Final Technical Report

of project 'Saline Aquifer CO_2 Storage' (SACS)

Work area 1: Geology

Task 1.6

The natural fluid flow in the storage reservoir

- *Basin modelling* -

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Introduction

The natural fluid flow in the storage reservoir contributes to the transport of free and dissolved CO_2. In the SACS phase 1 project it was decided to try to quantify the direction and the flow rate of the highly saline formation water in the Utsira Sand using pressure data. However, the SACS Phase 1 work revealed that only a limited amount of pressure data are available from the Utsira Formation and that the existing data points are uncertain. Therefore, in the SACS Phase 2 project, an alternative approach was introduced and a basin modelling study was set up to estimate the velocity of the natural fluid flow and to evaluate the ranges of natural flow velocities in the Utsira Sand. Since only a few hard data are available, a rather simple model was established, namely a 2-D model along a geological profile or cross-section.

Basin modelling and general model considerations

The natural fluid flow is simulated using a commercial basin modelling programme called 'PetroMod', which describes and quantifies all important basin processes as functions of time. The generation of overpressure and the fluid flow are simulated, and an essential output parameter is the fluid flow velocity, which is related to the compaction of the sediments. The flow is determined primarily by the permeability and the pressure distribution. The entire sedimentary section down to an impermeable barrier (Zechstein salt or basement) is included in the modelling.

Location of the cross-section

The cross-section used in the basin modelling study is placed in an up-dip position relative to the depth structures of the top of the Utsira sand (Figure 1) in a direction that we believe would be the preferred migration direction of the CO_2. The direction of the profile is SSE-NNW; it passes through the Sleipner area and northwards it runs into the UK sector. The length of the cross-section is about 200 km and it encompasses the following Norwegian wells: 7/1-1, 15/12-3, 15/9-13, 15/9-4, 15/9-3, 15/5-3, 15/3-1S, and in addition the four UK wells: 9/23-1, 9/17-1A, 9/13-1 and 9/12-3.

Input data

A number of geophysical and geological data along with information on the reservoir properties are needed in the basin modelling work. The various input data are listed below and the data come from seismic data, raw logs, completions logs, NPD papers, UK offshore regional reports (including Johnson et. al., 1993) and other published material.

1. ***Seismic data.*** The cross-section used in the basin modelling work is situated between the two seismic lines CNST82-18 and -19 and the seismic interpretation of those lines is utilised directly in constructing the 2D model. The seismic interpretation provides information on the structural elements and on the location of geological boundaries outside well control.

2. ***Lithology***. The lithology is determined from logs acquired in the wells along the profile, primarily the gamma-ray and the sonic logs. Furthermore, in the Norwegian sector, the log information is supplemented by information on lithology available from NPD completion logs. No UK completion logs were, however, available for the modelling work. Subsequently, the lithology interpreted in the wells was extended to the entire cross-section using a standard interpolation technique.

3. ***Reservoir properties.*** Porosity and permeability data are needed, both for the Utsira sand and for the formations above and below. The porosity of the Utsira Sand as interpreted from well log data is 35 - 40% and core data from well 15/9-A23 in the Sleipner area indicate that the horizontal permeability is about 10 Darcy in the Utsira Sand. In the formations above and below the Utsira Sand, preferentially standard porosity and permeability values were used, i.e. values defined by 'PetroMod' as function of lithology, geological age and depth.

4. ***Chronostatigraphic units***. The fluid flow is related directly to the degree of compaction of the sediments and therefore a robust chronostratigraphic subdivision of the sedimentary section is of key importance. Eidvin et. al. (1999) presented a revised Cenozoic stratigraphy in the Sleipner area, primarily based on biostratigraphic data from the Norwegian 15/12-3 well. According to their work, the Quaternary-Tertiary boundary corresponds to the Top Pliocene Prograding Unit as defined from the seismic interpretation. Their biostratigraphic work also indicates that the Utsira Sand is partly of late Miocene age and partly of early Pliocene age. Finally, top Oligocene is found some 100 metres below Mid Miocene Onlap Surface as also defined from the seismic interpretation. It is noteworthy that both the thickness and the modelled lithologies of the Quaternary sediments affect fluid flow velocities in the underlying Utsira Sand.

Geometry of the base case and basic parameters

The geosection which forms the basis for the 2D basin model is presented in Figures 2A and 2B. The basin modelling programme simulates basin processes as a function of time and it is fundamental therefore to define the basin development in terms of chronostratigraphic units: Quaternary, Pliocene, Miocene, Oligocene, Eocene, Palaeocene etc. down to top Zechstein or Pre-Permian, the latter two defining the no-flow boundary at the base of the model. Each series has been further subdivided into a number of events, and in total the model comprises 50 events (model layers). The events are characterised by the same time duration through the entire model. However, all other parameters for the various events (e.g. porosity and permeability) are allowed to vary laterally along the section. The geometry and lithology of the "base case" (the most likely) is shown in Figure 3.

The set-up of the base case, and the reservoir properties used for the various formations together with other premises of key importance are described below.

1. ***Utsira Sand***: The Utsira Sand pinches out towards the Southeast where it passes into a shaly succession between the Norwegian wells 7/1-1 and 15/12-3 as also evidenced by the seismic interpretation. Towards the Northwest the Utsira Sand pinches out approximately where the median line between the Norwegian and the UK sector is located. The porosity of the Utsira Sand varies from 35% to 40% depending on the structural depth of the sand body, and in the Sleipner injection area, a horizontal permeability of approximately 10 Darcy was used. This description of the reservoir porosities are in line with information from logs and core data. The permeability and porosity distribution used in the base case can be seen in Figure 4. A number of thin shale layers are found within the Utsira Sand and in order to reflect such a geometry in the model, the Utsira Sand unit was subdivided into 3 major sandy units separated by very thin shale layers, which could act as permeability barriers. Furthermore, a shaly unit at the base of the Utsira Sand has been included in the model to evaluate the hydraulic connection between the Utsira Sand and the sandy wedge to the north (Figure 5).

2. ***Shale Drape***: Above the Utsira Sand a pronounced shale drape, 50 – 100 m thick, can be interpreted from the seismic sections and well logs. The Utsira Sand pinches out in a south-easterly direction and shale drape becomes even thicker in the area south of the limit of the Utsira Sand. Northwards both the shale drape and the Utsira Sand seem to pinch out at the same point, i.e. approximately where the median line between the Norwegian and the UK sector is located. This interpretation of the geological layering is related to seismic interpretation, but as the seismic data are rather ambiguous in this area, it may turn out that the shale drape either

pinches out before or after the Utsira Sand. Both cases have been evaluated in separate model runs. The permeability of the shale drape is extremely low due to a very high clay content and consequently, a horizontal permeability of approximately 0.0001 milliDarcy was used in the modelling work.

3. ***Sandy wedge***: Both the log and seismic data from the UK sector suggest that the Utsira Sand onlaps a sandy wedge in a similar way as suggested by Chadwick et. al. (2000) in their Cairns conference paper. Basically it has been assumed that such a sandy wedge exists. The structural position of the sandy wedge is rather shallow (200 - 500 m) and consequently a fairly high horizontal permeability (10 - 100 Darcy) was predicted. The assumed porosity of the wedge is about 30 - 35%. The sandy wedge is not overlain by a shale layer similar to the shale drape described above, but apparently it is overlain by a sandy siltstone. Obviously such a high permeable sand body affects both pressure distribution and flow velocities in the Utsira Sand, and to evaluate the influence of the wedge, the model was run with different hydraulic parameters for the layer connecting the Utsira sand and the sandy wedge.

Boundary conditions

The entire sedimentary section from Quaternary to Zechstein/Pre-Permian is included in the modelling. The top of the Zechstein salt, or alternatively the top of the Pre-Permian sediments, are considered to form no-flow boundaries at the base of the model. The Norwegian well 7/1-1 is located close to the deepest and most shaly part of the basin and the model is closed to flow therefore at the southern end of the profile, i.e. immediately south of well 7/1-1. On the contrary the model is open to flow towards the north because the sediments are much more sandy at the northern end of the profile. The introduction of these boundary conditions means that the present pressure picture is reasonably simulated in the model: Overpressure cells are generated in the Tertiary shales, the Jurassic and Triassic formations become overpressured, but no overpressure is developed in the Chalk section. However, if also the northern boundary is closed to flow, the modelled overpressures become too high compared to observed pressures, especially in the chalk section (Figures 6 and 7).

Modelling results

A number of simulations of the natural fluid flow velocities have been carried out using the boundary conditions, modelling concepts and the geological framework described above. In all cases the 2D model is closed to flow at the southernmost part and open to flow at northernmost part of the profile. Similarly, the model is closed to flow at the base of the profile.

Case no. 1 (base case)

The base case, or the most likely case, is based on the following geological assumptions:

- The shale drape pinch out at the same location as the Utsira Sand.
- Thin, but not continuos shale layers exist in the Utsira Sand.
- The Utsira Sand is in hydraulic contact with the sandy wedge (Hutton Sand?).
- To some extent the sandy wedge is in hydraulic contact with the surface sediments beneath the sea bottom; the sediments in between consist of a ***mixture of sand and shale with moderate hydraulic properties***.

The geometry and lithology around the contact between the Utsira sand and the sandy wedge can be seen in Figure 8. The calculated flow velocities in the Utsira Sand in the injection area are between 2 and 4 metres per year . Towards the NNW, where the Utsira Sand is thinner and more shallow, flow velocities increase. This is due to the geometry of the model and the fact that both porosity and permeability normally increase at shallower depths. The calculated flow velocities in case no. 1 are shown in Figure 9.

Case no. 2

Case no. 2 is based on the following geological assumptions:

- The shale drape pinch out at the same location as the Utsira Sand.
- Thin, but not continuos shale layers exist in the Utsira Sand.
- The Utsira Sand is in hydraulic contact with the sandy wedge (Hutton Sand?).
- The sandy wedge is in hydraulic contact with the surface sediments beneath the sea bottom; the sediments in between consist ***mainly of silty sands***, which have ***better hydraulic properties*** than those used in case no.1

The geometry and lithology around the contact between the Utsira sand and the sandy wedge can be seen in Figure 10. The calculated flow velocities in the Utsira Sand in the injection area are between 2 and 4 m/year as also modelled above. In case no. 2 the improved hydraulic properties of the sediments do not significantly influence the flow velocities in the injection area (Figure 11).

Case no. 3

Case no. 3 is based on the following geological assumptions:

- The ***shale drape pinch out after (i.e. NNW of) the Utsira Sand***.
- Thin, but not continuos shale layers exist in the Utsira Sand.
- The Utsira Sand is ***not*** in hydraulic contact with the sandy wedge (Hutton Sand?).
- ***The basal shale layer separates the sandy wedge from the Utsira Sand.***

The geometry and lithology around the contact between the Utsira sand and the sandy wedge can be seen in Figure 12. Again the modelled flow velocities in the Utsira Sand in the injection area are between 2 and 4 m/year, indicating that the changes made around the shallower part of the Utsira Sand have almost no influence on the flow velocities in the injection area (Figure 13).

Case no. 4

Case no. 4 is based on the following geological assumptions:

- The drape pinch out at the same location as the Utsira Sand.
- Thin, but not continuos ***high permeable sand stringers*** exist in the Utsira Sand.
- The Utsira Sand is in hydraulic contact with the sandy wedge (Hutton Sand?).
- The sandy wedge is in hydraulic contact with the surface sediments beneath the sea bottom.

The geometry and lithology around the contact between the Utsira sand and the sandy wedge can be seen in Figure 14. Again the calculated flow velocities in the Utsira Sand in the injection area are between 2 and 4 m/year. The introduction of thin sand stringers with much higher permeability than the Utsira Sand focuses the flow into these stringers and consequently very high flow velocities can be reached, but the average flow velocity in the Utsira Sand in the injection area is still not significantly changed (Figures 15 - 16).

Conclusion

The 2D basin modelling study indicate that the natural fluid flow in the storage reservoir is limited. In all 4 model scenarios described above, the simulated flow velocities are in the range 2 - 4 m/year in the injection area, but increase up-dip in excess of 10 m/year at the NNW end of the model (i.e. towards the UK sector). This velocity increase is due to the structural configuration of the Utsira Sand, the structurally higher position of the sand towards NNW leads to a higher permeability, and the up-dip pinch-out of the Utsira sand results in narrowing of the hydraulic system accompanied by increasing flow velocities. In the 4 scenarios, the hydraulic properties of the Utsira Sand are kept unchanged, whereas the hydraulic properties of the adjacent formations have been partly changed outside the injection area. The low sensitivity of the modelled flow velocities to changes in the hydraulic properties is presumably due to the extremely high hydraulic conductivity of the Utsira Sand.

References

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Eidvin, T., Riss, F. & Rundberg, Y., 1999: Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields). Norsk Geologisk Tidsskrift (Norwegian Journal of Geology), Vol. 79, pp. 97-128.

Johnson, H., Richards, P.C., Long, D. & Graham, C.C., 1993: United Kingdom offshore regional report: the geology of the northern North Sea. British Geological Survey (BGS).

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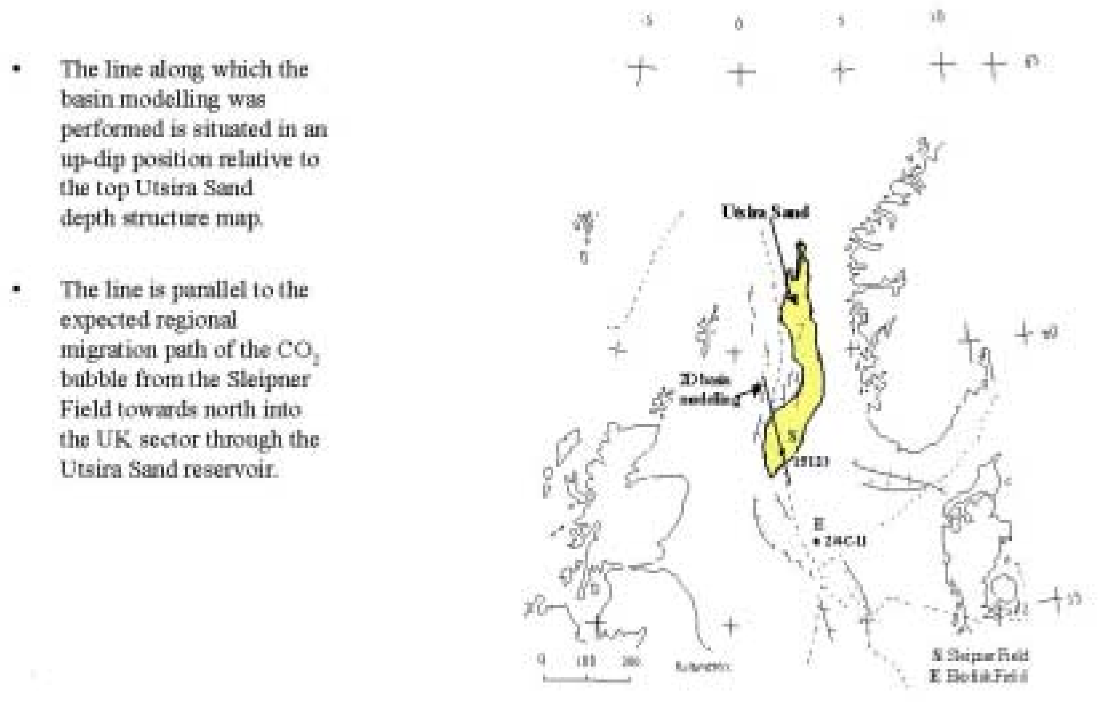


Figure 1. Location of the 2-D basin model section and the extent of the Utsira Sand.

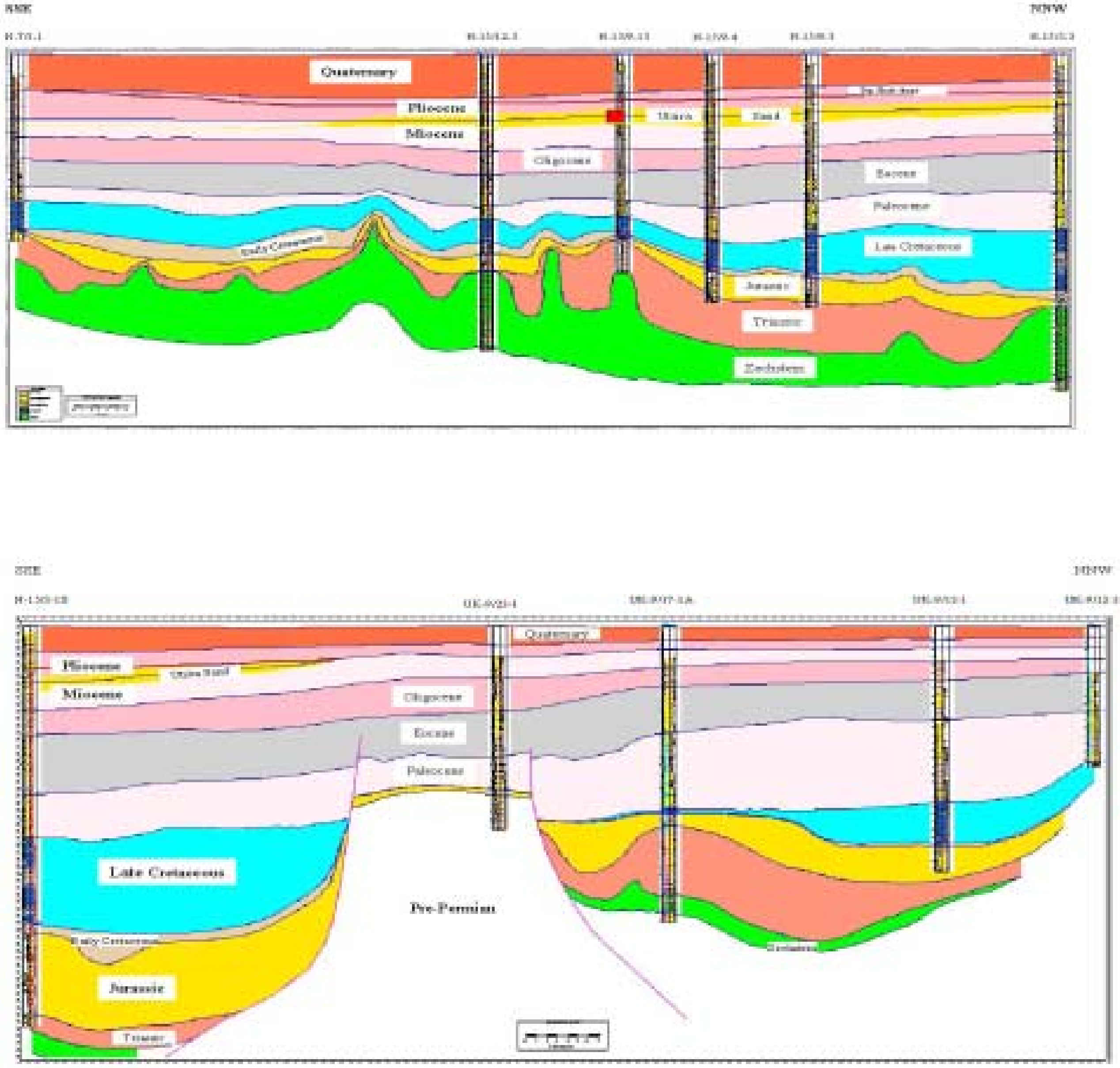


Figure 2. Outline of the 2D basin model. Upper: Northern part close to seismic line CNST82-18, Lower: Southern part close to seismic line CNST82-19. Chronostratigraphic subdivision, well locations and the approximate extent of the Utsira Sand are shown. The approximate location of the injection point is marked by a square.

Figure 3. Input section for the 2D basin modelling. Geological layering (events) and lithology are shown. The approximate extent of the Utsira sand is indicated with yellow and the injection area is marked with a red dot. Depth scale in metres; annotation for 'distance on section' is shown at the top of the profile (metres). The length of the profile is about 218 km.

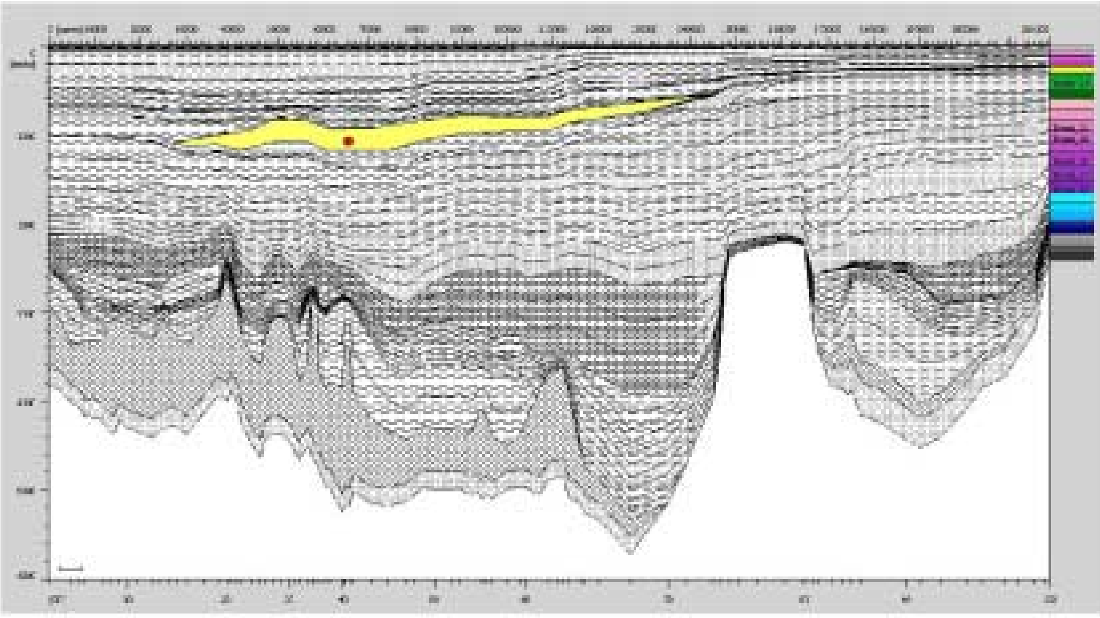


Figure 4. (A) Porosity of the Utsira Sand and adjacent formations (%)
(B) Permeability of the Utsira Sand and adjacent formations (logarithmic scale, log(mD))

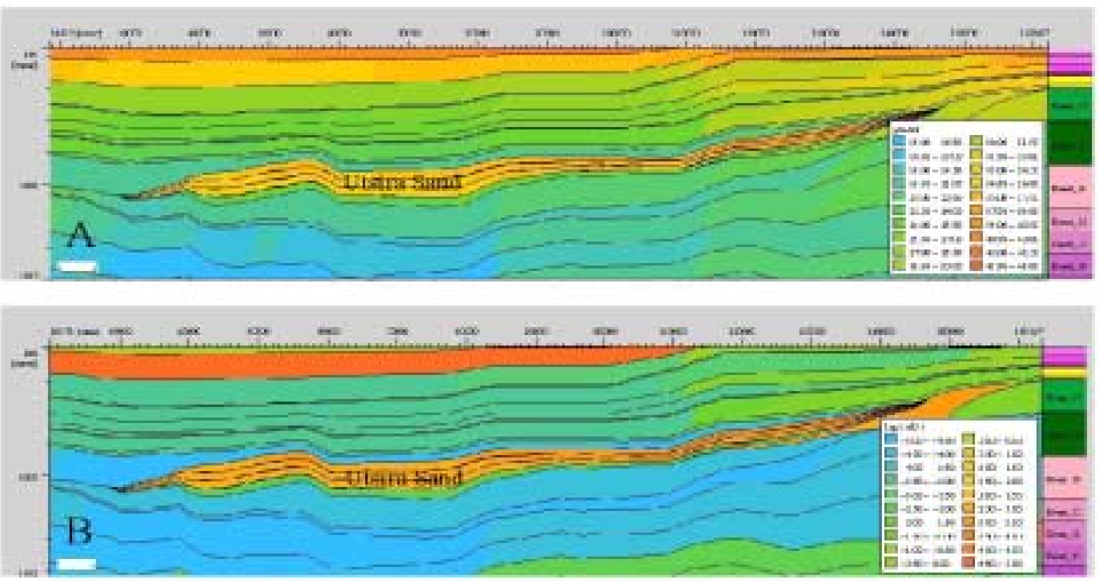


Figure 5. Utsira sand with thin layers that can act as flow barriers (shale) or high permeable layers (Sand). The shale layer at the base of the Utsira Sand is used to govern the hydraulic communication between the Utsira Sand and the sandy wedge below.

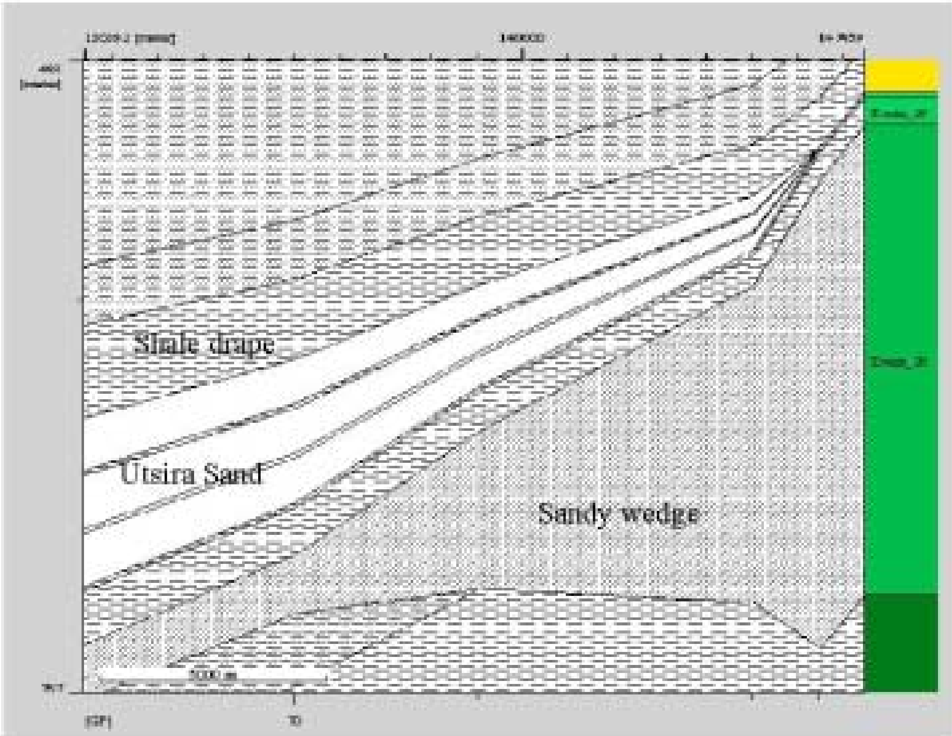


Figure 6. Excess pressure calculated with the following boundary conditions: model closed to flow to south (left) and open to flow to north (right). Excess pressure cells are generated in the Jurassic and Tertiary sections, but not in the chalk, which agrees well with observations.

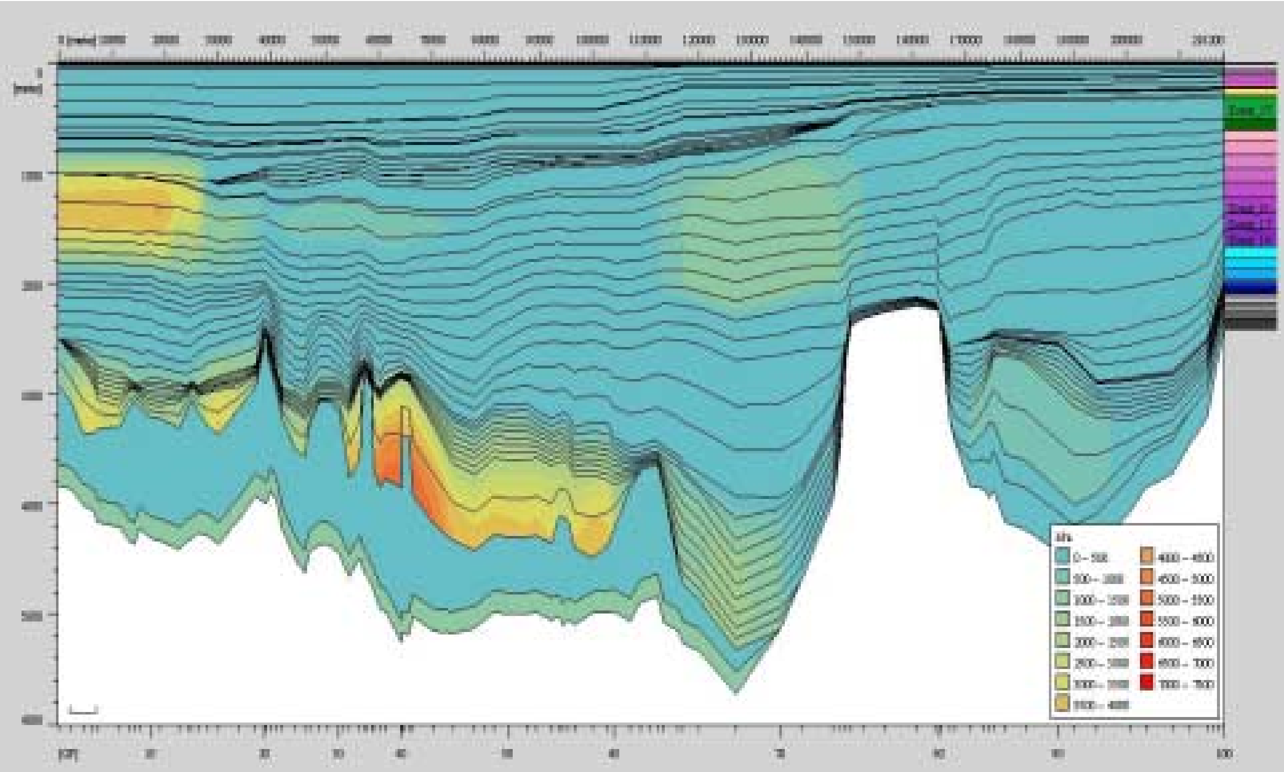


Figure 7. Excess pressure calculated with closed boundaries at both ends of the profile. Over-pressure is generated in almost the entire section, a situation which does not match observations.

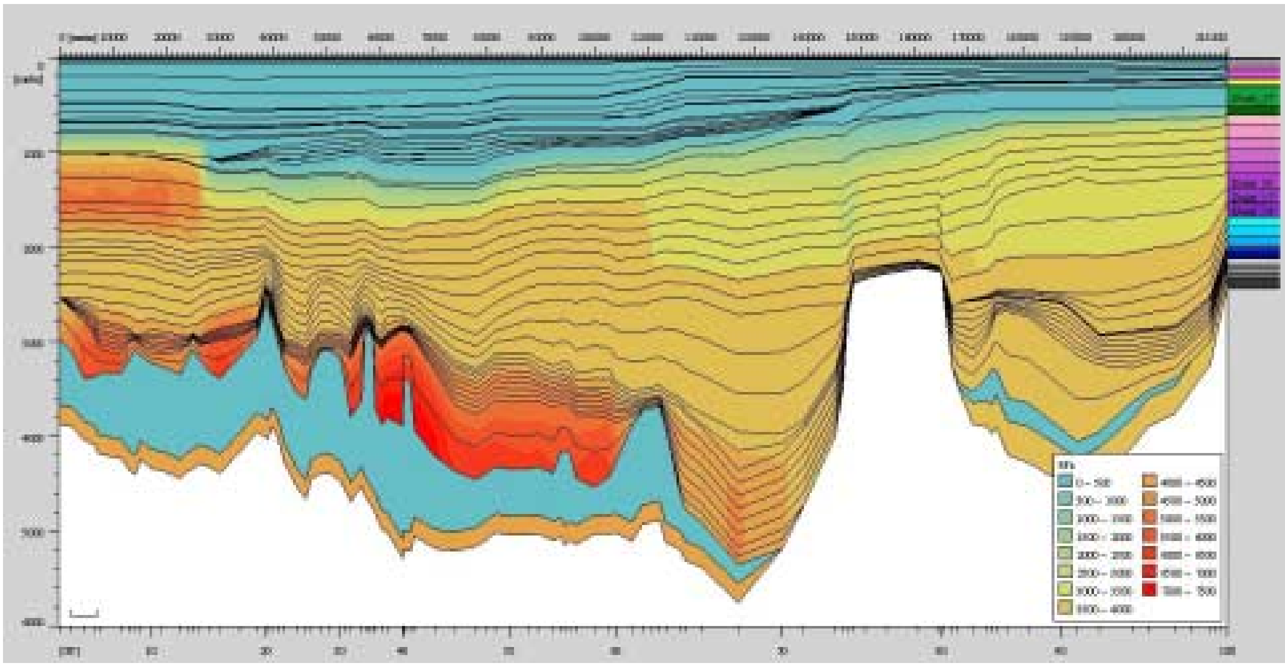


Figure 8. The lithology and geometry around the pinch out of the Utsira Sand in case no. 1.

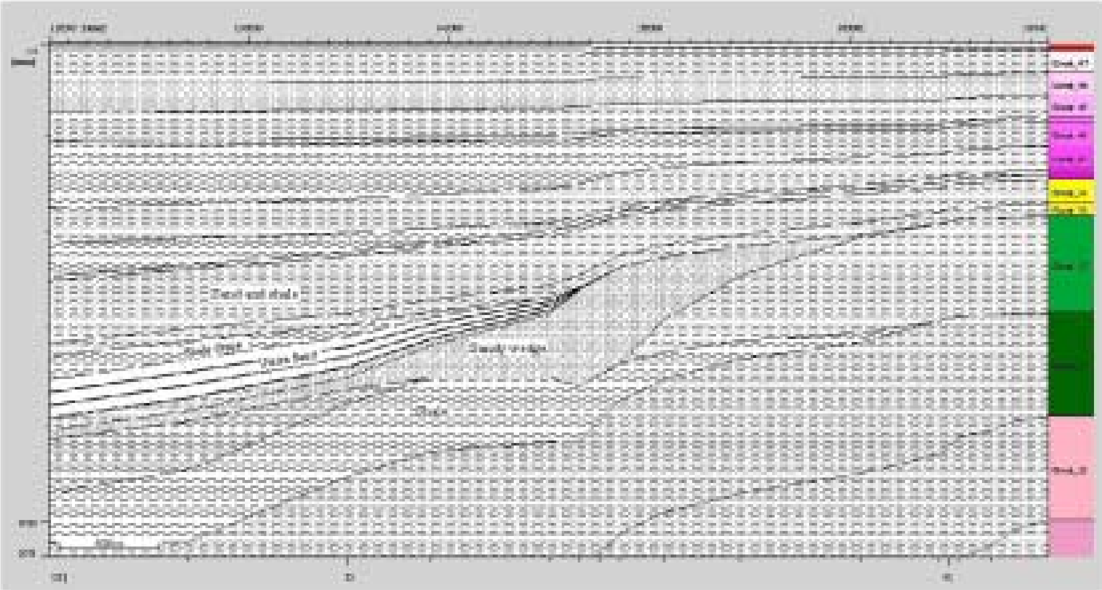


Figure 9 Calculated flow velocities in the Utsira Sand for case 1 (Base case). Flow velocities between 2 and 4 m/year are found in the injection area (red dot).

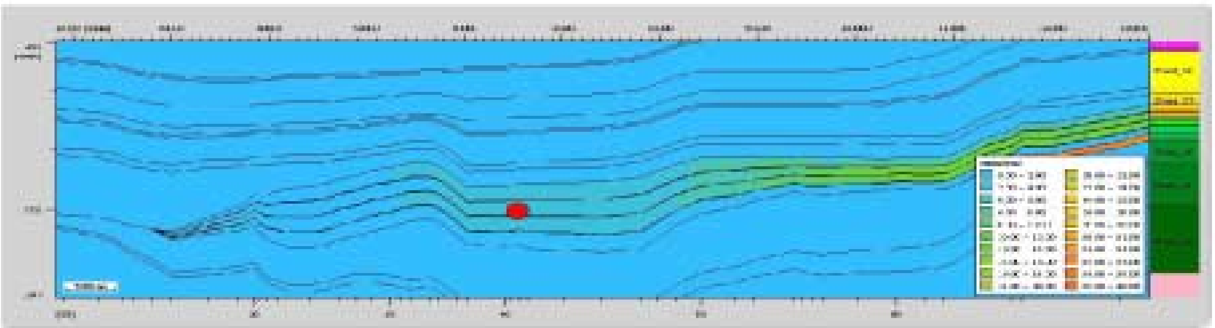


Figure 8. The lithology and geometry around the pinch out of the Utsira Sand in case no. 1.

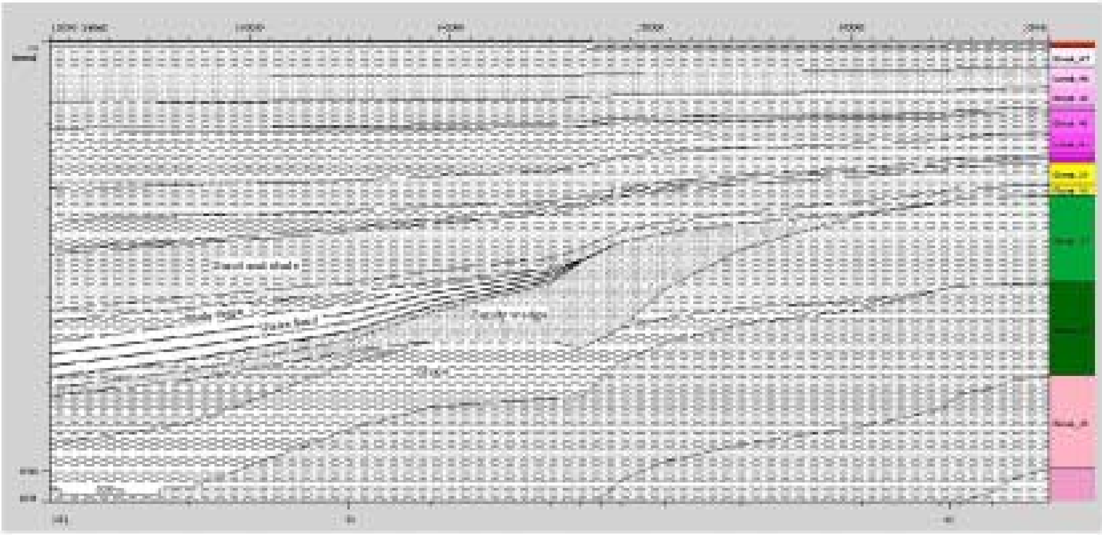
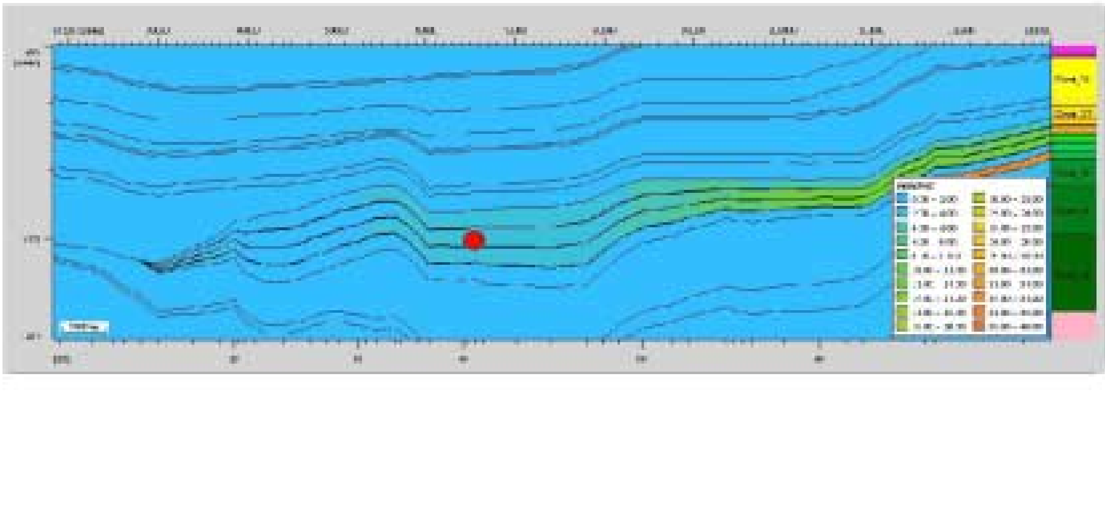


Figure 9 Calculated flow velocities in the Utsira Sand for case 1 (Base case). Flow velocities between 2 and 4 m/year are found in the injection area (red dot).



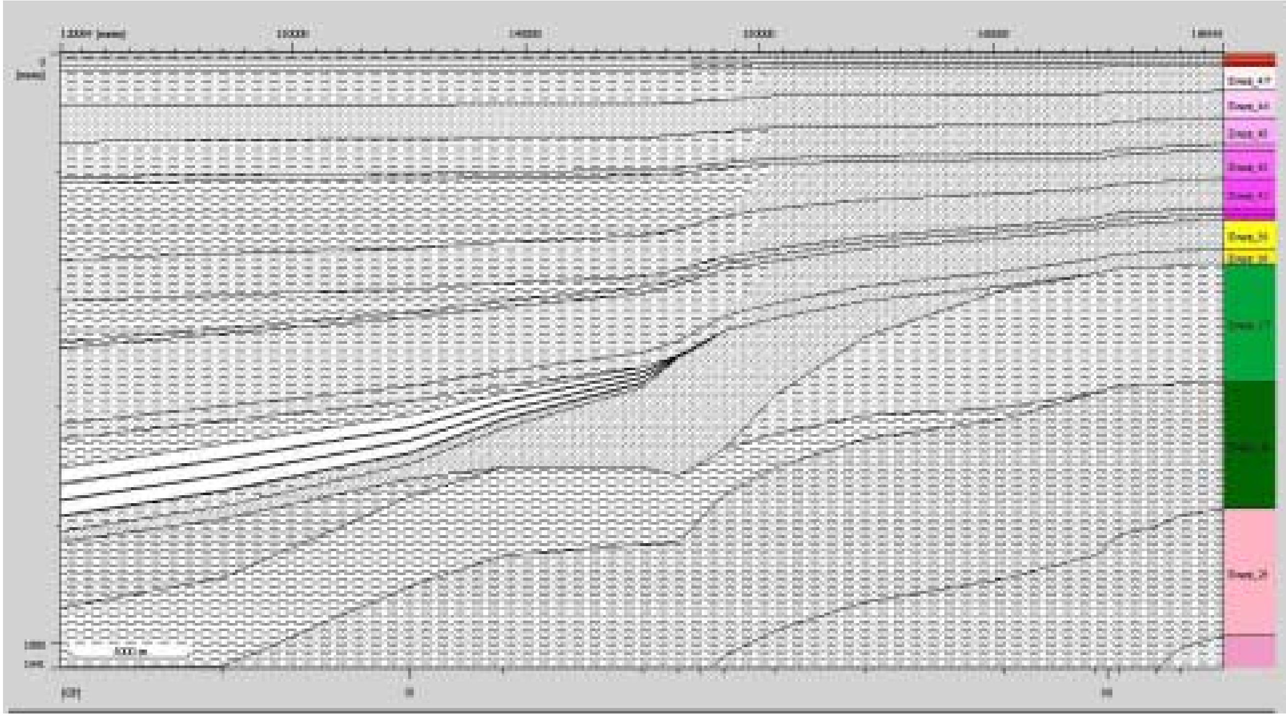
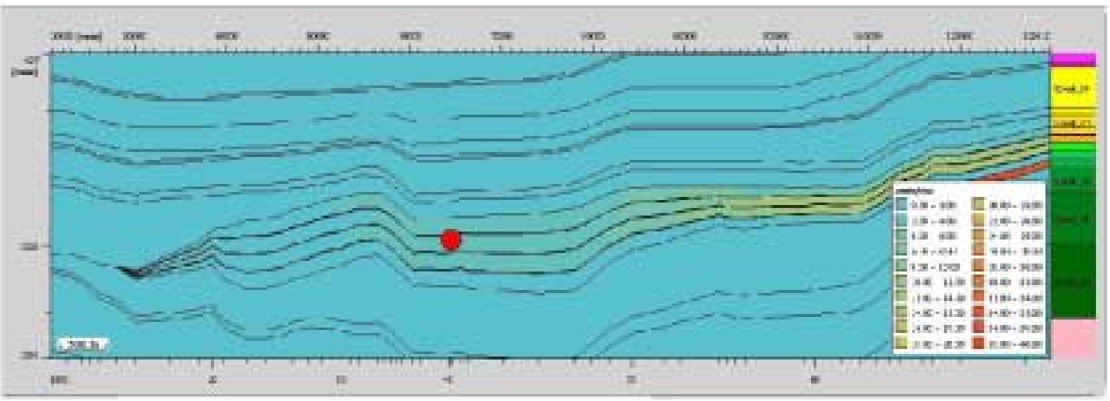


Figure 10. Lithology and geometry around the pinch-out of the Utsira Sand in case no. 2.

Figure 11. Calculated flow velocities in the Utsira Sand for case 2. Flow velocities between 2 and 4 m/year are found in the injection area (red dot).



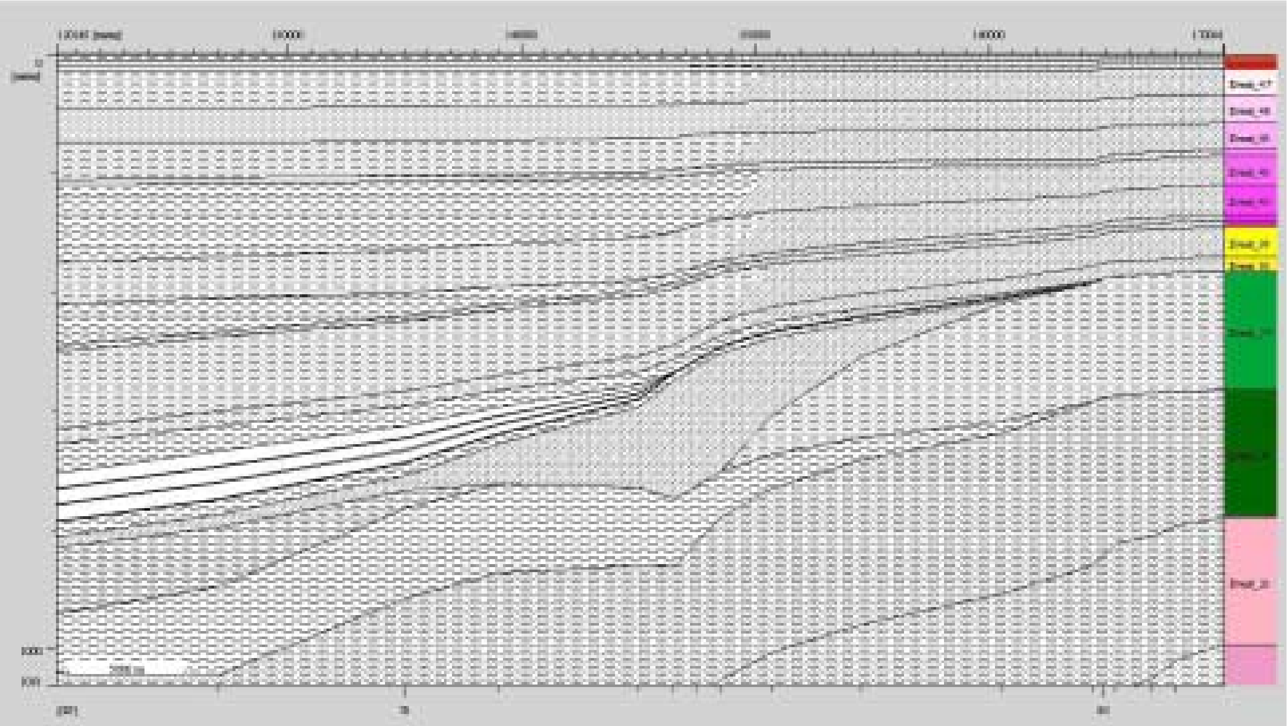
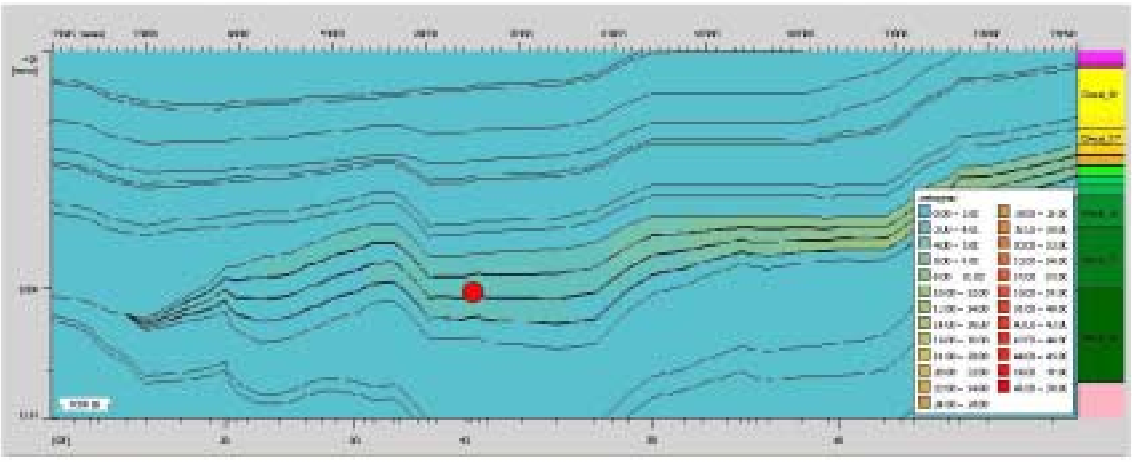


Figure 13. Calculated flow velocities in the Utsira Sand for case 3. Flow velocities between 2 and 4 m/year are found in the injection area (red dot).



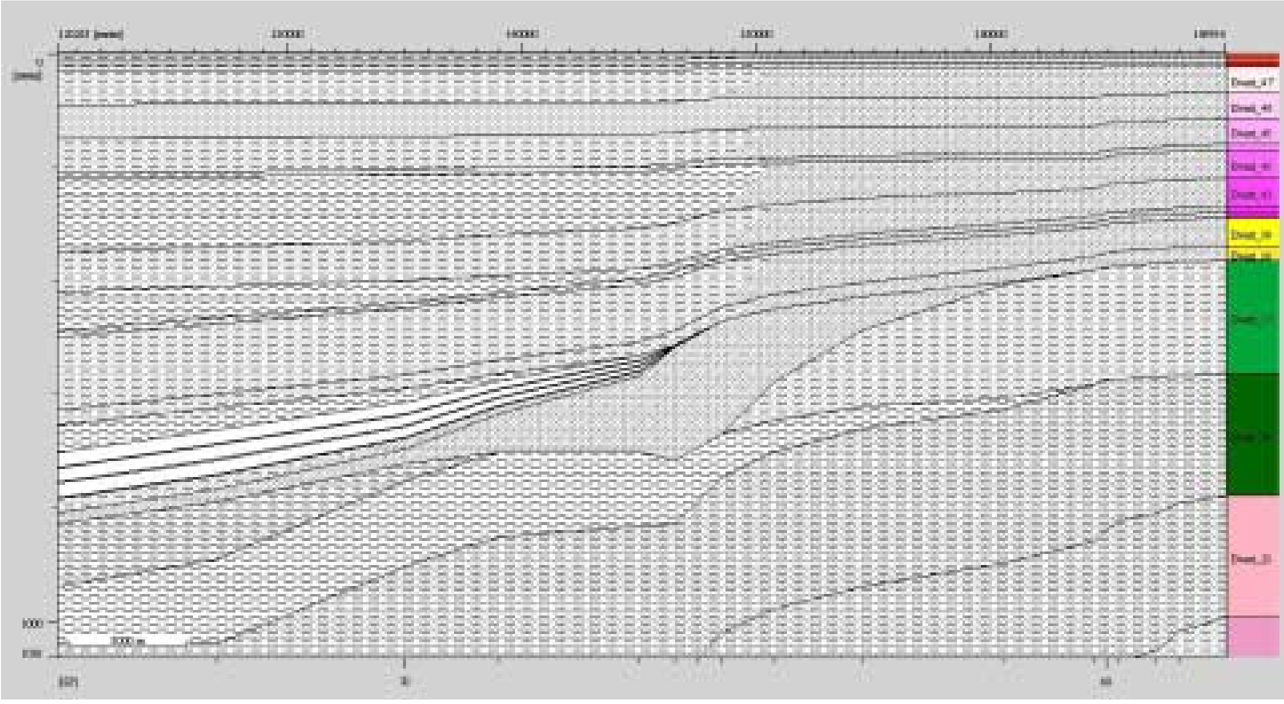
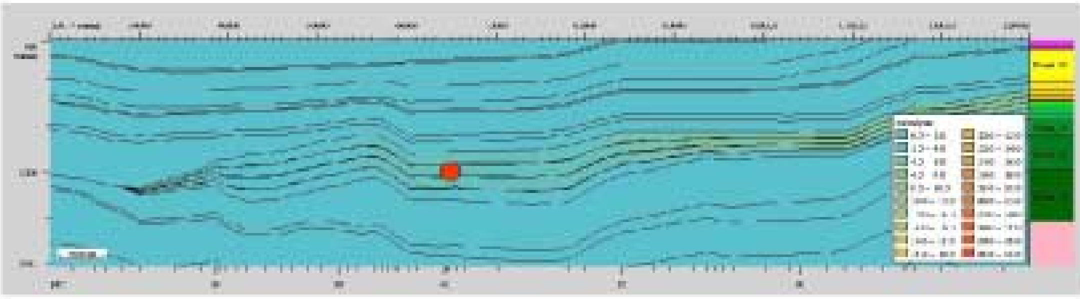


Figure 15. Case no. 4. Flow velocities in the injection area (red dot) outside the sand stringers, are still in the range of 2 and 4 m/year and are not significantly influenced by the high permeable sand stringers.



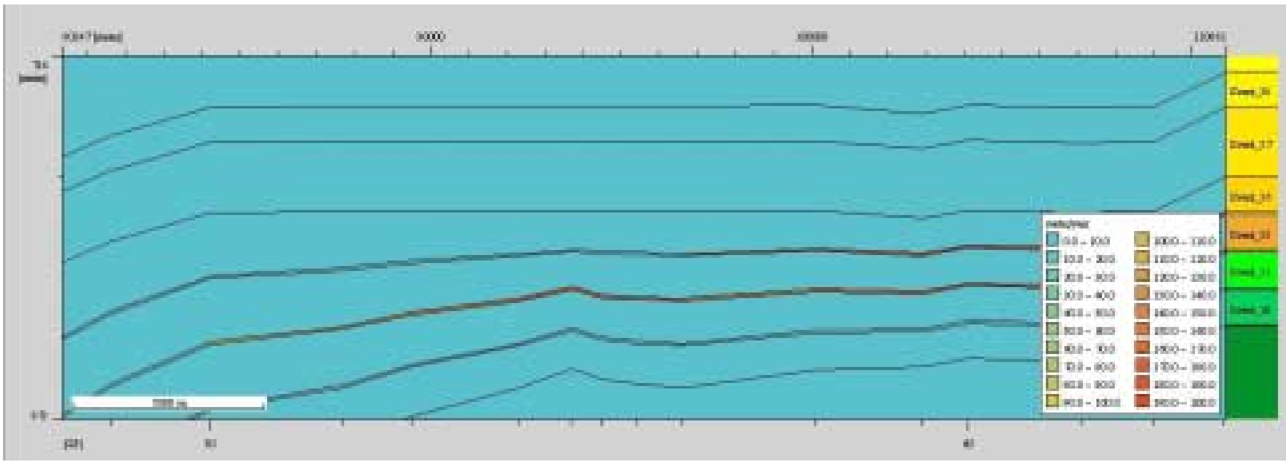


Figure 16. Case no. 4. Flow velocities in thin high permeable sand stringers in the Utsira Sand can be more than 100 m/year.