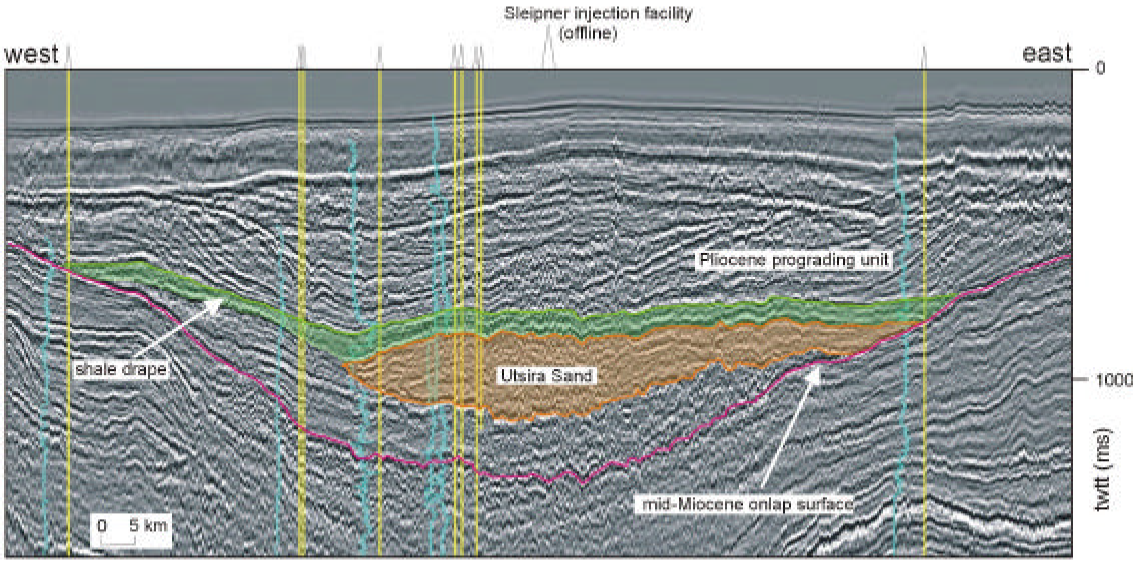
British Geological Survey
Natural Environment Research Council

# Saline Aquifer CO2 Storage Phase 2 (SACS2)

## Work Area 1 (Geology) - Progress Report 1 April to 31December 2000

## BGS Commissioned Report CR/01/11N

*Open*



# Saline Aquifer $CO_2$ Storage: A Demonstration Project at the Sleipner Field

## Work Area 1 (Geology) - Progress Report 1 April to 31 December 2000

**BGS Commissioned Report CR/01/11N (Open)**

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| Contract Number: | T-124.167-02 |
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## 1. Main Interpretative results

1.1 Summary

- Preliminary depth and thickness maps produced of Utsira Sand over its entire subsurface extent.
- Total Utsira reservoir storage volume estimated.
- Potential storage volume in traps estimated around Sleipner.
- Preliminary map of caprock around Sleipner produced.
- Seismic amplitude anomalies mapped in caprock around Sleipner.
- Samples of caprock obtained and preliminary analysis made.
- Core from possible caprock analogue at Ekofisk examined and analysed.
- 2-D basin modelling carried out to assess major controls on the regional fluid flow regime.

*Task 1.3 Stratigraphy and structure of the Greater Sleipner Area*
The reprocessed CNST82RE survey has been loaded. Interpretation of the Utsira Sand transferred onto the reprocessed data and extended onto previously unavailable seismic lines. Transferred reprocessed CNST82RE dataset to GEUS. Received additional Norwegian well information from GEUS. This completed the initial Greater Sleipner interpretation.

***Task 1.4. Characterise Caprock***
Cuttings samples have been obtained by BGS and SINTEF from a number of UK and Norwegian wells. Some SEM and XRD work has been carried out. Results will be available early in 2000. GEUS have examined core material from shales at Ekofisk (a possible analogue to the Sleipner caprock), further XRD and grain-size analysis is currently underway.

***Task 1.6 Determine Natural Fluid Flow***
GEUS constructed a 2-D basin model along a SSE-NNW cross-section, running through Sleipner, into the UK sector. The cross-section was based on detailed well interpretations and seismic data. A preferred flow model was established with alternative models to assess the uncertainty in structural configuration and permeability values. A Technical Report has been produced describing this work in full.

***Task 1.7 Iterative Development Of Full Regional Geological Model***
The preliminary BGS regional interpretation of the Utsira Sand (over whole dataset) was transferred to GEUS. BGS and GEUS are now working iteratively to develop a final agreed interpretation. Additional Norwegian well data have been incorporated. Revision of well formation tops has been started as a result of the preliminary interpretation. The VGST89 dataset has been identified as suitable for infill purposes. BGS have received digital data from SINTEF and loaded onto the workstation. SINTEF have continued with detailed work around Sleipner, concentrating on the area of the 1994 3-D survey. Amplitude anomalies in the caprock have been mapped and related to structural traps. In addition a study has been carried out to assess

trapping volumes at the top of the Utsira Sand. A seismic continuity cube has been generated (in cooperation with Statoil) over selected areas of the 1994 3-D survey.

## 1.2 Description of main Task results

The Tasks summarised above are described in more detail here. Rather than taking the tasks in strict numerical order we present regional aspects first, followed by more detailed work around Sleipner, caprock studies and finally the more theoretical basin-modelling work.

### 1.2.1 Regional Aspects (Tasks 1.3 and 1.7)

The preliminary regional interpretation of the Utsira Sand was based on nearly 14000 line kilometres of 2-D seismic data and over 300 wells. The reservoir sand comprises a basinally-restricted deposit of late Miocene or early Pliocene age, lying within the thick Cenozoic post-rift succession of the North Sea Basin (Figures 1 and 2). Its position, centrally in the basin above the Viking Graben, characteristic 'mounded' seismic motif, blocky ?-ray log signature, and accessory components (coal, glauconite, shells) all indicate that the Utsira Sand was deposited as lowstand massflows or turbidite fans in a restricted, but not very shallow basin. This is supported by biostratigraphic analyses of foraminifera and dinoflagellates, which both indicate depositional water-depths in exess of 100 m.

The Utsira Sand is mappable over an area of more than 2.6 x $10^4$ $km^2$, and lies between depths of about 550 and 1500 m (Figure 3a). It occupies two distinct depositional basins which are likely to be in poor hydraulic contact. A northern depocentre lies above the North Viking Graben, and Sleipner currently injects into the southern depocentre, close to where the reservoir attains its greatest thickness of about 300m (Figure 3b). The estimated pore volume of the reservoir (excluding a deeper sub-Utsira sand unit in the north, see below) is 5.5 x $10^{11}$ $m^3$, though only a small fraction of this is likely to form usable storage space (see below).

The Utsira Sand pinches out stratigraphically to the west and east, and narrows dramatically northwards, possibly occupying a channel feature deepening northwards into the More Basin. Towards the south, in the southern Norwegian sector the Utsira Sand passes into a clay facies and is absent south of 57º 50´. South of 57º 50' minor isolated sands occur such as the upper Oligocene Vade Formation (blocks 2/2 & 2/3), locally up to ca 70 m thick (well 2/2-2) and some minor Pliocene, probably massflow sands in the central North Sea. Further to the East, towards the coasts of southern Norway and Denmark, more significant Oligocene and Miocene sands occur.

The regional interpretation has shown that sand units in many wells, previously attributed to the Utsira, are in fact stratigraphically distinct. Thus, in the northern depocentre, seismic stratigraphy indicates that the Utsira Sand overlies an older sand unit which in the literature has been included in the Utsira Formation. This lower sand will considerably increase the total reservoir storage potential in the northern depocentre. This is typified by the Brage-Oseberg area, where the total Utsira plus lower sand thickness is more than 210 m (Norwegian well 30/6-20).

To the north-east, the East Sand Unit (Figure 2), locally more than 80 m thick (well 35/11-5), is dated as late Miocene to early Pliocene age and in the literature is taken as the Utsira Sand. However it is situated at the margin of the basin and appears to downlap the easternmost part of the Utsira Sand (Figure 2), being in consequence, somewhat younger. Though stratigraphically different, the three sand units may well be hydraulically connected, though minor local sealing clay layers may occur both within and between each unit. The East Sand Unit shallows eastwards, close to Pleistocene sands a few hundred meters below the sea-bed; further work is required here to assess the efficacy of the caprock seal.

The succession overlying the Utsira reservoir is rather variable, but principally comprises prograding deltaic wedges of Pliocene age (Figures 1 and 2). These form a succession coarsening upwards from shales, in the deeper, central parts of the basin to silt and sand in the shallower and more marginal parts. High amplitude reflections, which onlap the toe-sets of the prograding clinoforms, may be interpreted as sandy beds (Figure 4), perhaps deposited as turbidites. The height of the clinoforms, 300 - 400 m, indicates the approximate water depth at the time of deposition (not compensated for subsequent compaction/subsidence). Therefore a major relative sea-level rise must have taken place in latest Miocene or during the Early Pliocene. Subsequently, huge amounts of upper Pliocene sediments seem to have been deposited by major deltaic systems, first mainly from east and west or southwest, presumably due to relative uplift of southern Scandinavia and Scotland/Shetland, and later more dominantly from the south. Nearly all the easterly-derived clinoforms have been truncated along the Norwegian channel, parallel to the Norwegian coast and the most eastward clinoforms seem to miss their offlap breaks, meaning deep and significant glacial erosion and/or late Cenozoic uplift.

In the Sleipner area a shale drape forms the caprock to the reservoir, separating it from the overlying prograding wedges (Figure 1). The shale drape extends well beyond the area currently occupied by the injected $CO_2$ and seems to be providing an effective seal at the present time (Figure 5).

### 1.2.2 Detail around Sleipner (Task 1.7)

Seismic anomalies (zones of unusually high seismic amplitude which may indicate the presence of shallow gas), were identified in the Utsira Sand on 3-D seismic survey ST98M11 (see Figure 3 for location). Anomalies at the tops of the reservoir units (Utsira Sand and sand wedge) are all at structural traps (Figure 6) and are most likely caused by the presence of gas. They indicate retention potential of the reservoir seal, but the fact that the anomalies are only present in a small number of the traps, and that they do not fill these traps completely, may imply that migration into the cap rock is possible. The presence of a channel-like structure in the sand-wedge (Figure 7) and the observation that seismic anomalies at the reservoir tops are partly displaced from the structural culminations (Figure 6), may signal that the reservoir is not as homogeneous as previously assumed.

The storage volume in traps at the top of the Utsira Sand and at the top of the intra-Nordland Shale sand wedge has been calculated in the area of survey ST98M11 (Figure 8), employing a secondary hydrocarbon migration simulator. Results indicate that it amounts to 0.135 $km^3$, which corresponds to a theoretical storage efficiency of the Utsira Sand of 0.3%. Taking into account that only a proportion of these traps can be reached by economic placement of injection wells, the results support the contention of Holloway et al. (1996), that the typical total storage efficiency of an aquifer, in terms of structural traps, might be only a fraction of one percent.

A more detailed account of the work around Sleipner is given in Zweigel et al. (2000).

### 1.2.3 Caprock studies (Task 1.4)

Caprock cuttings samples from 9 UK wells have been described and some SEM images obtained. Quartz content and grain size can be used a proxy for the capillary entry pressure (= sealing efficacy); samples are currently being identified for XRD and grainsize analysis.

Caprock cuttings samples from 10 wells in the Norwegian sector around Sleipner (including a well drilled in 1999 by the Sleipner operators) have been obtained from the Norwegian Petroleum Directorate (NPD). Samples concentrate on the lowermost shales, directly overlying the Utsira Sand and the sand wedge (the 'Shale Drape'), but in several wells the whole Pliocene shale sequence has been sampled.

Macroscopic inspection of cuttings from the caprock showed that the upper part of the Pliocene shale sequence, which contains many seismic amplitude anomalies, seems to be coarser grained than the lower part, supporting the depositional model (Figure 4).

XRD analysis has been carried out for 24 samples, covering the whole shale sequence in one well and the lowermost part in 4 other wells. Analytical results will be ready early in 2001.

No caprock core material is currently available. At the Orleans Technical Meeting it was decided to investigate the possibility of obtaining some core in collaboration with the Sleipner Operating Group.

In the meantime, a possible analogue for the caprock may be available from Ekofisk where an Early Pleistocene clay/shale section has been cored in well 2/4-C11 (Figure 9). The NPD made available four 5" diameter full core sections preserved in glassfibre sleeves, for description and sampling. The clay core was still humid and found to be in a good condition, and 3 small clay samples were taken for mineralogical analysis (Table 1). However NPD was not equipped to take unconsolidated samples on site. Permission to transfer the core to a local core laboratory for plugging was not granted by NPD, and further work was not possible.

Table 1. Samples from Ekofisk well 2/4-C11, core # 3.

| Box no. | Depth interval, feet | Description | Sample depth, feet |
|---|---|---|---|
| **1** | 1733' – 1736' | preserved, still humid, homogeneous plastic clay; dark and bright spots of mm to cm size are visible, but bedding is not discernible. | 1735'4" |

| | | | |
|---|---|---|---|
| **2** | 1739' – 1742' | preserved, homogeneous plastic clay; dark and bright spots of mm to cm size are visible, but bedding is not discernible; humid but superficial drying cracks; 45° fracture in mid of box. | 1741'0" |
| **3** | 1745' – 1748' | preserved, homogeneous plastic clay; more silty 10 cm thick layer approx. 20 cm b.t.; slightly humid but with superficial drying cracks. | 1747'4" |
| **4** | 1751' – 1754' | preserved but core surface mechanically damaged; still humid, homogeneous plastic clay; dark and bright spots of mm to cm size are visible, but bedding is not discernible. | not sampled |

3 clay samples from the Ekofisk area are undergoing further analysis:

- Specific surface area and pore size distribution in the range 8000-1000 nm by nitrogen absorption
- Grain size analysis (>20 µm, 20-2 µm, 2-0.2 µm and <0.2 µm) by particle size centrifuging
- Clay and fine clay mineralogy by XRD

The analytical work will be finished by the end of 2000, with a final report in preparation.

### 1.2.4 Basin modelling (Task 1.6)

Natural fluid flow in the storage reservoir contributes to the transport of free and dissolved $CO_2$. SACS 1 established that only a limited amount of pressure data are available from the Utsira Sand. A basin modelling study was set up therefore to estimate the velocity of the natural fluid flow and to evaluate the ranges of natural flow velocities in the Utsira Sand.

A simple 2D model, based on well and seismic data, was established along a section running NNW through Sleipner and into the UK sector (Figure 10). The interpreted stratigraphy, from the seabed to the top of the Zechstein (Permian), was subdivided into a number of events which define a preferred input model comprising 50 model layers (Figure 11). Porosities and permeabilities (based on well log data) were assigned to the model layers. The Utsira Sand, with a porosity of 35 – 40 % and a horizontal permeability of about 10 Darcy, was sandwiched between layers of much lower permeability. In particular, the Shale Drape which acts forms the caprock seal around Sleipner was assigned a permeability of 0.0001 mDarcy (Figure 12).

Initial boundary conditions were assumed as follows: no-flow boundaries at the top of Zechstein salt and at the south end of the section, where the Utsira Sand passes southwards into shales; open-flow boundary at the NNW end of the section where the sediments are much more sandy. Fluid pressures calculated with these preferred boundary conditions (Figure 13) are consistent with observed data in the North Sea, indicating potential overpressure in the Tertiary shales and in the Jurassic and Triassic formations, but no overpressure in the Chalk.

A number of simulations were carried out using the above boundary conditions. The preferred model assumes that the Utsira Sand is sealed above by the Shale Drape, but is in hydraulic contact with a sandy wedge at the NNW end of the model. Results from the preferred model (Figure 14) indicate NNW-directed flow in the Utsira Sand. Flow velocities are in the range 2 – 4 $myr^{-1}$ around the Sleipner injection point. These increase updip to in excess of 10 $myr^{-1}$ at the NNW end of the model, principally due to updip pinchout of the Utsira reservoir, which results in narrowing of the hydraulic system. Other model scenarios were simulated, but the overall results remained similar with flow values generally less than 5 $myr^{-1}$ around the injection point, but greater farther north.

Full details of the modelling are available in a Kristensen & Bidstrup (2000).

## 2. Dissemination of results

Papers presented/published in the review period.

Christensen, N.P. & Gerling, P. 2000. Assesment of the European potential for geological storage of CO2 from fossil fuel combustion. 62nd EAGE meeting, Glasgow, Paper B-18.

Gregersen, U.; Johannessen, P.N., Kirby, G.A., Chadwick, R.A. & Holloway, S. 2000. Regional study of the Neogene deposits in the southern Viking Graben area - a site for potential CO2 storage. 62nd EAGE meeting, Glasgow, Paper B-19.

Chadwick, R.A., Holloway, S., Kirby, G.A., Gregersen, U. & Johannessen, P.N. (in press). The Utsira Sand, Central North Sea – an assessment of its potential for regional $CO_2$ disposal. Conference Proceedings: 5th International Conference on Greenhouse Gas Control technologies, Cairns (Australia), August 2000.

Chadwick, R.A., Holloway, S. & Riley N. (in press) Deep Subsurface $CO_2$ sequestration – a viable greenhouse mitigation strategy. Geoscientist: Geological Society Publishing House.

Chadwick, R.A., Holloway, S. & Riley N. (in press) Deep Subsurface $CO_2$ sequestration – a viable strategy for reducing greenhouse emissions: an example from the North Sea. Offshore Magazine.

Zweigel, P., Hamborg, M., Arts, R., Lothe, A., Sylta, O. & Tommeras, A. (in press). Prediction of migration of $CO_2$ injected into an underground depository: reservoir geology and migration modelling in the Sleipner Case (North Sea). Conference Proceedings: 5th International Conference on Greenhouse Gas Control technologies, Cairns (Australia), August 2000.

# 3. References

Holloway, S, (ed) 1996. *The Underground Disposal of Carbon Dioxide*. Final Report of Joule II Project NO. CT92-0031. 355 pp. British Geological Survey, Keyworth, UK.

Kristensen, L. & Bidstrup, T. Determination of natural fluid flow in the utsira Sand reservoir using basin modelling. SACS project (Phase 2). Final Technical Report of Task 1.6. GEUS Report 2000/2.

Zwiegel, P., Lothe, A.E., Arts, R. & Hamborg, M. 2000. Reservoir geology of the storage units in the Sleipner $CO_2$ injection case. SINTEF Report No. 23.4285.00/02/00. CR-ROM.

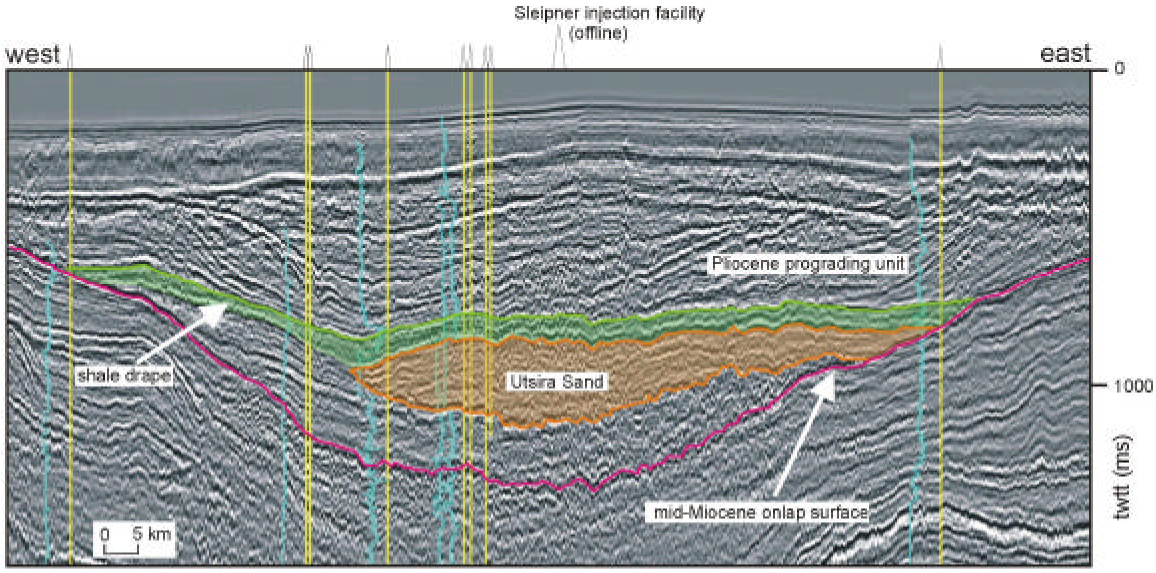
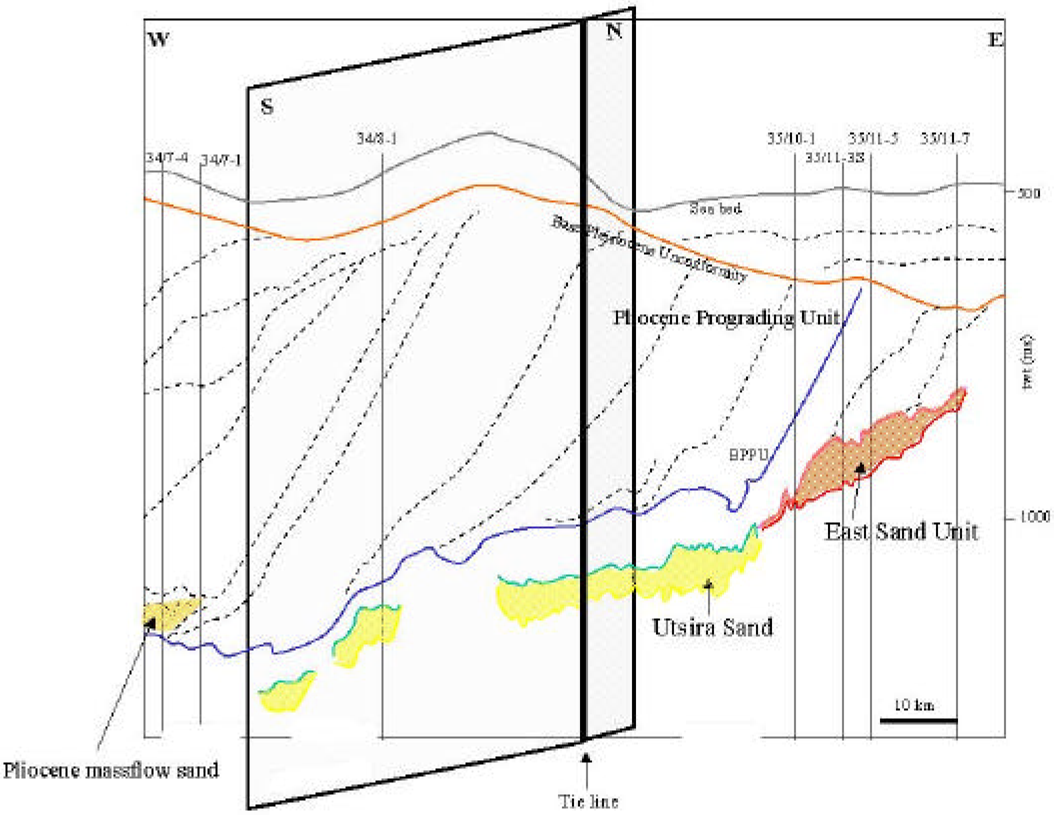



Figure 1 Regional seismic line through the southern part of the Utsira Sand, close to Sleipner. Well traces show gamma-ray logs.



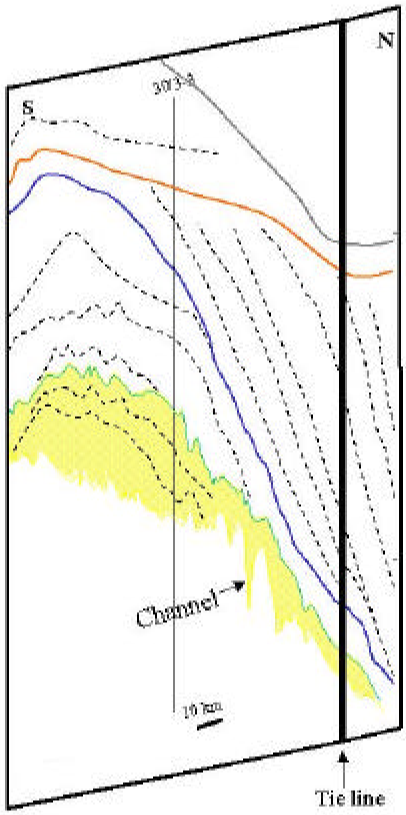




Figure 2 Interpretive sections through the northern depocentre, showing the relationship of the Utsira Sand to adjacent sandy wedges and the caprock succession.

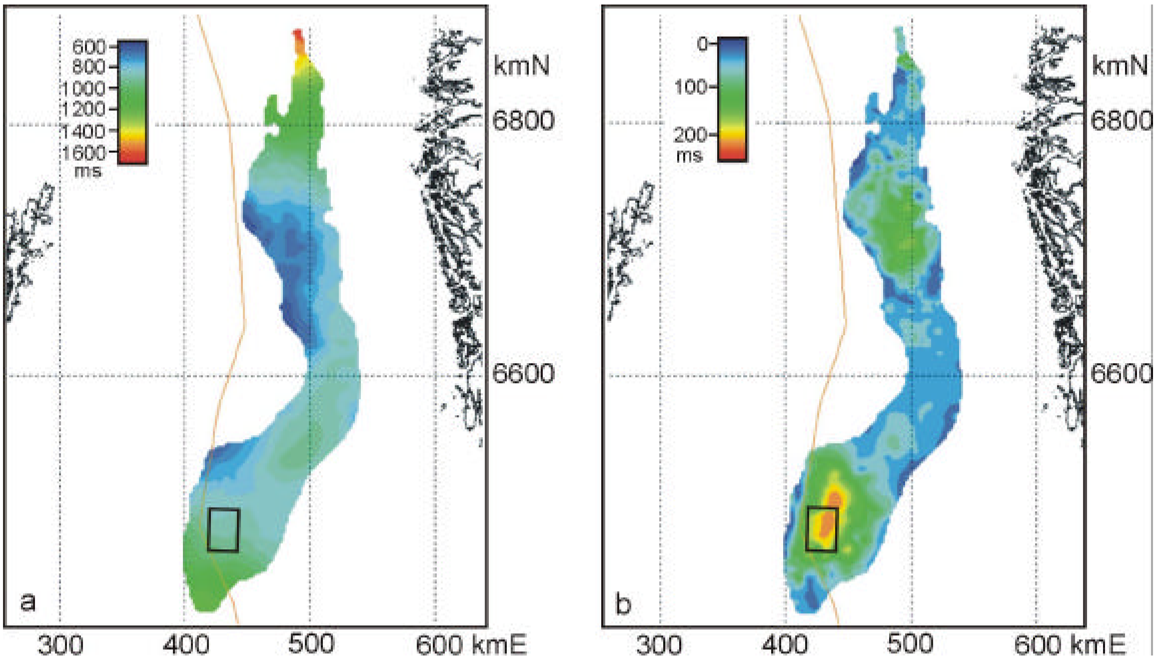



Figure 3 Maps of Utsira Sand based on preliminary interpretation a) two-way travel-time map to top reservoir  b) two-way isochore map. Rectangles denote 1994 Sleipner 3-D survey (ST98M11). Note thicknesses in depocentre do not include the sub-Utsira Sand.

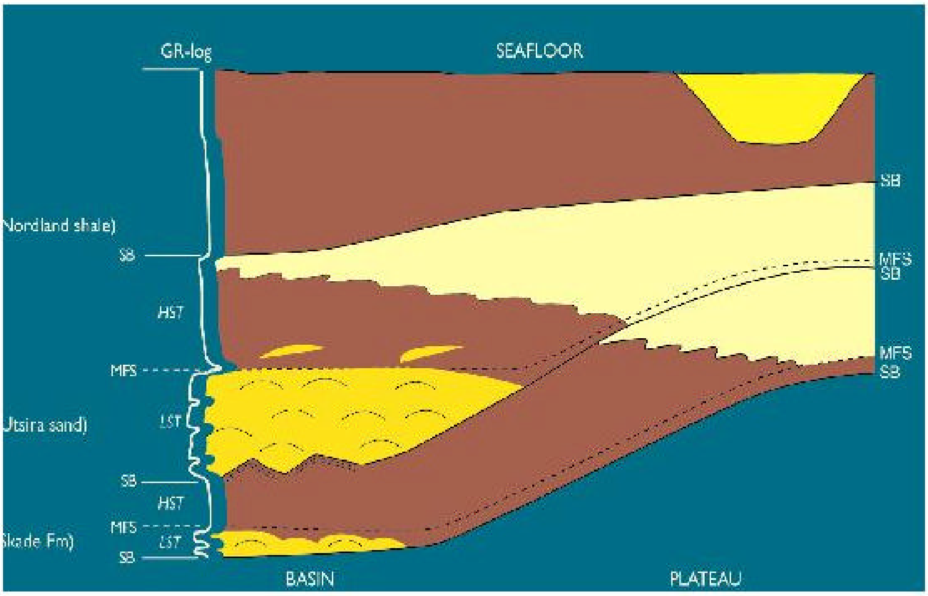



Figure 4 Schematic section at the eastern edge of the reservoir. The Utsira Sand was probably deposited as lowstand turbidite fans in a restricted basin. The Pliocene caprock is interpreted as a prograding delta with an upward coarsening succession from shales to silt. At the toe-sets of the Pliocene prograding unit, sandy bodies may occur, interpreted as localised turbidite sands.

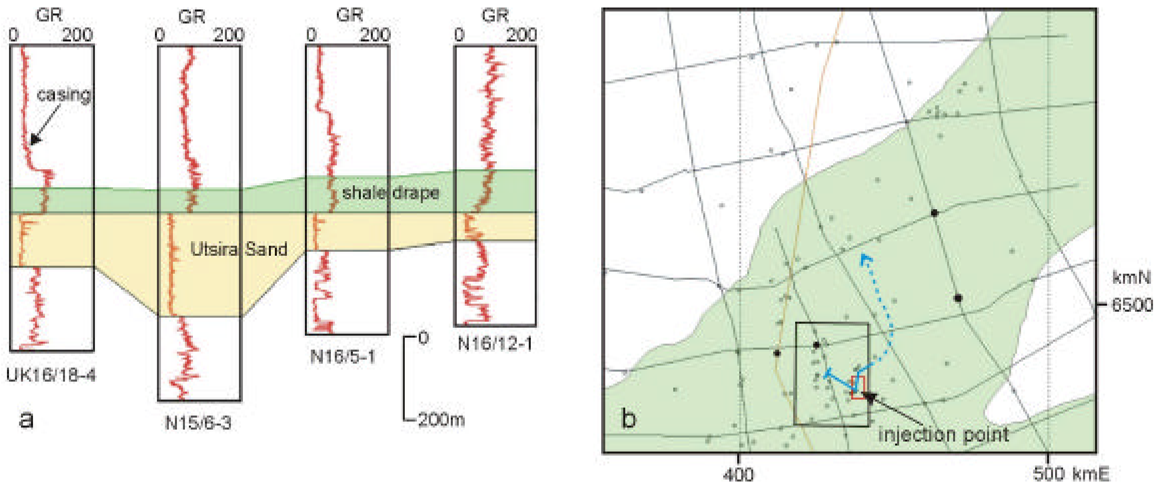



Figure 5 a) Detail of the shale drape from gamma-ray logs in the Sleipner area. b) approximate extent of the shale drape (green) and predicted $CO_2$ migration trends. Large and small rectangles denote 1994 and 1999 3-D seismic surveys respectively.

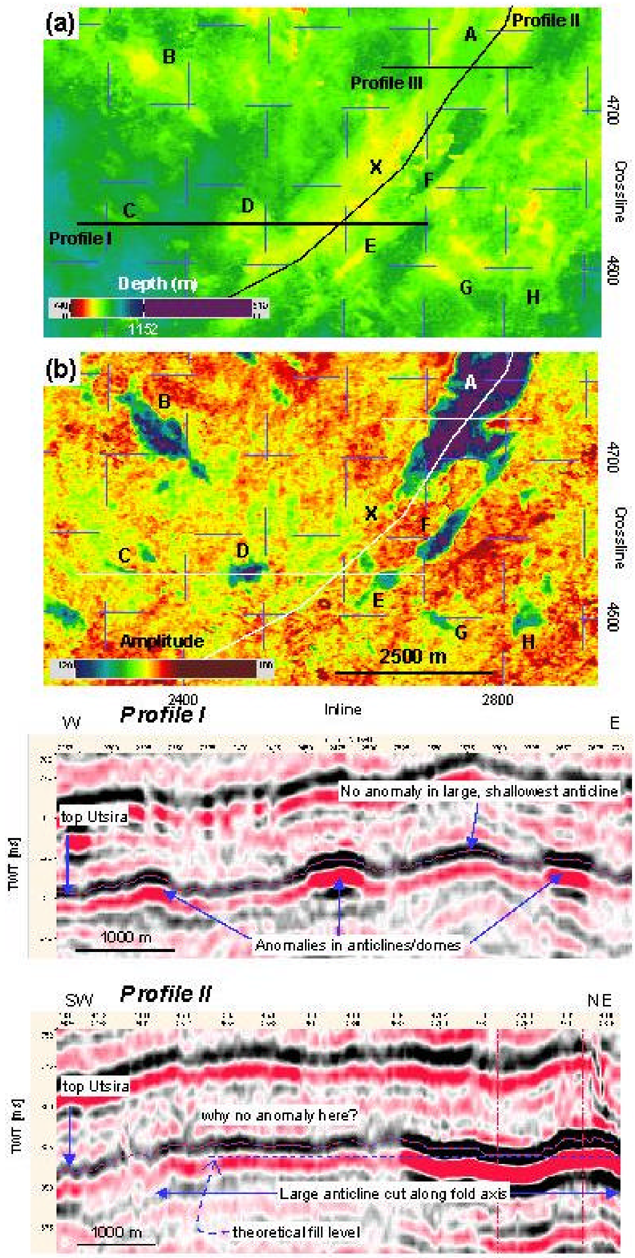



Figure 6 (a) Topography of the top Utsira reflector and (b) amplitude strength at this reflector in the northern part of seismic survey ST98M11. Note that all amplitude anomalies are situated in structural traps (anticlines, domes), which makes it likely that they are due to gas accumulations. The seismic profiles illustrate the location of the anomalies. However, the anomalies are not always positioned in the culmination zones of the structures nor do they follow always contour lines; this may indicate reservoir heterogeneity.

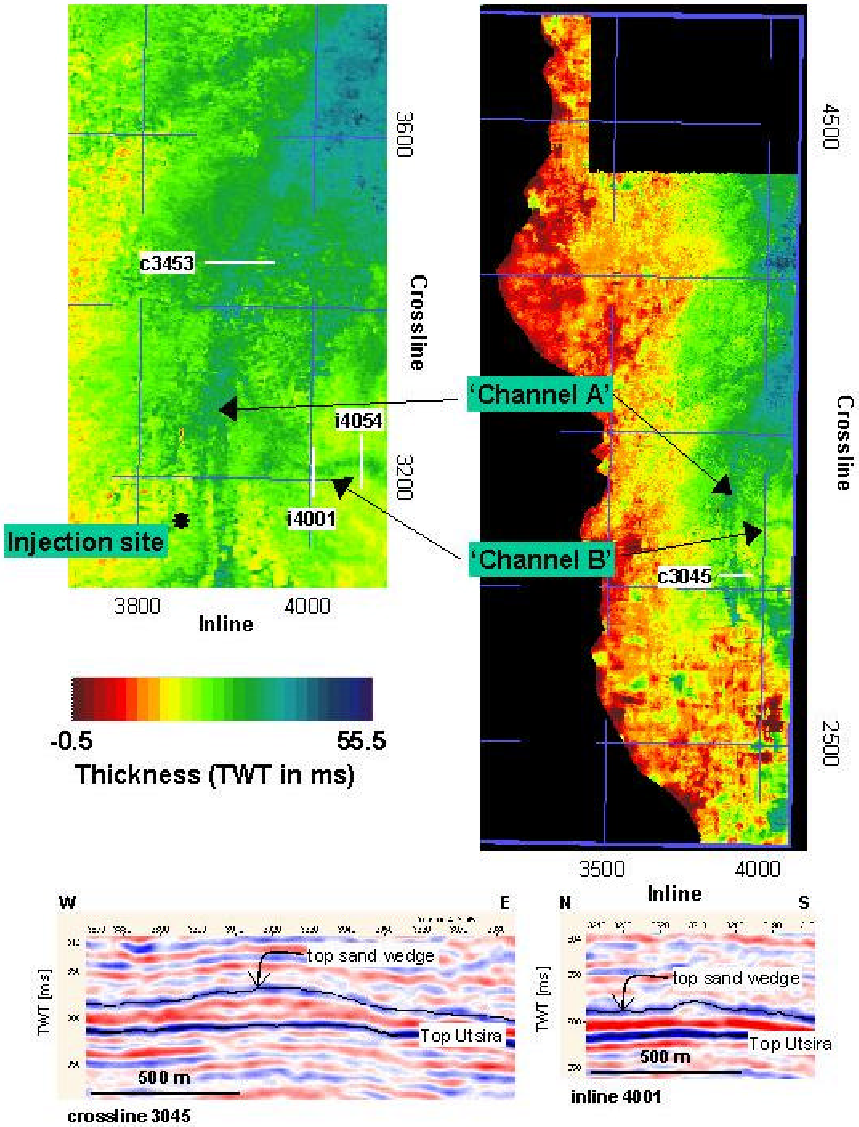
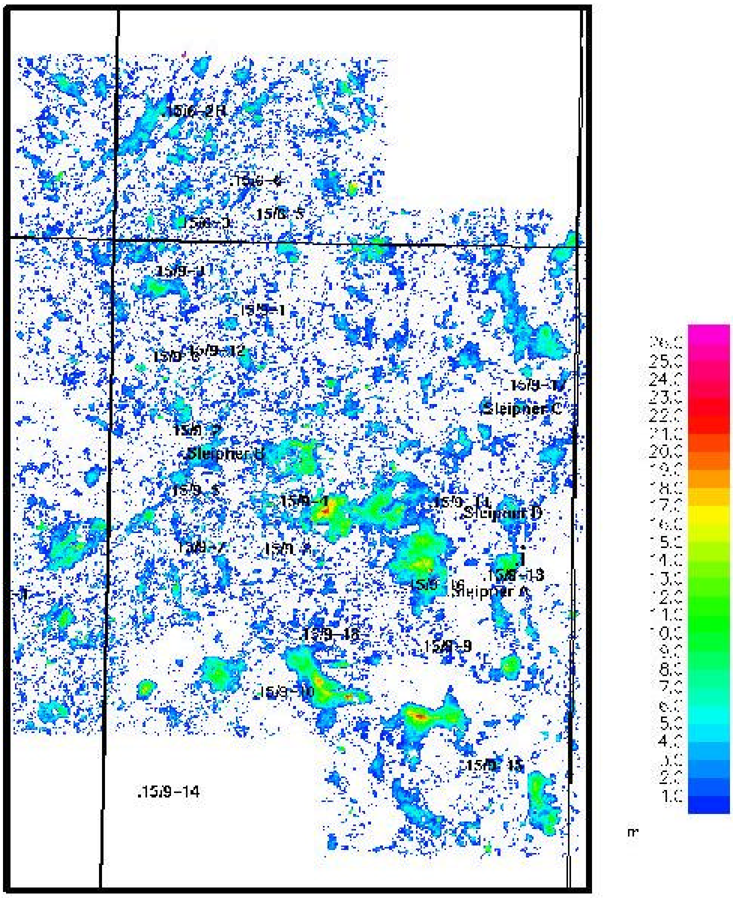



Figure 7 The thickness map of the sand wedge in the lower part of the Nordland Shales shows channel-like features (upper part of figure), which are also evident from seismic sections (lower part). Since the sand wedge and the Utsira Sand are lithologically very similar, such features may be present in the Utsira Sand, too, where they may be difficult to identify.

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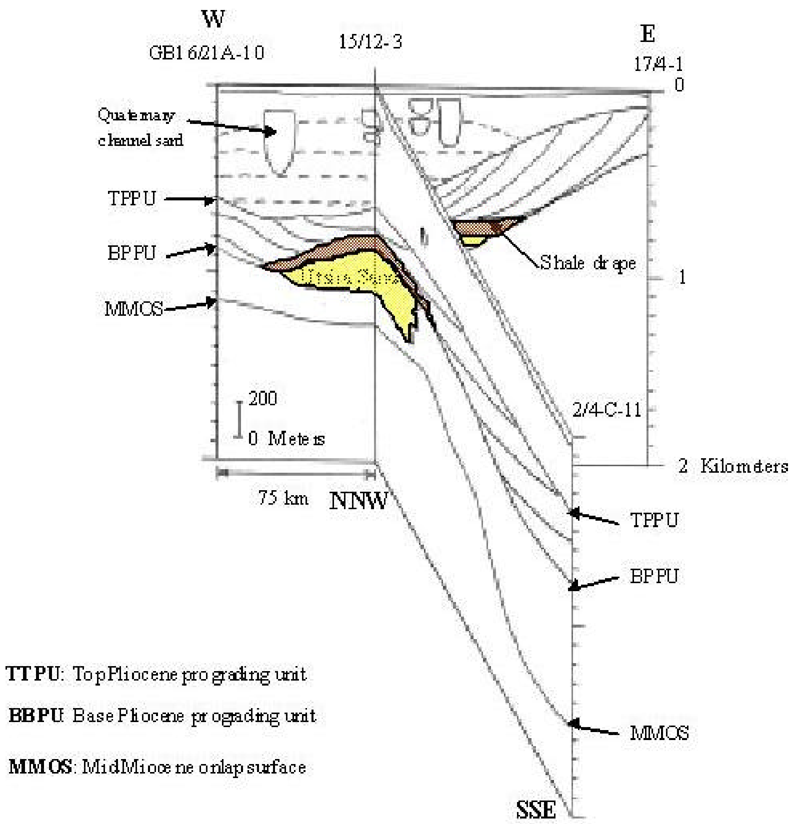



Figure 9 Fence diagram from the Sleipner field to the Ekofisk area. Clinoforms in the Pliocene caprock indicate progradation from the west, south and east towards the deepest part of the basin above the Utsira Sand (yellow shading). Core from early Pleistocene shale in the Ekofisk well 2/4-C-11 may be broadly comparable to caprock shales in the Sleipner area.

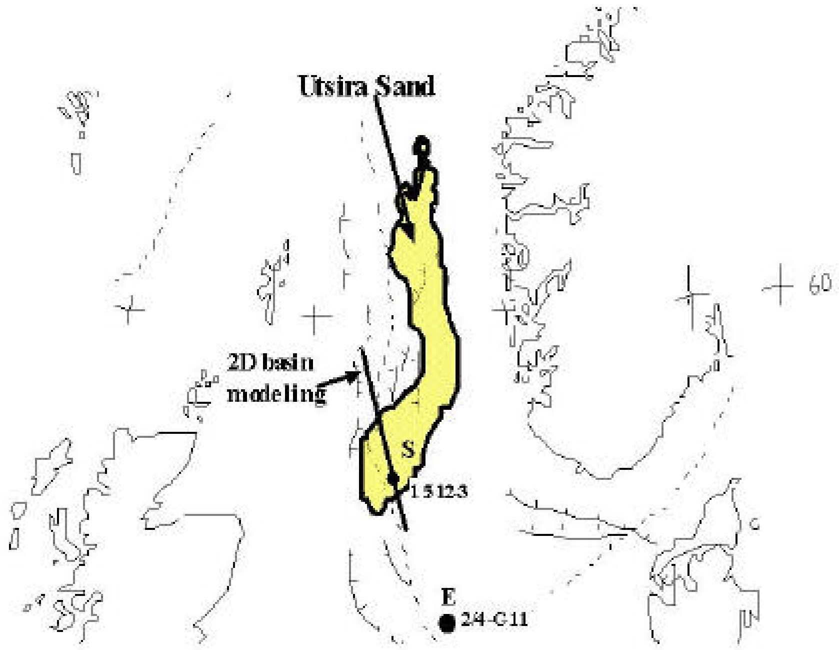
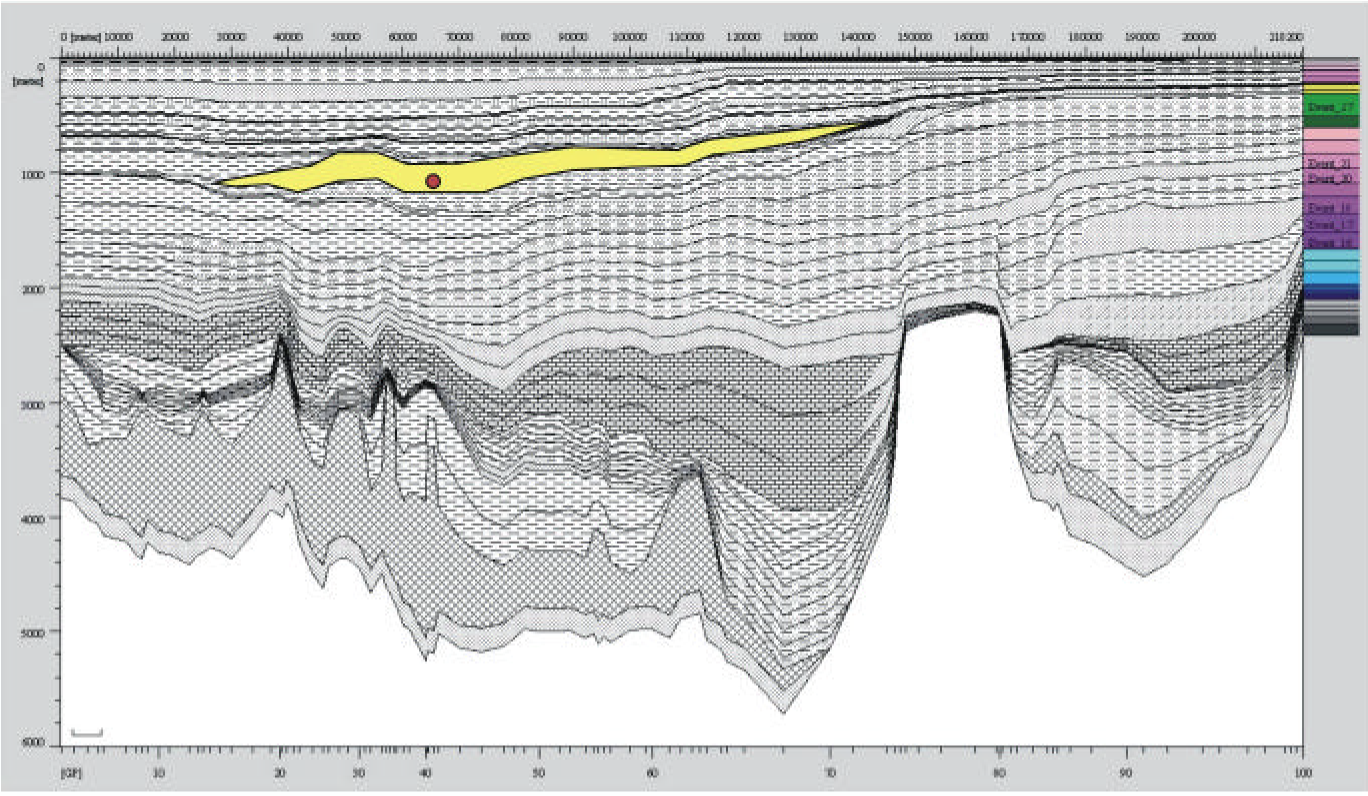



Figure 10 Location of the 2-D basin model section and the extent of the Utsira Sand



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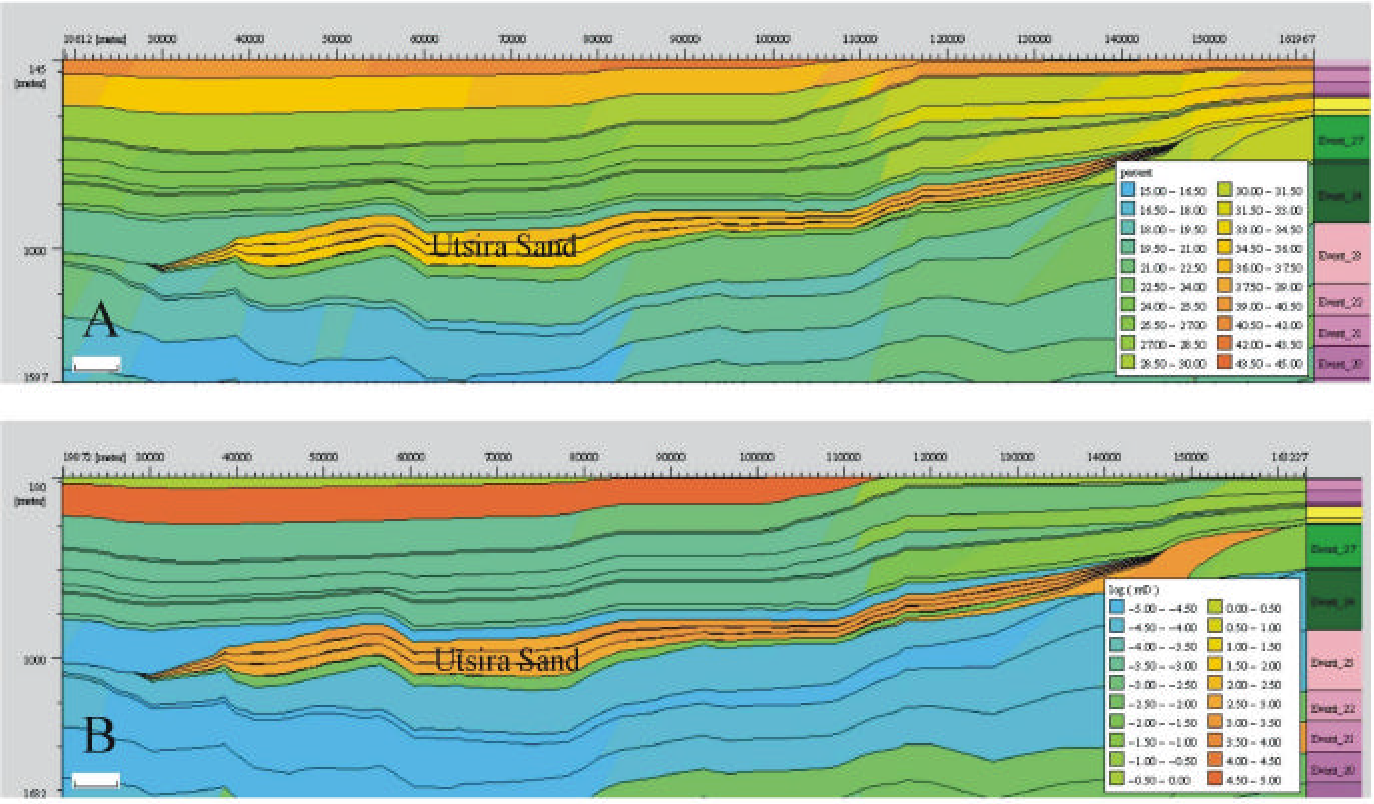


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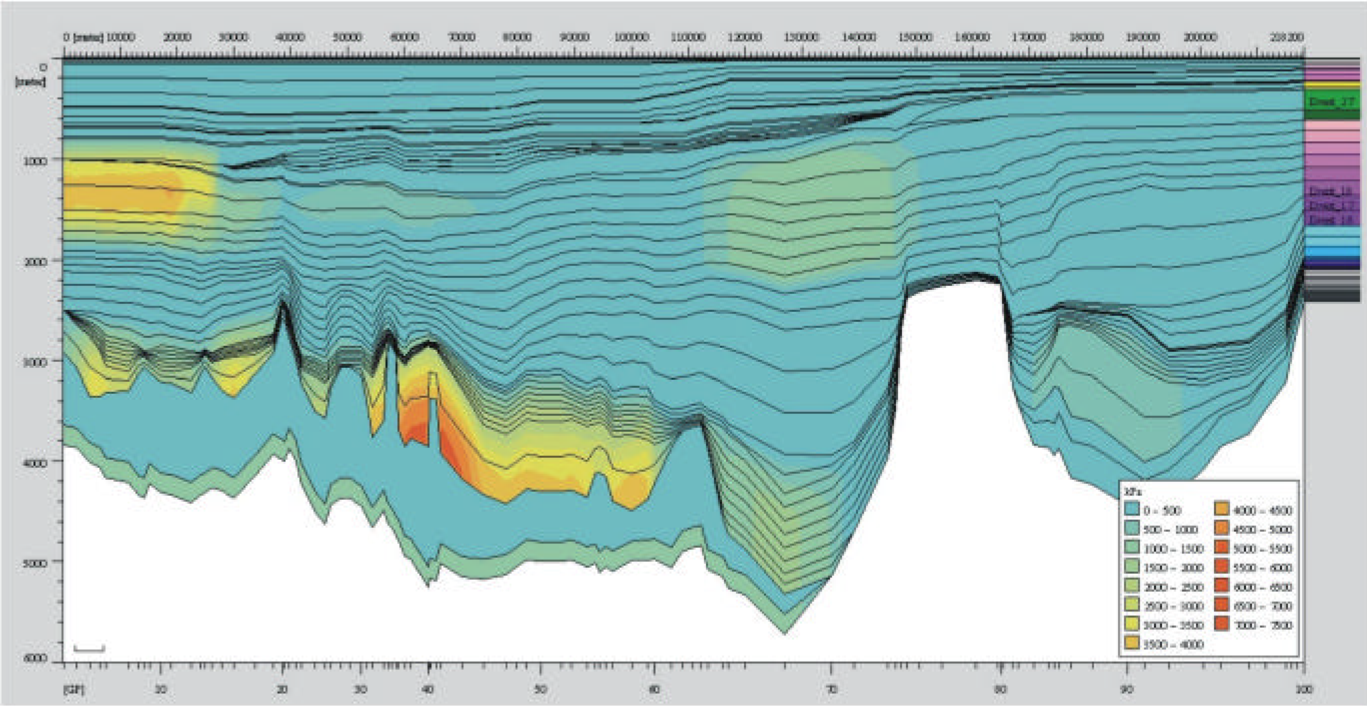


Figure 13  Excess pressure calculated with the following boundary conditions: model closed to flow to south (left) and open to flow to the north (right). Excess pressure cells are generated in the Jurassic and Tertiary sections, but not in the Chalk, which agrees well with observations.

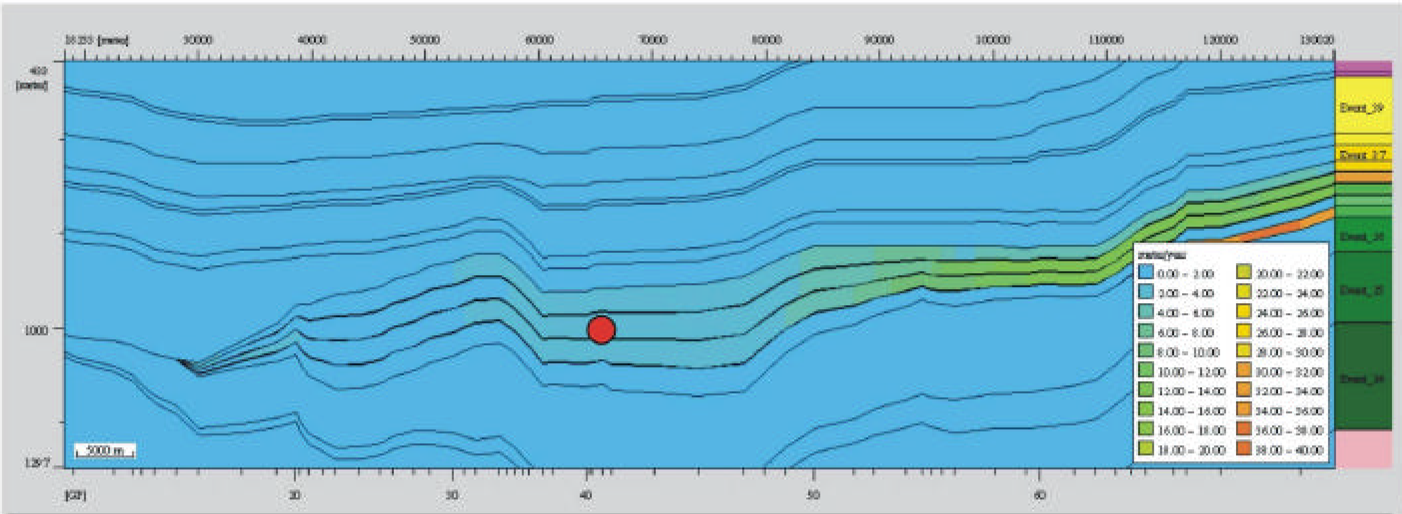


Figure 14  Calculated flow velocities in the Utsira Sand for the preferred model. Flow velocities are between 2 – 4 $myear^{-1}$ around the injection point, but are higher towards the updip (NNW) pinchout of the reservoir.