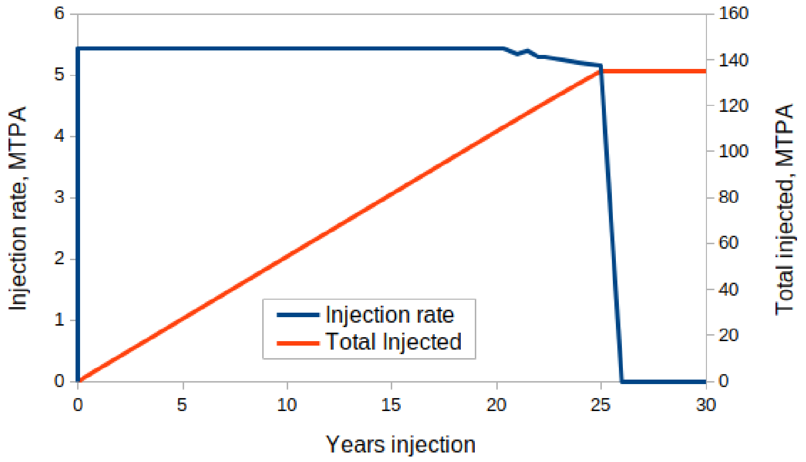
J-1



Top Gassum depth

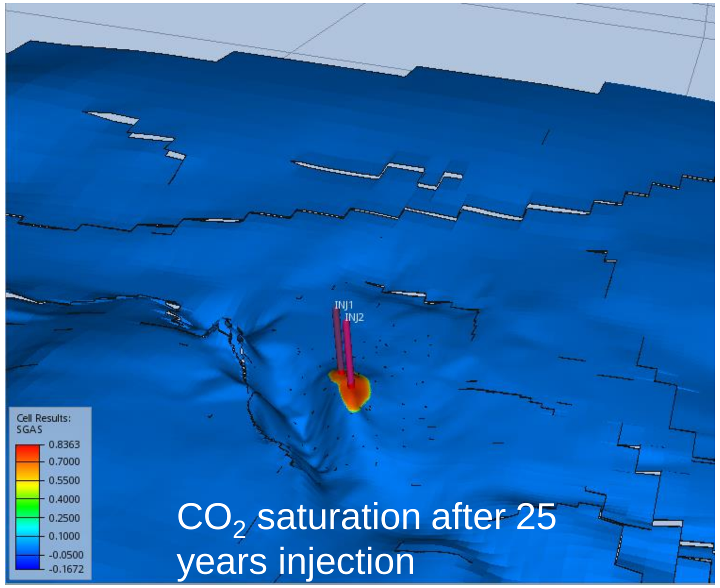




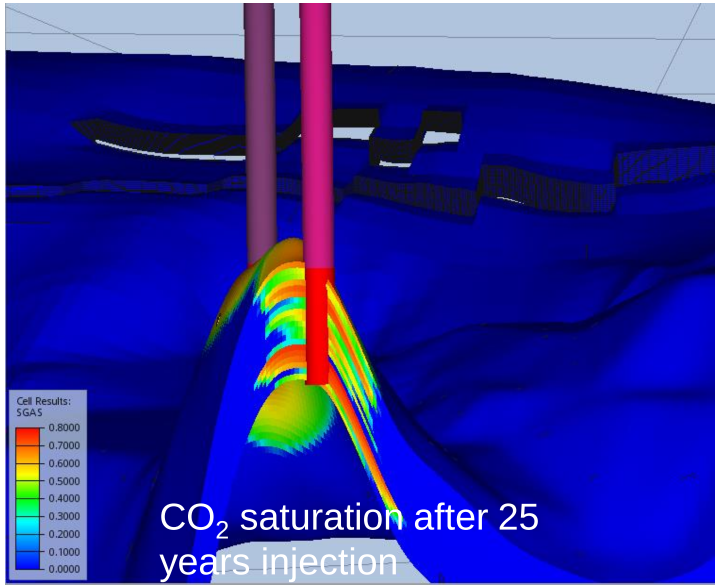


Lisa

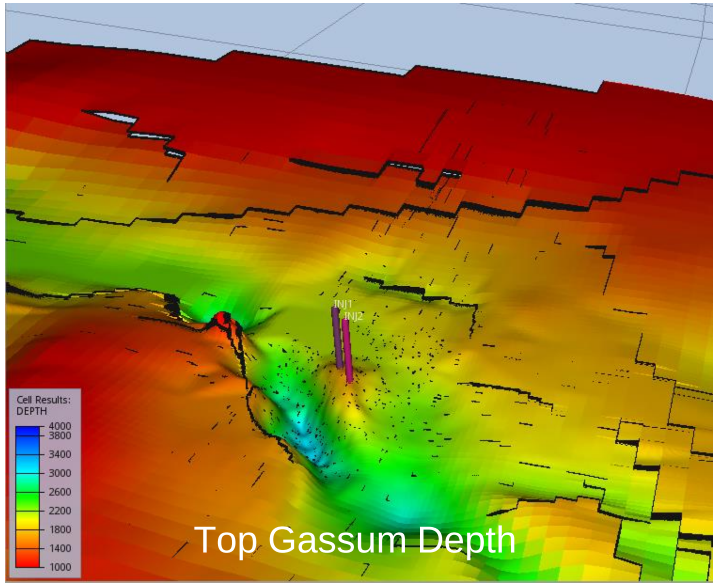
- The excess pressure map shows that the dissipation of injection pressure into the aquifer is largely to the west, with the fault acting as a barrier.
- The saturation plots indicate a relatively slow migration of the CO_2 from the injection point to the crest of the structure, with vertical barriers restricting flow. Nonetheless the injected CO_2 is modelled to remain in the structural closure.



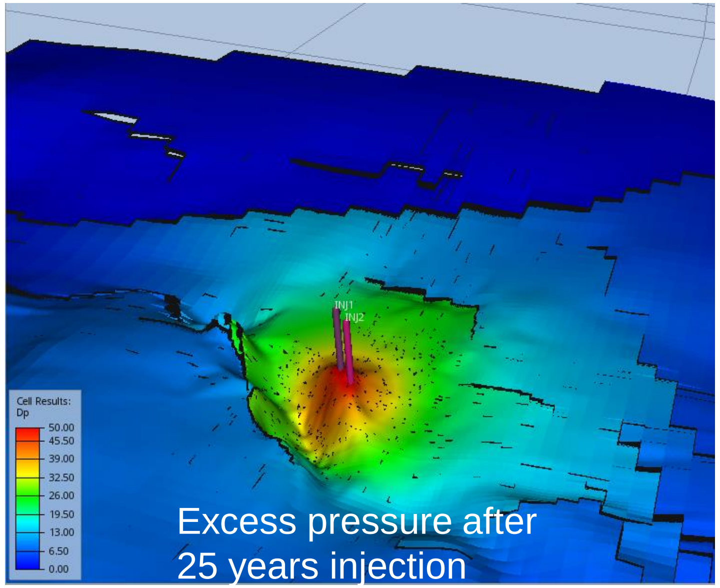
CO_2 saturation after 25 years injection



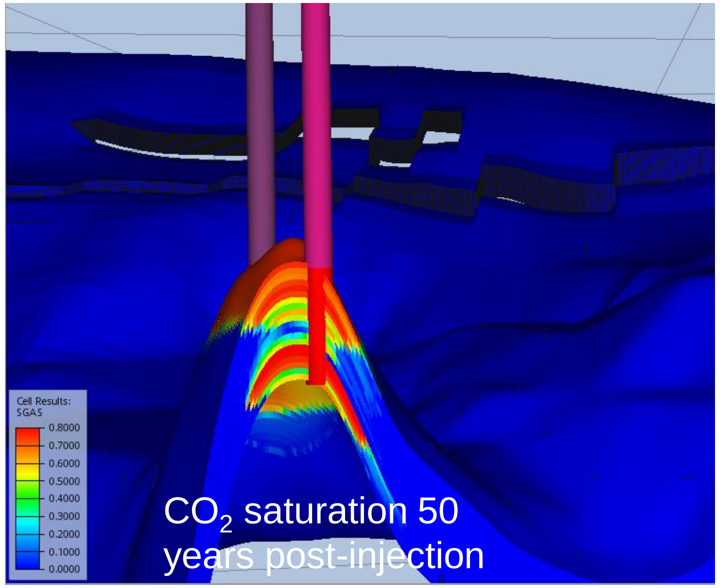
CO_2 saturation after 25 years injection



Top Gassum Depth



Excess pressure after 25 years injection

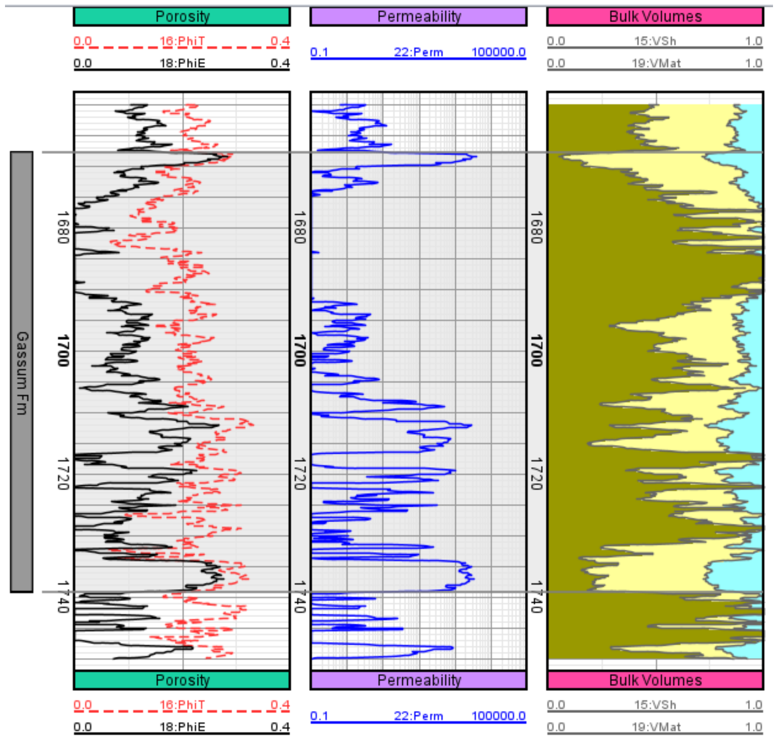


CO_2 saturation 50 years post-injection

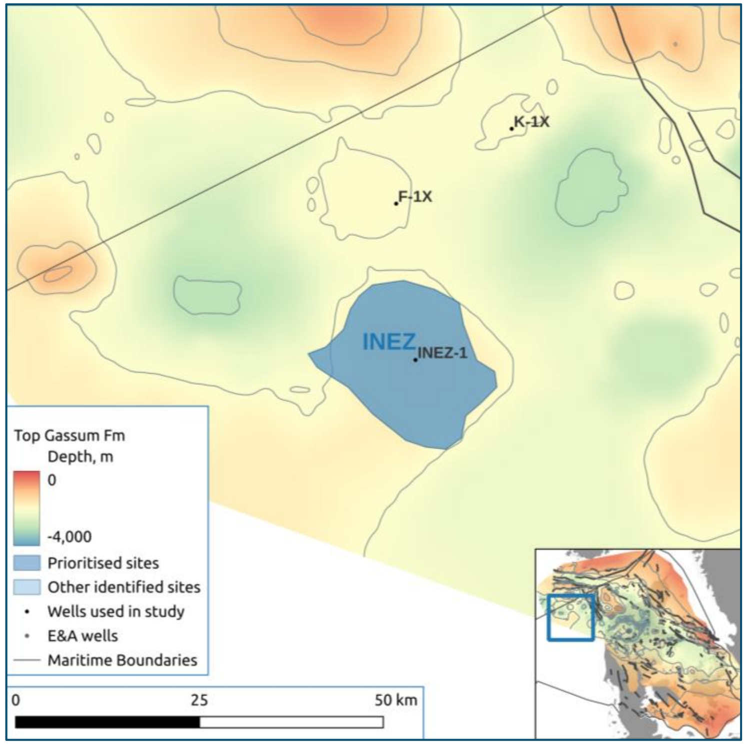
Inez

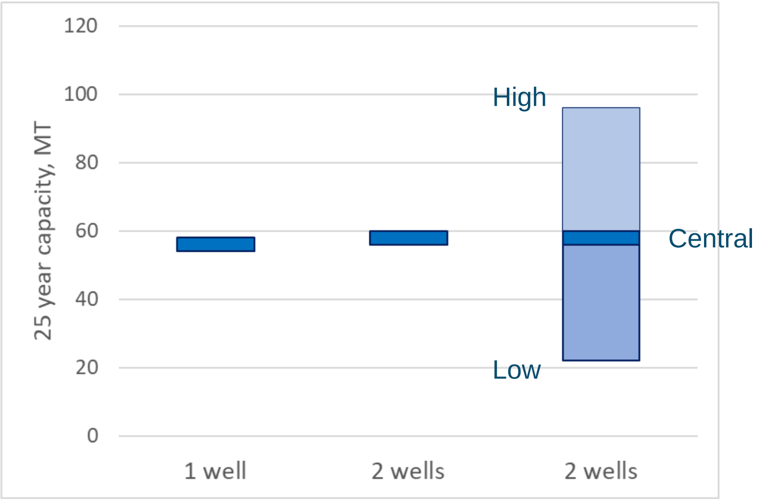
- The Inez structure consists of a broad, shallow anticline, well connected to the surrounding aquifer.
- The Inez-1 well, drilled on the structure, encountered 29 m of net sand with average porosity of 19% and a relatively high shale content, which is expected to reduce the permeability to a circa 10 - 300 mD range.
- Simulation shows that the capacity of the structure is limited by the relatively poor aquifer quality with initial rates of 2 – 2.5 Mtpa reducing to 1.7Mtpa after 25 years.
- 1 well is modelled as being sufficient to meet the injection capacity, but the base case assumes 2 wells for redundancy.

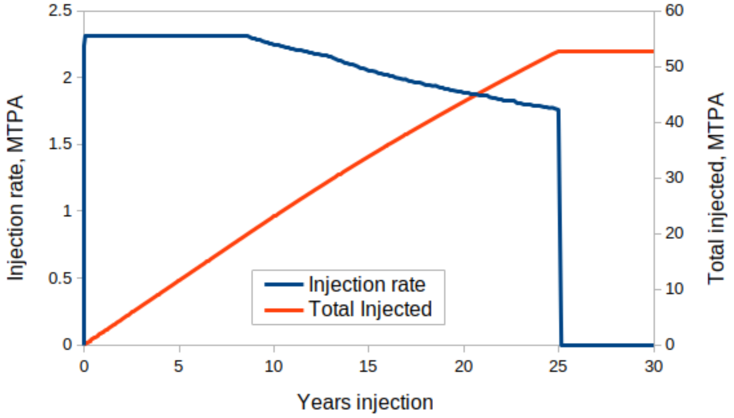
Inez-1



Top Gassum depth

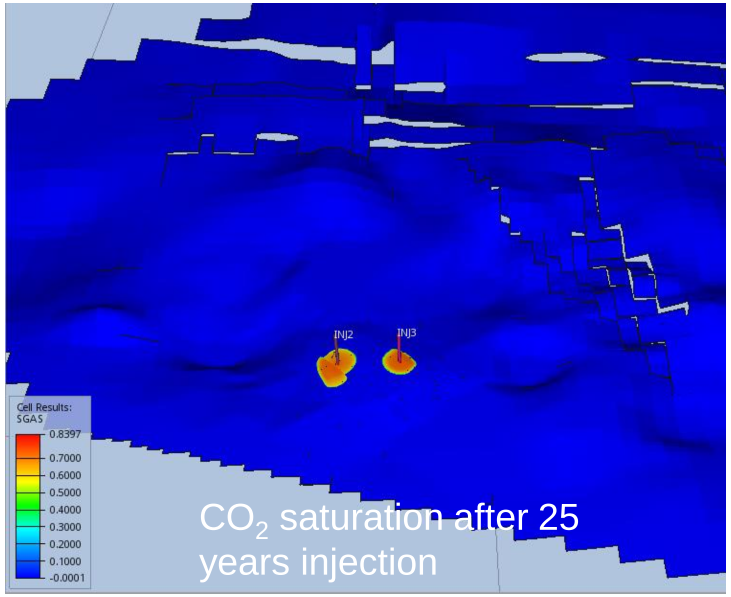




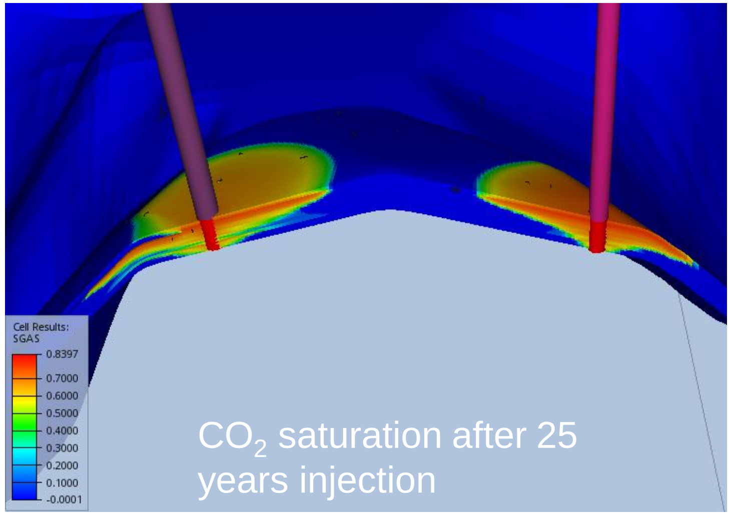


Inez

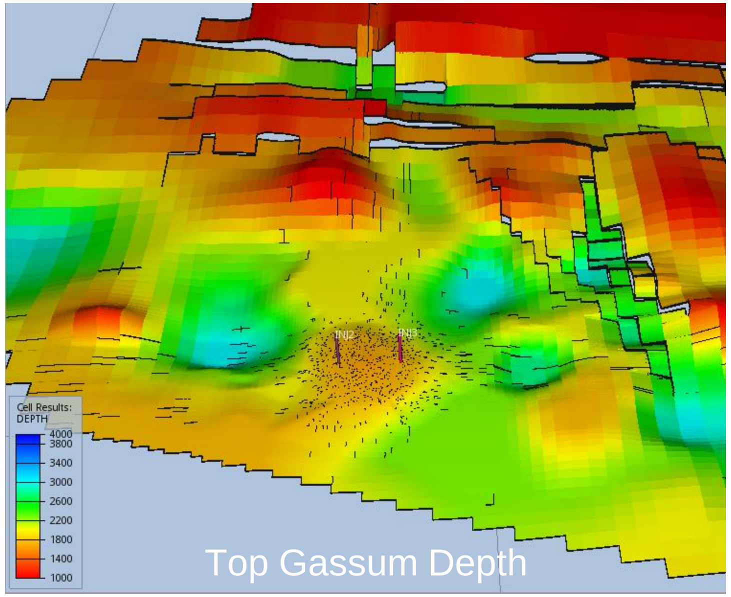
- The excess pressure map shows a dissipation of injection pressure into the aquifer in all directions but that faults to north and east limit brine movement and hence pressure dissipation into the wider Gassum Formation aquifer.
- The saturation plots show that the relatively uniform aquifer quality without major intra-formational barriers allows the formation of an inverted cone shaped plume, which is slow to relax given the relatively low permeabilities.



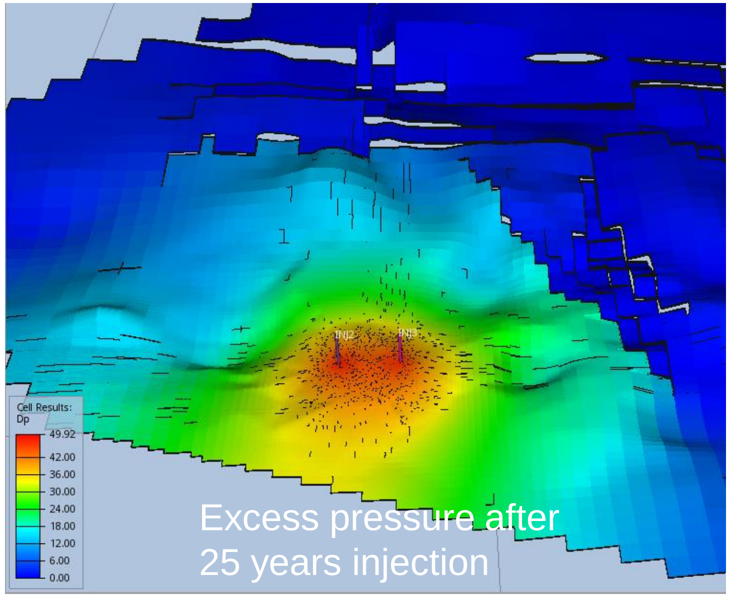
CO_2 saturation after 25 years injection



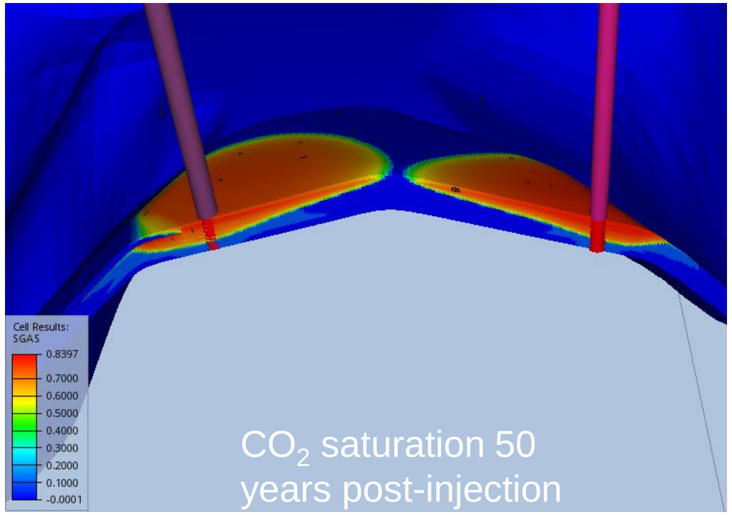
CO_2 saturation after 25 years injection



Top Gassum Depth



Excess pressure after 25 years injection

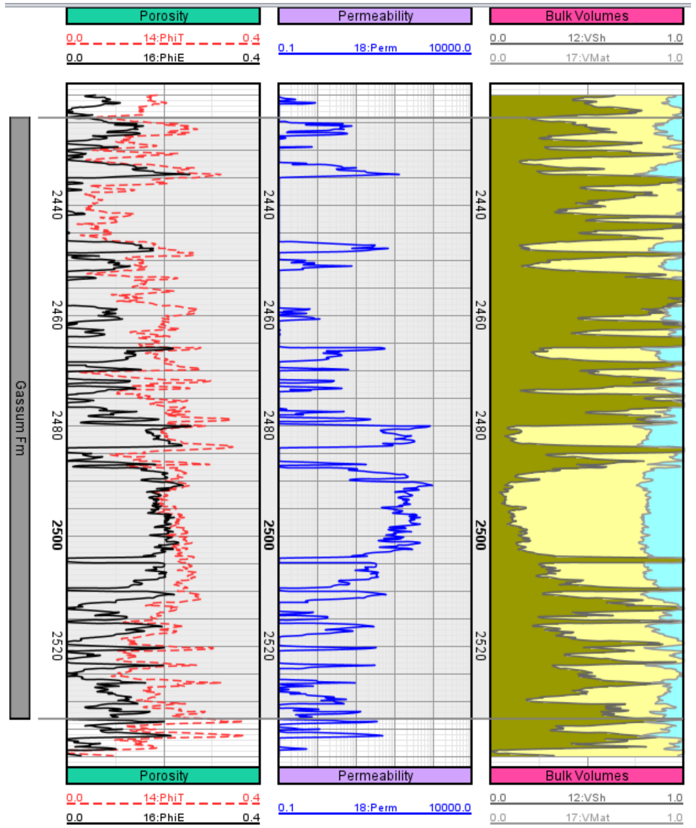


CO_2 saturation 50 years post-injection

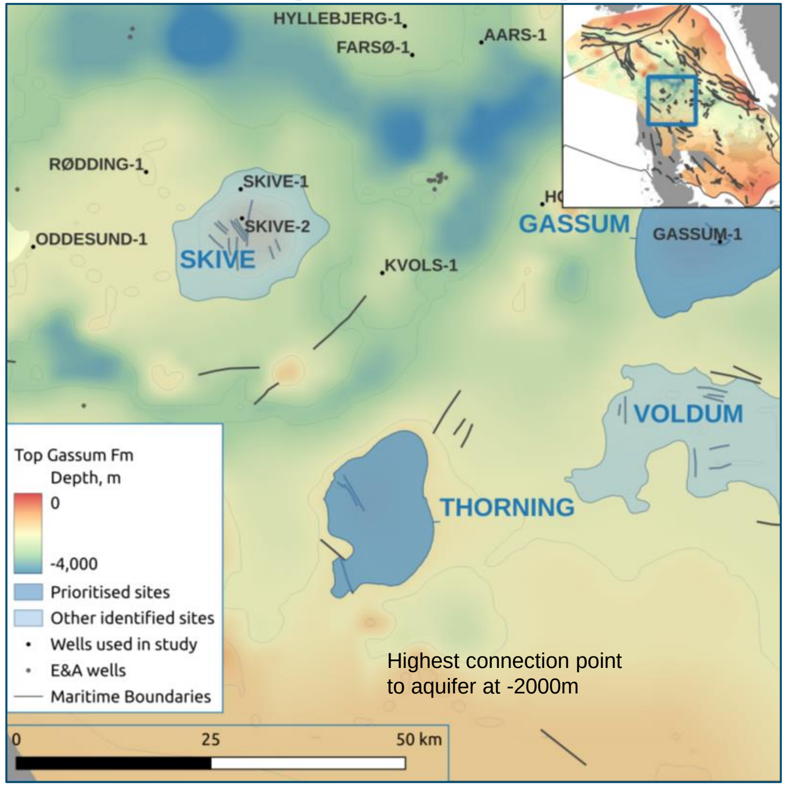
Thorning

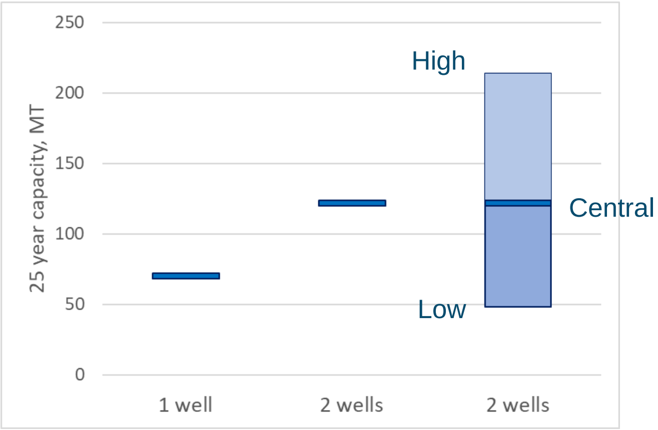
- The Thorning structure consists of a broad, relatively shallow anticline, connected to the regional aquifer to the south by shallow saddles, but bounded to the north by deep rim synclines.
- There are no wells in the immediate vicinity of the structure, but those within 50 km, such as Kvols-1, show a low net-to-gross system with 30 - 40m net sand and porosities in the region of 20%.
- Simulation shows that the capacity of the structure is limited by the aquifer quality which is expected to reduce northwards into the salt synclines. The base case maximum injection rates are simulated to be approximately 4 Mtpa, with 25-year injection capacity range of 50 - 200 Mt.
- These base case rates are possible with two injection wells.

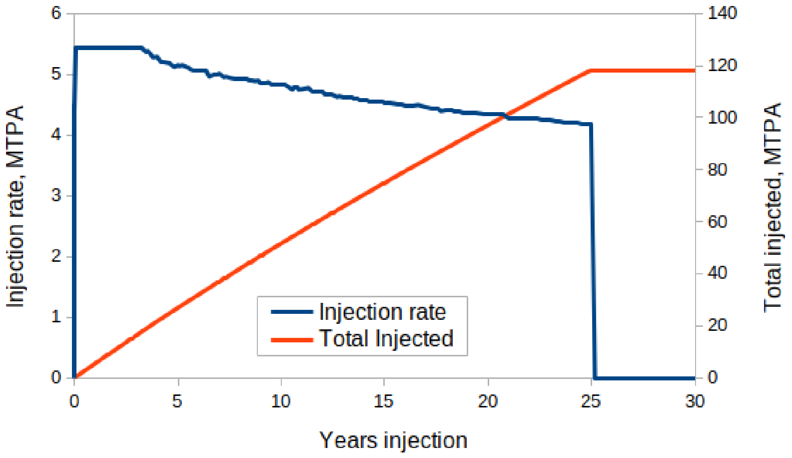
Kvols-1



Top Gassum depth

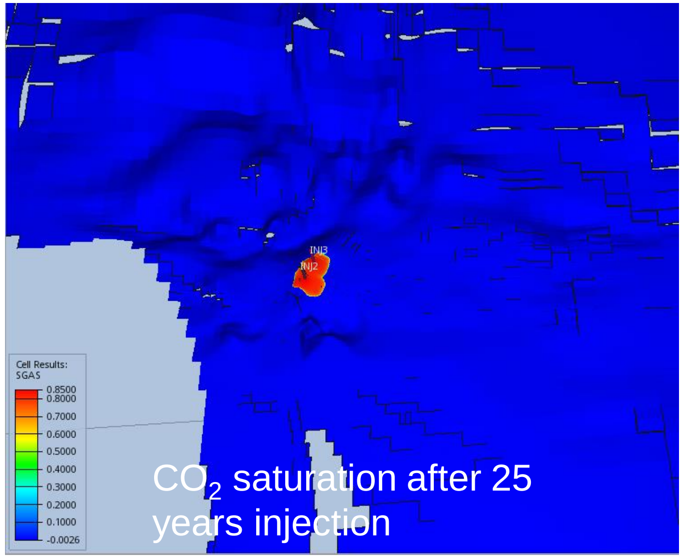


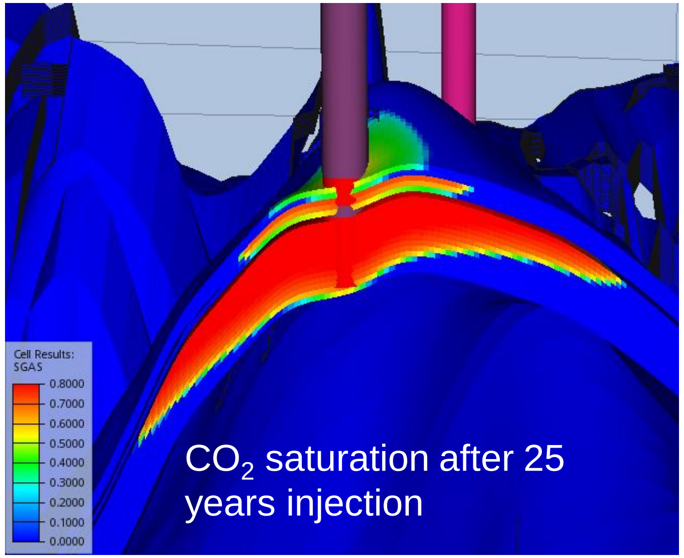


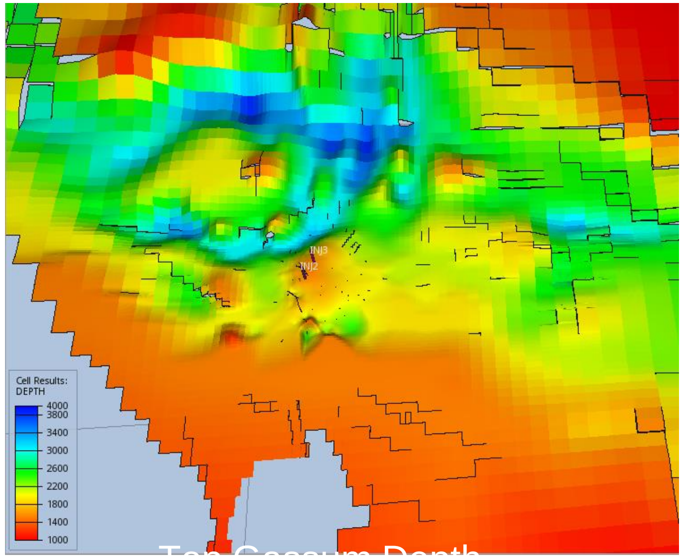


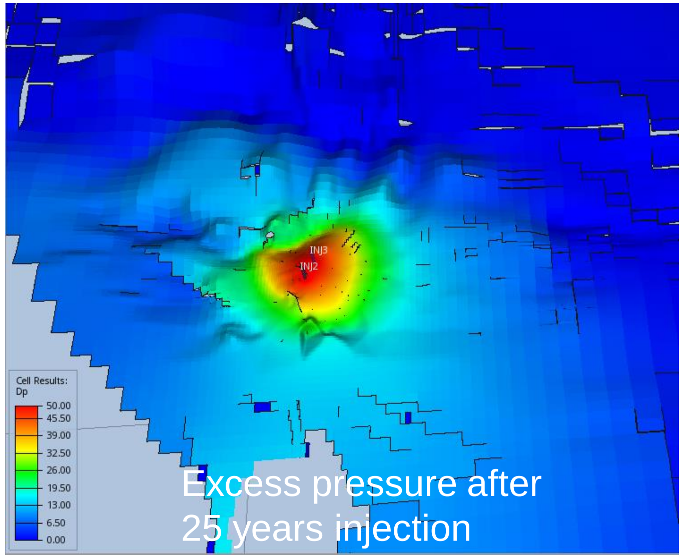
Thorning

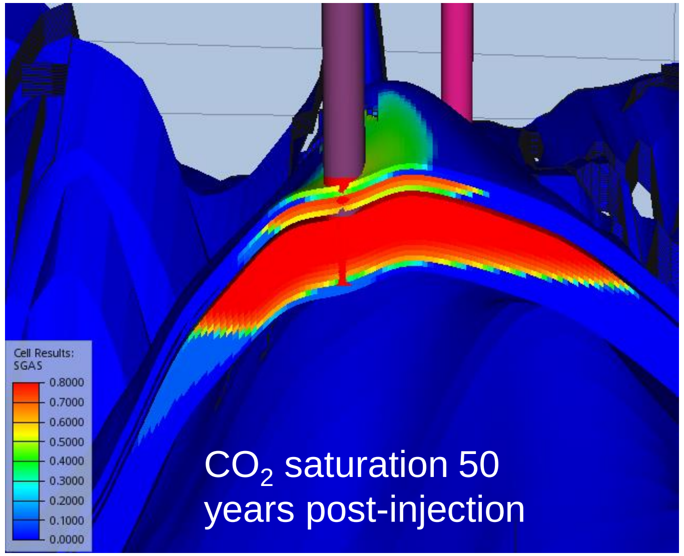
- The excess pressure map shows that the deep rim syncline system to the north limits pressure dissipation in this direction, with most dissipation taking place to the south-east.
- The saturation plots show that most of the CO_2 is injected into the better quality lower section, with shale layers in the upper section expected to act as vertical flow barriers, resulting in stacked columns after 50 years relaxation. Nonetheless the injected CO_2 is modelled to remain in the structural closure.





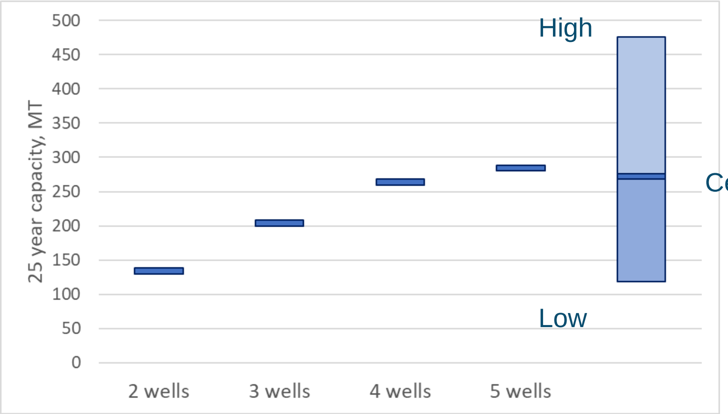




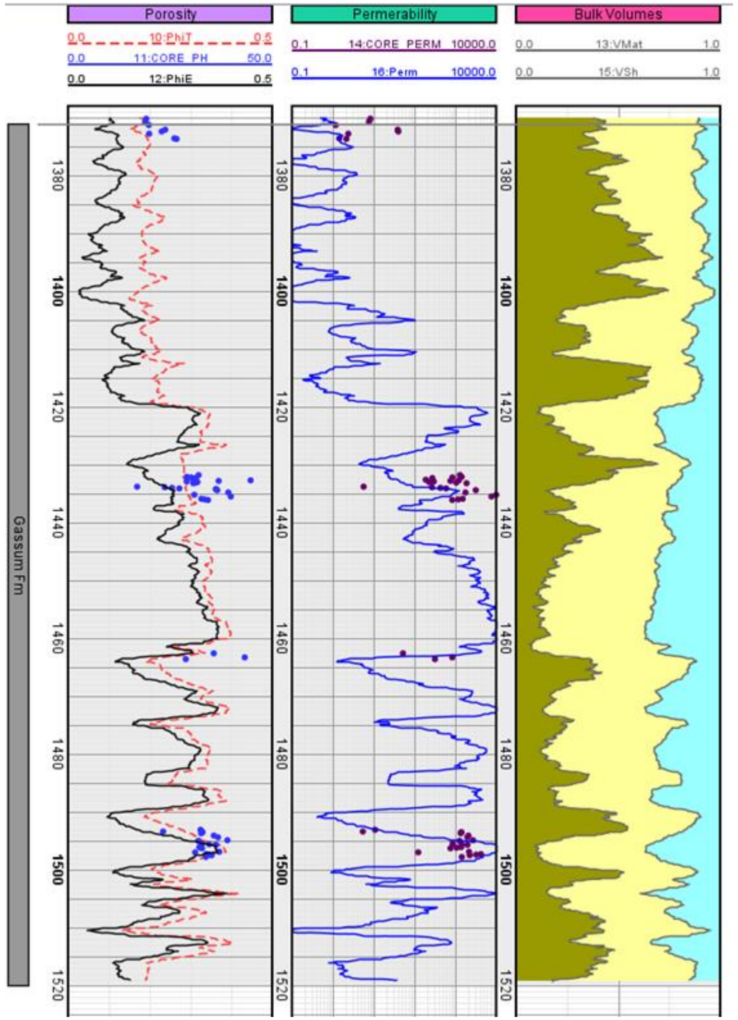


Jammerbugt

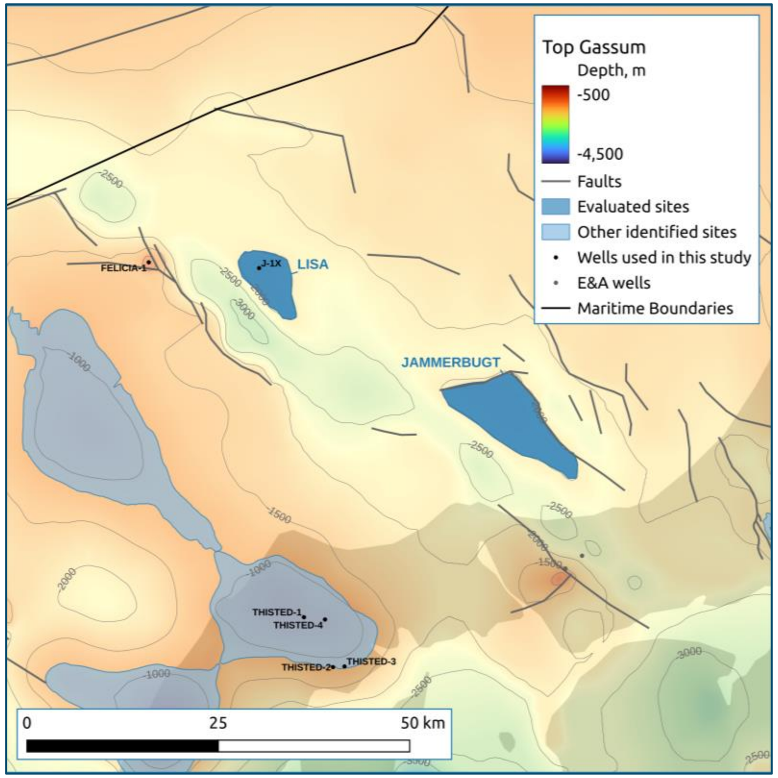
- The Jammerbugt structure is bounded to the east and north by large faults which fully offset the Gassum Fm. The structure dips relatively steeply to the west into a narrow graben.
- There are no wells in the immediate vicinity of the structure, but the Børgium-1 and Vedsted-1 wells to the east, albeit in more proximal locations for sediment input, have net sand of 80 -100 m and excellent quality.
- The simulation shows that despite the aquifer disconnection to west and north and an expected reduction in permeability in the graben to the west, long-term injection rates of 8 – 10 MTPA could be maintained, resulting in a modelled capacity of 250 MT over 25 years, which is insufficient to fully fill the trap.

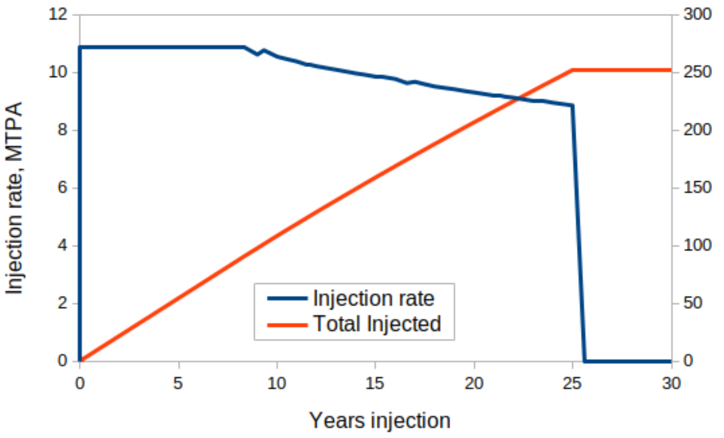


Børgium-1



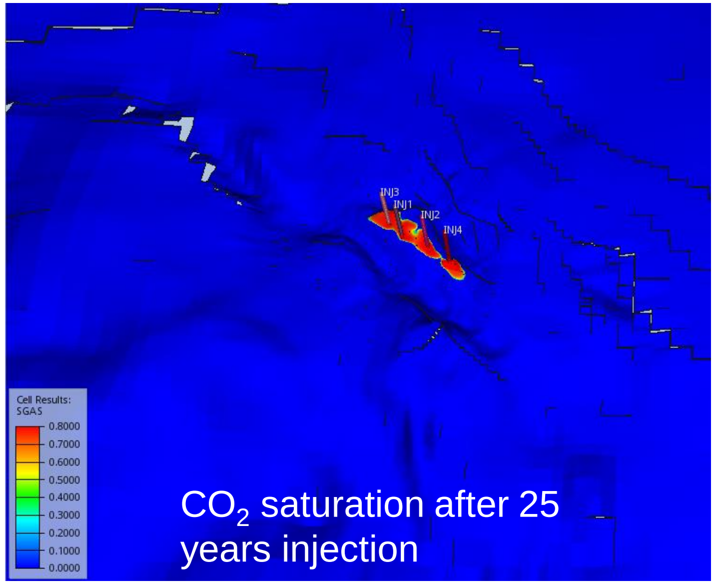
Top Gassum depth

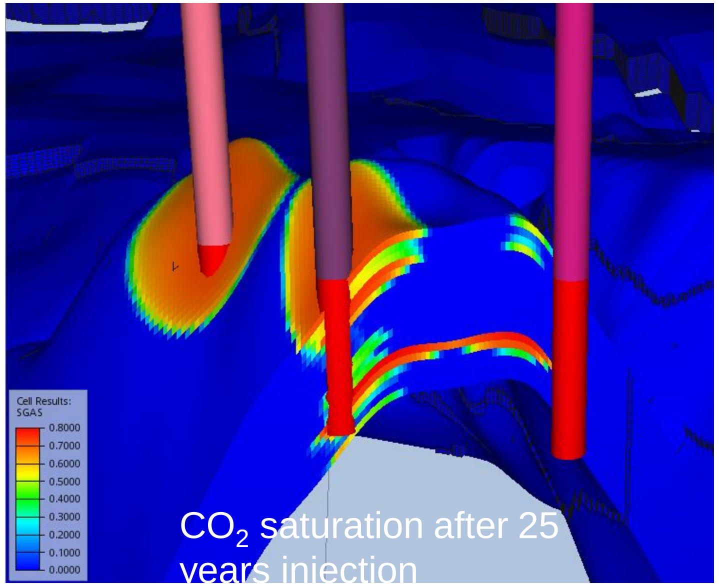


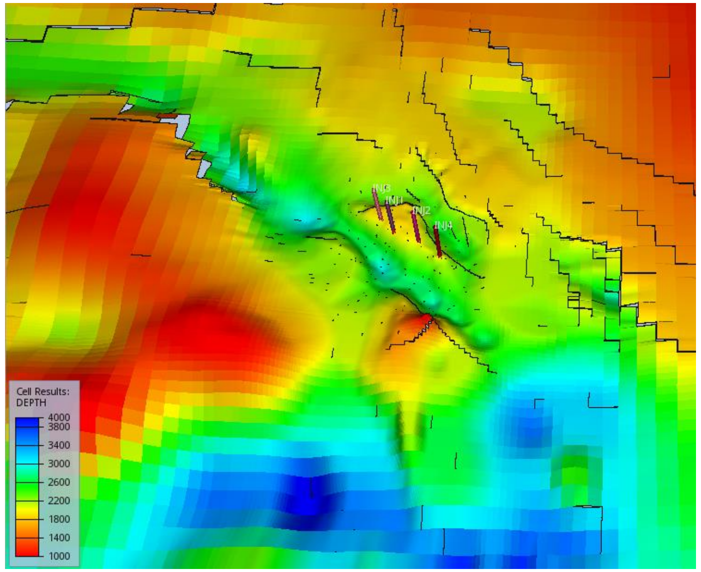


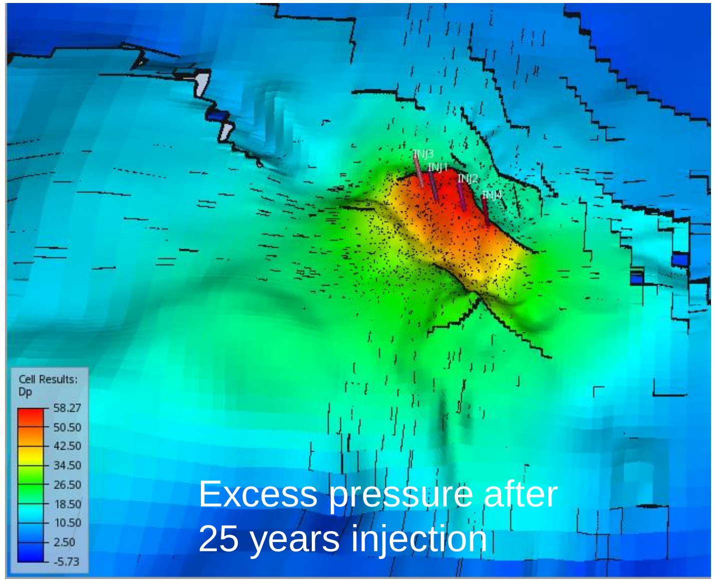
Jammerbugt

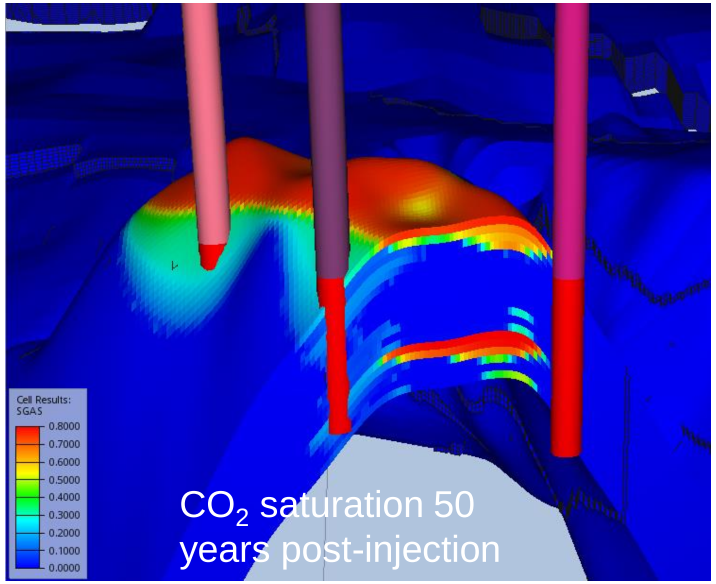
- The excess pressure map shows the effect of faults on brine movement which limits pressure dissipation to the north-west. Nonetheless, the structure is well connected to good quality aquifer to south and west despite some permeability degradation expected in the intervening low.
- There is significant vertical aquifer quality variation with injection concentrated in the highest permeability layers and internal shale layers within are modelled to act as vertical permeability barriers for a 50 year and possibly longer relaxation period.











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