British Geological Survey
Natural Environment Research Council

Saline Aquifer CO2 Storage (SACS)

Final Report :Work Area 1 (Geology)

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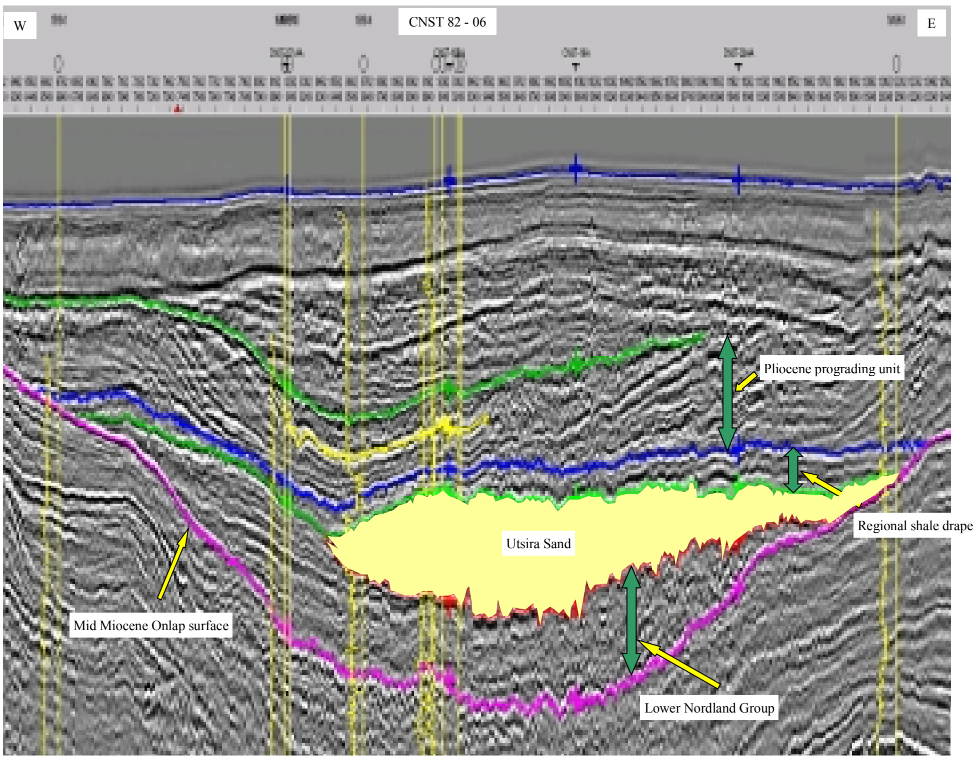

Final Report of the SACS 1 project -

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

Work Area 1 – Geology

BGS Technical Report WH/2000/21C (Confidential)

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1. DATA OBTAINED AND WORK CARRIED OUT

TASK 1.1 CHARACTERISATION OF CORE AND CUTTINGS FROM THE UTSIRA SAND (SINTEF/BGS)

Core from the Utsira Sand

Near the start of the SACS project, Statoil cut a 9m core from the Utsira Sand in Norwegian sector well 15/9-A23, a Sleipner field development well. This was done specifically to provide data for the project. The drilled depth of the 9m core was 1079-1088 m, corresponding to 905.4-910.8 m TVDSS. Sections of core were sent to Sintef Petroleum Research, BGS and GEUS as below:

- Two1m long segments of core were sent to SINTEF Petroleum Research (1080-1081 m and 1087-1088 m drilled depth; 906.0 - 906.6m and 910.2-910.8m TVDSS).
- One 1m segment was sent to BGS (1085-1086 m drilled depth; 909.0-909.6m TVDSS).
- One 0.9m segment was sent to GEUS (1084.1 – 1085.0m drilled depth, 908.47-909.0m TVDSS). GEUS were not involved in Task 1.1 One sample of this segment was taken by SINTEF.

The SINTEF segment of core was sampled and analysed. The analysis included microscopy and mineralogical modal analysis.

The BGS segment of core was inspected and photographed. The core was sampled and characterised mineralogically and petrographically. The analyses involved mineralogical characterisation by X-ray diffraction (XRD) analysis, petrographic analysis by secondary scanning electron microscopy (SEM) including backscattered scanning electron microscopy (BSEM), and limited electron probe microanalyses (EMPA) of selected minerals. A single sample was examined micropalaeontologically, to obtain information on the age and sedimentary environment of the Utsira Formation.

Cuttings from the Utsira Sand

Cuttings from 3 Statoil-owned wells in the Norwegian sector were sampled. Several of the samples were washed and examined. Modal analyses on thin sections from some sand-rich samples (Utsira Fm) were carried out.

Washed cuttings from 39 wells in the UK sector of the North Sea were inspected, and selected samples were collected. The cuttings samples were examined by binocular microscope to check and supplement existing descriptions in well reports and on composite logs.

Well logs from the Utsira Sand

Greater Sleipner Area

Well logs from released wells penetrating the Utsira Sand in the UK and Norwegian sectors have been compiled. Regional scale correlation diagrams were made for wells held digitally (this is not a fully comprehensive dataset). Depth to top and base Utsira Sand was determined. Net sand and total pore volume were mapped in the UK sector. Porosity was determined from sonic logs in all released wells in the UK sector. Porosity was also determined from geophysical logs in several wells in the Norwegian sector.

Sleipner Area

Geophysical logs from wells close to the injection well were compiled, analysed, and arranged into profiles. The presence and regional distribution of shale horizons in the Utsira Sand was deduced, and two major shale horizons were mapped. The depth of the top Utsira Sand (base cap-rock) and the base Utsira Sand was determined and mapped. The well log data were compared with mud logs from selected wells.

TASK 1.2 REINTERPRETION OF THE EXISTING SLEIPNER 3D SURVEY (TNO/SINTEF)

The existing 3D seismic dataset ST98M11 covers a rectangular area of about 400 km^2, over the Sleipner gasfields, close to the UK/Norway median line (Figure 1.1). Four seismic reflectors were interpreted on the 3D dataset, these are from top to bottom: Top Pliocene Prograding Unit, Intra-Pliocene Prograding Unit, Top Utsira Sand and Base Utsira Sand. These were linked to well-logs via synthetic seismograms. They were also linked to the corresponding reflectors in the 2D seismic datasets to integrate with Task 1.3. The reflectors were interpreted on a fine grid, down to every line at features of interest (e.g., at the injection site, at mud volcanoes, in faulted areas). Two-way travel time maps and isopach maps were generated. Attribute maps (especially mean interval amplitudes) were also generated, to help map amplitude anomalies that might signify the presence of shallow gas. A time-depth conversion table based on the well log data in the 3D area was produced. Interpretation concentrated on aspects of the deposition and deformation of the Utsira Sand in the context of CO_2 migration and storage safety.

TASK 1.3 STRATIGRAPHY AND STRUCTURE OF THE GREATER SLEIPNER AREA (BGS/GEUS/SINTEF)

Seismic data from three regional surveys (CNST82, NNST84, NVGT88, VGST89) in the North Sea was loaded on to workstations. Problems were encountered because the various datasets were incomplete, and data from various sources (Norwegian Data Centre, SINTEF and Geco-Prakla) were utilised. The problems have now been mostly overcome. Reprocessed data for the CNST survey (CNST82RE6) has also been purchased and will be loaded shortly. A large number of wells have also been loaded onto the workstations, most with interpreted stratigraphy, geophysical logs and time-depth information. Current data holdings are summarised in Table 1.1 and Figure 1.1.

Table 1.1 Data Summary – Greater Sleipner area

SEISMIC DATA			WELL DATA		
survey (source)	UK	Norway	UK	Norway	
CNST82 (NGC)	no	yes	137	240	number of wells loaded onto workstations
CNST82 (SINTEF)	part	part	101	138	interpreted stratigraphy
CNST82RE (GECO)	yes	yes	87	103	geophysical logs
NNST84 (NGC)	yes	yes	81	89	time-depth information
NNST84 (Sintef)	yes	no			
NVGT88 (NGC)	yes	yes			
VGST89 (SINTEF)	yes	yes			

The current lithostratigraphic scheme used in the Norwegian sector for the Utsira Sand and surrounding strata is not well-suited to the detailed interpretation of the reservoir system. This is because the Utsira Formation as lithostratigraphically defined includes both the main reservoir unit (up to 300 m of clean sand) and also overlying shaly strata which form a cap rock to the storage reservoir in parts of the North Sea. Consequently, we have adopted a seismic stratigraphical framework to subdivide the storage reservoir and surrounding strata into depositional units. The main storage reservoir is referred to as the Utsira Sand throughout this account. The surrounding seismo-stratigraphical units have not yet been named, but reflectors defining the main components of the geotechnical system which comprises the storage reservoir and its surrounding strata are described below.

Regional interpretation concentrated on the CNST82 survey in the Greater Sleipner area (Figure 1.1). Five main reflectors define the Utsira geotechnical system. These are, from top to bottom: Top Pliocene Prograding Unit, Base Pliocene Prograding Unit, Top Utsira Sand, Base Utsira Sand and Mid-Miocene Onlap Surface (Figure 1.2). Top and base Utsira Sand correspond to the sand as defined in the wells in the Sleipner field. Three of the reflectors, Top Pliocene Prograding Unit, Top Utsira Sand and Base Utsira Sand were integrated with the picks on the 3-D seismic dataset (Task 1.2).

More localised prograding sandy wedges, both above and below the Utsira Sand were identified, and the geometry of these and other seismic stratigraphic units between the interpreted horizons was used to gain insights into depositional processes. Reflectors and unit-internal patterns on seismic data were compared with well log data on regional well profiles.

The Utsira Sand has so far been picked over an area of about 9500 km^2 . Provisional two-way travel-time maps were made of Top Utsira Sand, Utsira Sand Isochore, Base Utsira Sand and the Mid-Miocene Onlap surface.

The only core from the Hutton Sand (from well 211/29-D37) was examined and described. The Hutton Sand is a term used by Shell to describe all sands above the early Eocene Balder Formation in the Northern North Sea). Selected samples from this core were collected and will be analysed during the SACS2 project. This well is still confidential at present.

TASK 1.4 EVALUATION OF THE RESERVOIR CAP ROCK (SINTEF/GEUS)

During the year it became clear that no core material was available from the cap rock for testing. However, wireline log and mud log data from the cap rock was compiled and interpreted.

Ten wet cuttings samples from three wells in Norwegian block 15/9 were obtained and described and a representative selection from two of the wells was analysed by X-ray diffraction.

Preparation of cuttings from the wet samples is difficult because the soft shale is washed away if preparation is carried out using normal routine methods. Because of the fragile cuttings, the mud was removed by soaking and gently stirring the samples in distilled water and decanting the dispersed drilling mud until the cuttings samples appeared to consist predominantly of clean cuttings.

The cuttings samples were disintegrated and the clay fraction separated into size fractions using a particle size centrifuge. The size fractions 2-0.2 μm and <0.2 μm were investigated by XRD. The following oriented specimens were prepared by the pipette method:

- Mg-saturated and air-dry
- Mg-saturated and saturated with glycerol
- K-saturated and air-dry
- K-saturated and heated to 300°C.

Search for further cap rock samples (preferably wet samples and/or cores) from close to the injection site will be continued in SACS2.

Wireline log data from the cap rock in the UK sector of the South Viking Graben was compiled and interpreted. Cuttings samples from 39 wells were inspected and selected samples were collected for analysis. Analysis will take place mainly in the SACS2 project due to budget deferral to SACS2 (BGS in any case has no budget for this task). Initial results indicate that the cap rock consists of medium grey to dark grey mudstone in the South Viking Graben.

Petrophysical analysis of the cap rock was carried out using wireline log data. Shale volume has been estimated, but ideally needs to be calibrated to the shale volume determined from other methods (e.g. core).

TASK 1.5 EVALUATION OF FORMATION FLUIDS (GEUS)

No fluid samples from the Utsira Formation were available for analysis. Both GEUS and BGS extracted pore fluid from their core segments. However the recovered fluid samples were found to be heavily contaminated by drilling mud (see Work Area 3 – Geochemistry for analyses).

TASK 1.6 ESTIMATE OF THE NATURAL WATER FLOW IN STORAGE RESERVOIR (GEUS)

Given that only three pressure measurements are available from the Utsira Formation in the North Sea, it was not possible to determine the natural fluid flow in the Utsira Sand with any confidence. There are moreover, serious doubts about the accuracy of the pressure data in the Sleipner area. Preliminary calculations of fluid flow were made however, on the basis that the pressure measurements are accurate.

2. OVERVIEW OF RESULTS FOR WORK AREA 1

THE UTSIRA SAND

Regional Interpretation

Regional interpretation of seismic and well logs has, so far, concentrated on the Greater Sleipner area, roughly corresponding to the CNST82 seismic survey. Sequence stratigraphical interpretation of the data has provided key insights into the subsurface geology. The Utsira Sand is probably a simpler unit than previously thought, corresponding to a clean, basin-restricted sand. The seismic data show that other sand or sand/shale bodies, previously interpreted from well logs as belonging to the Utsira Sand, are actually completely different sedimentary units. Some of these have a progradational geometry, and some lie above and some below the Utsira Sand.

The regional interpretation shows that the Utsira Sand covers an area of at least 10000 km^2. The top of the sand lies at about 1300 ms twtt (~1250 m) in the south, shallowing to less than 700 ms (~650 m) in the north (Figure 1.3). The thickness of the Utsira Sand is, in detail, quite variable, partly as a consequence of its irregular base. In general terms however, it is thickest in the Sleipner area, with a maximum thickness of more than 280 ms twtt (~ 300 metres) a few kilometres to the north of the Sleipner fields (Figure 1.4). The sand thins away from this depocentre in all directions. Thinning is most rapid towards its western pinchout, and more gradual to the east and south. Updip pinchout limits for the reservoir have been established to the west and east.

Our current interpretation suggests that the Utsira Sand may also pinch out to the north and northeast, in the vicinity of the likely migration path. However, further interpretation of the northern North Sea well and seismic datasets is required to prove or disprove this. The preferred regional migration trend, assuming a gravity drive, would appear to be northwards from Sleipner. The distribution of the Utsira Sand to the southwest is currently uncertain because of data availability, but the recently purchased seismic dataset will resolve this problem (in any case CO_2 migration in this direction is considered unlikely).

More detailed interpretation in the Sleipner area

In the immediate vicinity of the Sleipner fields (Norwegian Block 15/9 and adjacent blocks), a more detailed network of seismic lines and well data were interpreted. These data show the general dip of the top Utsira Sand towards the south, in accordance with the regional interpretation, and the presence of a north-striking depression of the top Utsira Sand ~20 km west of the injection site. Gravity-driven migration of CO_2 on a more regional scale is consequently likely to take place towards north.

Within the Utsira Sand, several (up to 14) thin (<1m thick) shale layers were identified. These intra-Utsira shale layers are expected to influence migration of CO_2 (discussed below).

Interpretation of the area immediately surrounding the injection site

The existing 3D seismic survey ST98M11 provided important insights into the local geology in the area immediately surrounding the injection site. The correlation of the logs with the seismic data has been established through synthetic seismograms (Figure 1.5). Mounds at the base of the Utsira Sand (Figure 1.6) were mapped and were interpreted as being due to mud volcanism and mud diapirism that was active during deposition of the lower part of the Utsira Sand. The presence of these shale mounds (Figure 1.7) induced compaction and subsidence anomalies which led to depressions of the Utsira Sand and overlying units above the mud volcanoes. These depressions constitute local modifications of the general southward dip of the top Utsira Sand, including local domal and anticlinal structures which probably will act as traps and/or channels during CO_2 migration (Figure1.8).

The base of the Utsira Sand is locally faulted (small reverse faults predominate), but in cases identified up to now, faulting has not affected the Utsira Sand itself or its cap rock (Figure 1.9).

Anomalously high amplitudes occur occasionally within the lower part of the Pliocene shales and the Utsira Sand and are abundant in the upper Pliocene shales (Figure 1.10). Most of the anomalies in the Utsira Sand were identified as probable artefacts (multiples), whereas some of them, and the anomalies in the overlying Pliocene shale units, are considered to be real phenomena, which might be at least partially due to the presence of shallow gas. These anomalies seem in some cases to be linked to mud volcanoes by zones of weak amplitudes ('gas chimneys'). Many of the anomalies, however, are not linked directly to features at the base of the Utsira Sand. Only a few amplitude anomalies have been observed at the top of the Utsira Sand.

Characterisation of the Utsira Sand core and cuttings

Macroscopic and microscopic analysis of core and cuttings samples of the Utsira Sand show that it consists mainly of fine sand, but contains medium and occasional coarse grains. The sand grains are predominantly angular to sub-angular and consist primarily of quartz with some feldspar and organic components (shell fragments). They are almost completely uncemented. Sheet silicates are present in small amounts (a few percent). The cores through the Utsira Sand show no visible layering or preferred orientation of minerals. Shell fragments are common and seem to be randomly oriented. This lack of layering might be due to high energy deposition (e.g. as a turbidite) or due to bioturbation.

The core sample from 1085 – 1086 m is a medium grained, moderately to well sorted, very poorly cemented and friable subarkosic sand. It comprises predominant quartz with minor plagioclase, K-feldspar, calcite (probably shell fragments) and common bioclastic debris including foraminifera, radiolaria and sponge spicules. Some detrital grains are covered in a thin, <10 µm, clay coating which XRD indicates comprises mainly smectite with minor illite and chlorite. Limited SEM evidence indicates that some smectite morphologies are indicative of authigenic development. Pyrite is a minor but commonly distributed authigenic mineral occurring as framboidal aggregates, especially within foraminifera tests. The most notable diagenetic modification is the development of two minor zeolites, phillipsite and clinoptilolite. Phillipsite is the dominant zeolite. Both zeolites have developed through precipitation directly from porewaters with the dissolution of radiolaria and sponge spicules providing a likely source of biogenic silica. Although common the zeolites only form a very small component of the sand and do not represent a significant modification to porosity and permeability.

A full description of the analysis of this core segment is given in a separate technical report:

Pearce, J.M., Kemp, S.J. and Wetton, P.D. 1999. Mineralogical and petrographical characterisation of a 1m core from the Utsira Formation, Central North Sea. Report WG/99/24C. British Geological Survey.

Porosity of the Utsira Sand

Porosity of the Utsira Sand core determined by microscopic modal analysis of thin sections ranges generally from 27% to 31%, but reaches values as high as 42%. However, these measurements were made from thin sections of frozen loose sand from a single part of the reservoir. As a guide to regional reservoir properties they may therefore be less reliable than porosities derived from wireline logs.

The sonic log was used for the regional porosity calculations, but the log response coefficients differ from values normally used in sandstones, possibly because the Utsira Sand is loose and completely unconsolidated. To overcome this problem, in the Norwegian sector, the density log was used for porosity determination where available. Subsequently, the porosities derived from the density logs were used to calibrate the sonic log response coefficients in order to derive a modified dataset to be used for determining a more accurate sonic log porosity in the Utsira Sand (Table 1.2).

Table 1.2 Sonic log - porosity calibration

Sonic log response coefficients	Sandstone micro-sec/ft	Shale micro-sec/ft	Water (porosity) micro-sec/ft
Standard values, compacted sands	55	100	189
Used for the Utsira sand, uncompacted sand	55	155	330

The porosity determination in the Norwegian sector is thus based on the sonic log and the shale volume as calculated above. The log interpretation indicates that the porosity of the Utsira Sand ranges from 30 to 40%; the highest porosity values are found within the Sleipner area and the porosity of the Utsira Sand decreases slightly away from the Sleipner area. The variation in porosity (PHIS) is illustrated as a cross-section (Figure 1.11).

Petrophysical analysis in the UK sector (using sonic logs only, not calibrated by density logs) indicates that the porosity of the Utsira Sand (excluding the shale layers) is ≥ 40% in nearly all wells. In SACS2, a common approach to porosity determination will be decided on.

Total pore volume of the Utsira Sand

In the UK sector, net sand thickness was calculated and contoured in 60 wells. The total volume of clean sand was computed to be 1.72×10^{11} m^3. Pore volume was estimated at 5.16×10^{10} (asuming 30% porosity) or 6.88×10^{10} m^3 (assuming 40% porosity). Given a CO_2 density of about 660 kgm^{-3}, the amount of CO_2 that could be stored in this volume is estimated at 3.41×10^{10} tonnes (ϕ = 30%) or 4.54×10^{10} tonnes (ϕ = 40%).

From the provisional sand isochore map (Figure 1.4), a total pore volume of the Utsira Sand, neglecting the area in the south not mapped in detail, is estimated at between 3.1 $\times 10^{11}$ m^3 (ϕ = 30%) and 4.1×10^{11} m^3 (ϕ = 40%). Again, given a CO_2 density of about 660 kgm^{-3}, the total storage capacity of the Utsira Sand (as defined in Figure 1.4) is estimated at 2.05×10^{11} tonnes (30% porosity) or 2.71×10^{11} tonnes (40% porosity). Note however, that these figures assume the ability to fill the whole reservoir porespace with CO_2, true filling efficiency is likely to be much lower than this.
[N.B. These estimates are very provisional and will be refined in SACS2.]

Natural fluid flow in the Utsira Sand

Only three formation pressure measurements are available from the Utsira Sand, so it is difficult to quantify accurately the natural water flow in the aquifer. Two Utsira pressure measurements are available from the Sleipner 15/9-A-23 well. In addition, the formation pressure has been measured in a formation termed the Utsira Sand in the Brage Field, approximately 250 km north of the Sleipner area (Table 1.3). No Utsira well test data are available from elsewhere within the Greater Sleipner area, including the injection well (this information was provided by Statoil).

Table 1.3. Formation pressure measurements in the Utsira Sand

Area	Formation pressure	Depth, TVDss	Pressure gradient	Source

	(bar)	(m)	(bar/m)	
Sleipner	106.1	853.6	0.124	Statoil
Sleipner	108.0	854.4	0.126	Statoil
Brage	65	638	0.102	Norsk Hydro

The pressure gradient in the Brage Field is consistent with hydrostatic pressure, whereas the Sleipner data indicate a pressure environment slightly above hydrostatic (Figure 1.12). However, Statoil believe there is uncertainty related to the accuracy of the pressure gauge used to acquire the Sleipner pressure data. The pressure gradient calculated for the Sleipner area may therefore be too high (cf. Baklid et. al. 1996) which states that the Utsira Sand is water filled and the pressure is hydrostatic.

Fluid flow on the assumption that the pressure gradient is hydrostatic at Sleipner and Brage

If the pressure gradient is hydrostatic both at Sleipner and Brage the natural water flow in the storage reservoir will insignificant because then the difference in overpressure will be close to zero. However, the presence of a tight seal at Sleipner (indicated by the raw stacks of the new 3D seismic survey) suggests that the actual formation pressure could reasonably be above hydrostatic.

Fluid flow on the assumption that there is slight overpressure at Sleipner

If the figures for Sleipner quoted above are accurate and representative, and thus that there is overpressure at Sleipner, and that the density of the formation water is 1.03 g/cc, corresponding to a hydrostatic pressure gradient of 0.101 bar/m, the overpressure can be calculated as follows:

$$\text{overpressure } (mH_2O) = (\text{formation pressure} / 0.101) - \text{depth}$$
$$\text{overpressure (bars)} = \text{formation pressure} - (0.101 \times \text{depth})$$

Table 1.4 Possible overpressure in the Utsira Sand

area	formation pressure (bar)	depth, TVDss (m)	overpressure (m)	overpressure (bar)	comments
Sleipner	106.1	853.6	196.8	19.8	slightly overpressured
Sleipner	108.0	854.4	214.8	21.7	slightly overpressured
Brage	65	638	5.5	0.56	no overpressure

Using the figures tabulated above, the difference in overpressure between the Sleipner and Brage Fields is approximately 20 bar, the distance between the two fields being about 250 km. If it is assumed that the Utsira Sand is not hydrogeologically compartmentalised between Sleipner and Brage, then a very approximate estimate of the natural fluid flow (V) can be calculated from Darcy's Law.

Assuming a permeability of 1 Darcy (average for the Utsira Sand) and a formation fluid (brine) viscosity of 0.9 cP, a flow velocity of approximately 10^{-8} m s^{-1} is obtained. This approximates to 0.3 m per year or about 3 km in 10000 years.

This determination of the natural fluid flow in the Utsira Sand is based on only three data points. Nevertheless, available data suggest that the natural flow is very slow and apparently directed toward areas where the Utsira Sand is found at structurally high levels, i.e. in a northerly and northwesterly direction. Two or three data points are, however, insufficient to determine a reliable flow velocity. In addition, the considerable distance between the data points means that the velocity calculation is associated with considerable uncertainty; the assumption that the overpressure decreases linearly from Sleipner to Brage, may not be perfectly valid.

Reference

Baklid, A., Korbøl, R. and Owren, G., 1996: Sleipner vest CO_2 disposal, injection into a shallow underground aquifer. SPE paper no. 36600.

THE CAP ROCK

The 'Greater Sleipner' area

The thickness and lithology of the cap rock varies on a regional scale. The lowest part, immediately above the Utsira Sand, is interpreted as a regional shale drape (Figure 1.2), the continuity and lithology of which may be of crucial importance to the integrity of the seal. Above this the Pliocene Prograding Unit progrades into the basin from both west and east. It has a tendency to coarsen upwards into a sandy facies in its marginal prograding parts, whereas it remains shaly in the basin centre (around Sleipner). There is however, the possibility that sandy beds exist on some clinoforms, thereby potentially degrading the caprock seal. The prograding unit is itself overlain by a basin-restricted Pliocene shale unit that thins towards the eastern basin margin. Above this lies a thick Quaternary shaly to sandy succession.

The Sleipner area

The regional shale drape and the Pliocene Prograding Unit exhibit locally anomalously high amplitudes. The uppermost Pliocene shale unit is characterised by irregular internal reflectors and frequent very high amplitudes (Figure 1.10). The amplitude anomalies in these units might be due to isolated high-velocity lithologies, or alternatively to the presence of shallow gas (discussed below).

The area immediately surrounding the injection site

Above the top of the Utsira Sand, separated from it by a ~5 m thick shale unit, a westward thinning sand wedge is locally present (Figure 1.13). The areal distribution of this sand wedge has been mapped. It is present above the injection site and disappears about 3 km to the west of it.

Characterisation of cuttings from the cap rock

Cuttings samples of the Pliocene shales overlying the Utsira Sand in the Norwegian sector were successfully washed from three wells (Table 1.5). In the selected size fractions a minor number of whitish and rusty cuttings appeared, indicating cementation with carbonate and siderite.

Table 1.5 List of cuttings washed from three wells in the Sleipner Field

Well no.	depth (m)	description
15/9-15	650-660	approx. 1 mm in size, flaky
15/9-16	700-710	approx. 1-4 mm in size, flaky to subrounded
15/9-18	850-860	1-4 mm in size, flaky or slightly rounded

XRD analysis indicates sheet silicate contents in the range 40 to 66%. The diffractograms show that the different wells have very similar clay mineralogy, namely a mixture of approximately equal amounts of smectite, vermiculite, illite, and kaolinite, with traces of chlorite. This demonstrates that the content of drilling mud, usually containing the clay mineral smectite, is negligible, since the different size fractions have approximately the same content of smectite and since smectite is not a dominating mineral in the diffractograms. Furthermore, cavings are not a significant problem, similarly because the different cuttings sizes have nearly identical clay mineralogy.

Cuttings samples from the cap rock in the UK sector were examined under a binocular microscope. They appear to show that the regional shale drape consists of grey mudstone and that the upper part of the Pliocene Prograding Unit consists of siltstone. However, a more rigorous study of these cuttings is essential to make sure that samples are representative of the lithology at the depths from which they were collected (i.e. not cavings).

Log characteristics of the cap rock

Log data from selected wells have been interpreted quantitatively in order to estimate the shale volume of the cap rock. Gamma ray, resistivity and sonic logs are available from most wells and in a number of wells, a density log is also available.

Shale volume

The shaliness of the sealing formation was estimated from the gamma ray log. Only a rough calculation can be made, because the log-derived shale volume needs to be calibrated to the shale content determined from core or cuttings data. The log interpretation carried out so far suggests that, although the shale volume varies considerably within the cap rock, in most of the area studied, the Utsira Sand is overlain by a unit at least 100 m thick which comprises approximately 80% shale. However, northwest of the Sleipner Field, in the area defined by the wells N-15/3-1S, UK-9/23-1 and N-24/9-4, both the thickness and the shaliness of the capping shale decreases as illustrated in the cross-section (Figure 1.11). In the cross-section, the shaliness curve is denoted VSHGRL (shale volume calculated from the gamma ray log). The cross-section also shows that the Utsira Sand gradually becomes more shaly within this area.

3. PRELIMINARY DISCUSSION OF RESULTS FROM WORK AREA 1

REGIONAL GEOLOGY

The interpretation of regional seismic profiles has identified sand units in some wells that have been classified as Utsira Sand on the basis of well correlation but which are actually separate and distinct sedimentary bodies. These sands need to be distinguished to allow accurate mapping of the Utsira Sand. This will require additional, infill seismic and well data, the latter with accurate velocity information.

The nature of the pinchout of the Utsira Sand to the northwest (in the vicinity of a suggested migration pathway) is not clearly imaged on the available seismic data. It appears to lap out against a variably sandy unit and to be downlapped by a local sand-prone wedge of sediment. Both of these units provide potential migration routes for the CO_2. This needs to be mapped as accurately as possible, and will require additional seismic data.

Basinally restricted sands have been identified to the northeast of the Greater Sleipner area. On the basis of the present interpretation these are suspected to be older than the Utsira Sand and not in physical contact. These relationships will be clarified in SACS2, and individual sand bodies mapped to define their storage potential.

RESERVOIR PROPERTIES OF THE UTSIRA SAND

All lines of evidence show high porosity in the Utsira Sand. Even though permeability as measured in laboratory experiments (Work Area 2) is high, it is lower than might be expected from the high porosity determinations. The presence of clay minerals and of oblate shell fragments may contribute to some permeability reduction, though their random orientation would minimise this effect. This random (isotropic) orientation is, on the other hand, in line with the similarity of measured horizontal and vertical permeability (Work Area 2),

Individual seismic reflectors within the Utsira Sand can be traced over considerable distances (often several kilometres), consistent with rather uniform lithologies and reservoir properties on that scale. Unfortunately, no direct information is available about the thin intra-Utsira shale layers since they are not present in the single core and because they cannot be identified with any certainty in the cuttings.

Since the shale layers within the Utsira Sand are probably impermeable to CO_2 on a time scale of up to a few thousand years, their presence above the injection point may be expected to retard upward migration of the CO_2 and perhaps cause its lateral dispersion. Raw stacks from the recently acquired time-lapse seismic survey suggest that a degree of lateral migration has occurred along certain layers within the Utsira Sand, but further work is required to determine whether this is caused by the presence of shale layers or by vertical variations in the permeability of the sand. On the other hand, the time-lapse seismic data also suggest that CO_2 has already migrated to the top of the Utsira Sand. This suggests that the intra-Utsira shale layers do not significantly inhibit vertical migration in the area immediately around the injection point. This is consistent with the shales being discontinuous or broken on a local scale.

MIGRATION PATHWAYS

The spill point of the dome above the injection site is difficult to determine, as there are two elevated 'channels' leading away from the dome at nearly identical depths (Figure 1.14). CO_2 can thus migrate either northward into a second dome, from where it can migrate westward into a large domal structure, and/or migrate directly from the southern dome into this westerly, large dome. This dome is then connected northward to a set of domal and anticlinal structures. Migration pathways through these structures and volume estimates have not yet been established. The time-depth conversion is crucial in determining the spill points of the local small domes. The time-depth conversion of the 3D survey is based on a velocity model derived from the near-vertical exploration wells. The estimated error in depth conversion at top Utsira Sand level is within 1.2% (<10m).

On a more regional scale, CO_2 would then, following the local maximum top reservoir topography gradient, migrate first north-westward and then northwards. This could ultimately take the CO_2 towards its pinchout in the northwest (Figure 1.4).

With regard to natural fluid flow within the Utsira Sand, its high permeability (1 Darcy or higher) suggests that if pressure differences do really exist, they may reduce significantly over geological timescales, provided that the Utsira Sand is a regionally continuous aquifer.

It is suggested that a basin modelling study based on seismic data, well log data and pressure information should be considered. The feasibility of applying basin modelling should be examined on the basis of a 2D study. In this context the seal integrity (shaliness and thickness) should be studied further, especially in areas where the cap rock is relatively thin. Additional information on pressure and temperature would be valuable in order to calibrate the model. Furthermore, the question of whether the Utsira Sand reservoir is in pressure communication on a regional basis or whether it consists of separate, isolated pressure systems should be examined.

EFFECTIVENESS OF THE CAP ROCK

In previous studies, the efficacy of the cap rock of the Utsira Sand, i.e. the Pliocene shales of the Nordland Group, as an efficient seal for injected CO_2 has not been studied in detail. The nature and effectiveness of this potential seal, on a regional basis, will be examined more closely in SACS2.

Preliminary stacks from the time-lapse seismic survey show no change in the reflections from within the cap rock, indicating that it is currently forming an effective barrier to CO_2 migration above the injection point.

The possibility that amplitude anomalies seen on the seismic data (Figure 1.10) may be due to the presence of shallow gas in the Pliocene shales should not be discounted. Small amounts of gas at this level have been reported in mud logs and drilling reports from wells in the Sleipner area. The reports indicate the presence of higher hydrocarbons (ethane, propane, butane, etc.) which may point to a thermogenic origin for the gas. This implies that the gas has migrated from depth within the basin, upwards through the Utsira Sand and into the cap rock. However, the fact that it is trapped in the cap rock is evidence for its sealing capacity. Furthermore, it should be remembered that migration of natural gas into, and even through, the shales making up the cap rock may not automatically imply a risk for the safety of the CO_2 storage site. Natural gas migration (possibly only in minute quantities) may have slowly taken place over a time span of up to a few million years, whereas CO_2 storage safety needs to be proven for an interval of a few thousands to tens of thousands of years.

An oil show is present in the top of the Utsira Sand in UK well 22/5a-1. This demonstrates that there has been some upward migration of hydrocarbons into and/or through the Utsira Sand, but neither conclusively supports nor refutes the effectivness of the cap rock.

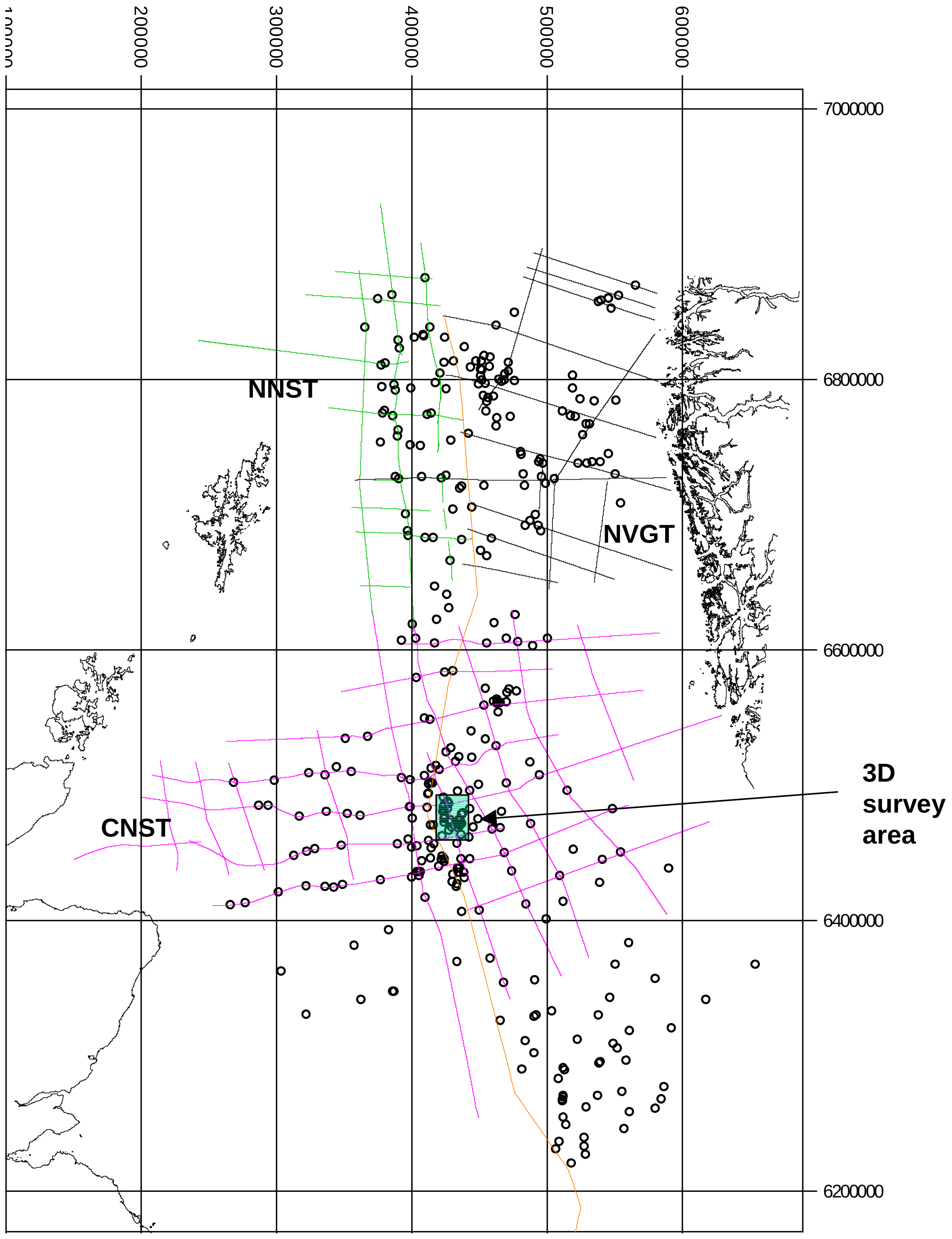


Figure 1.1 Data location map showing regional CNST, NNST and NVGT seismic surveys and wells. Location of 3D survey ST98M11 also indicated.

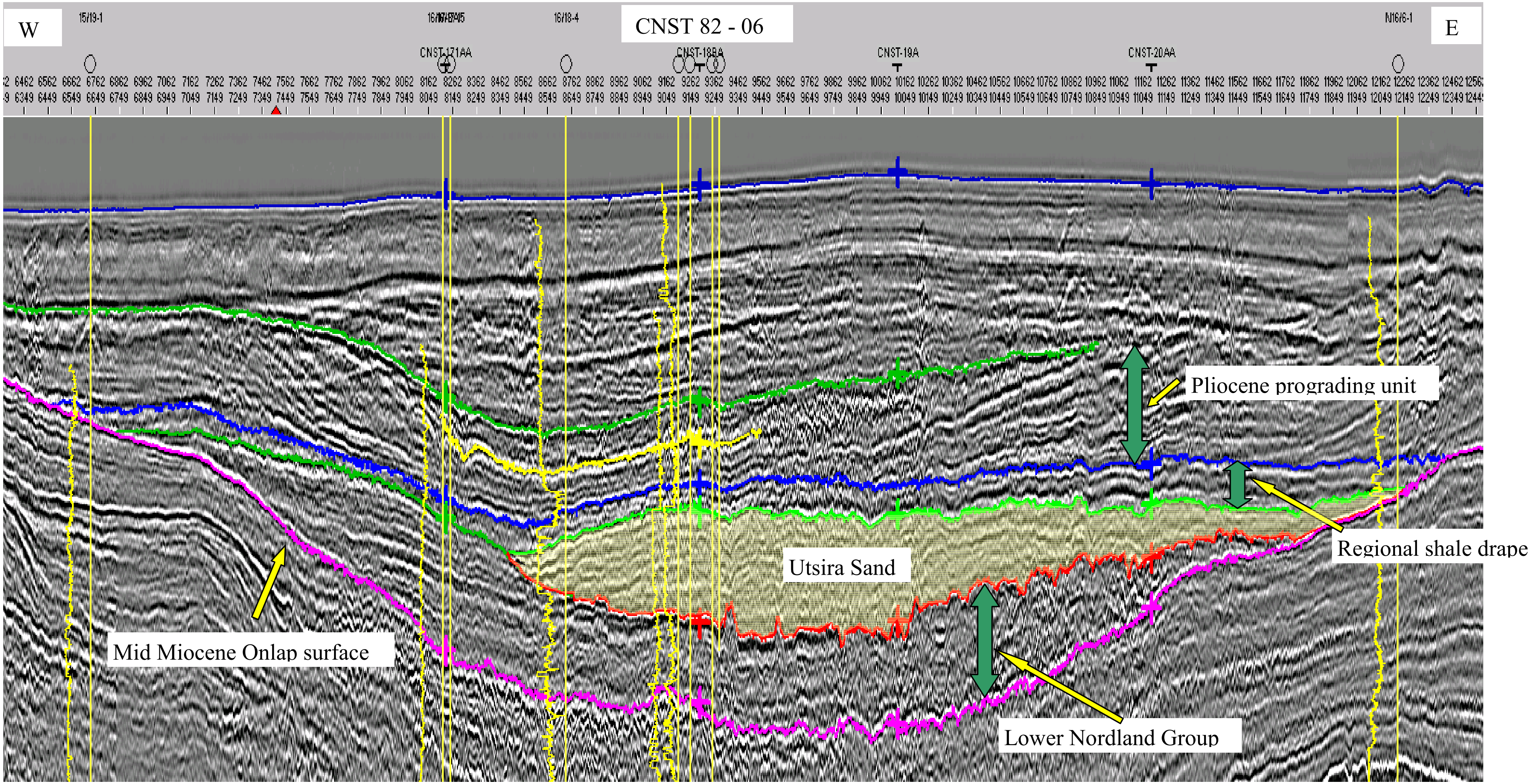


Figure 1.2 Regional seismic line through the Utsira geotechnical system

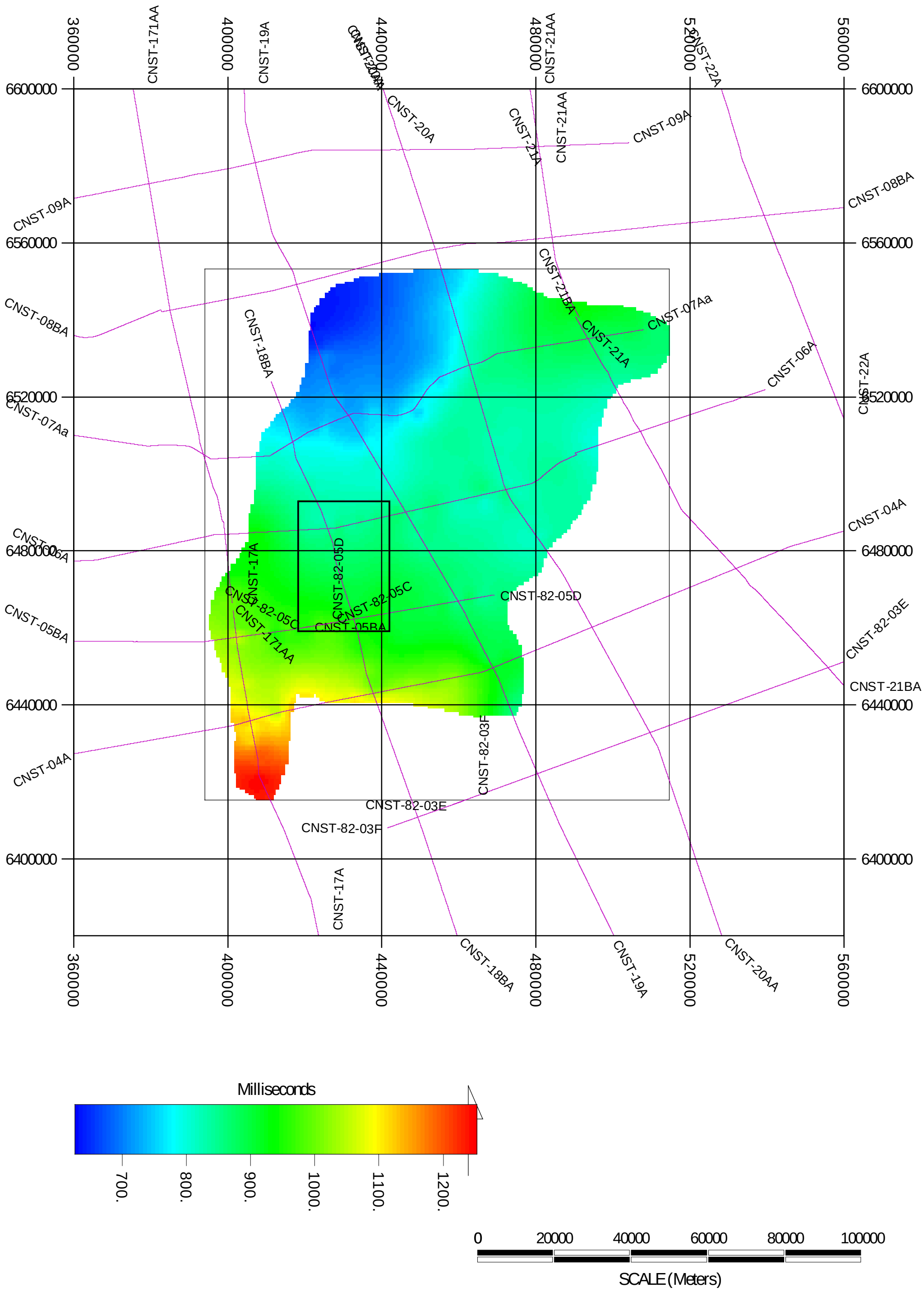


Figure 1.3 Two-way time map to Top Utsira Sand (preliminary interpretation)

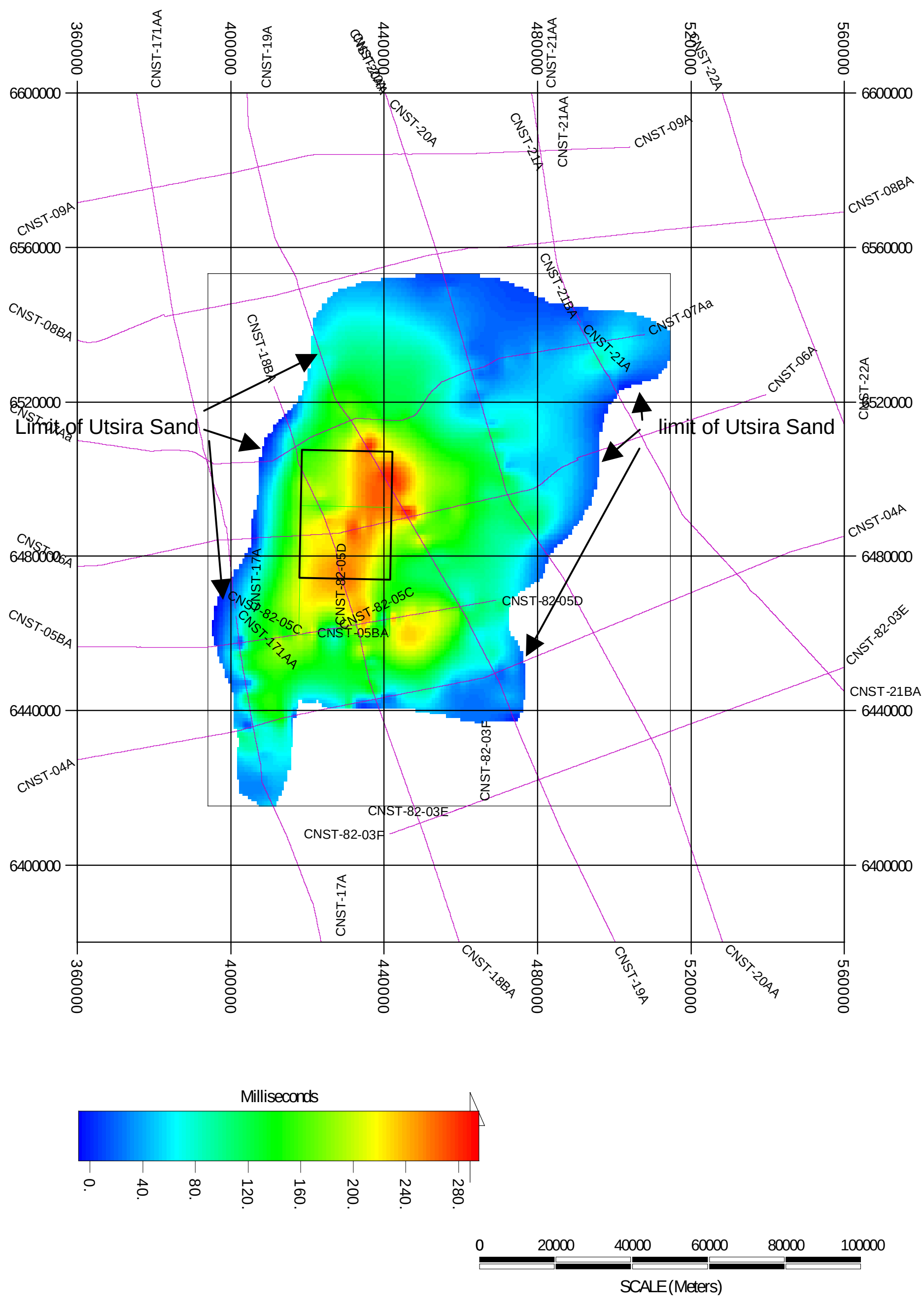


Figure 1.4 Two-way time isochore map of Utsira Sand (preliminary interpretation)

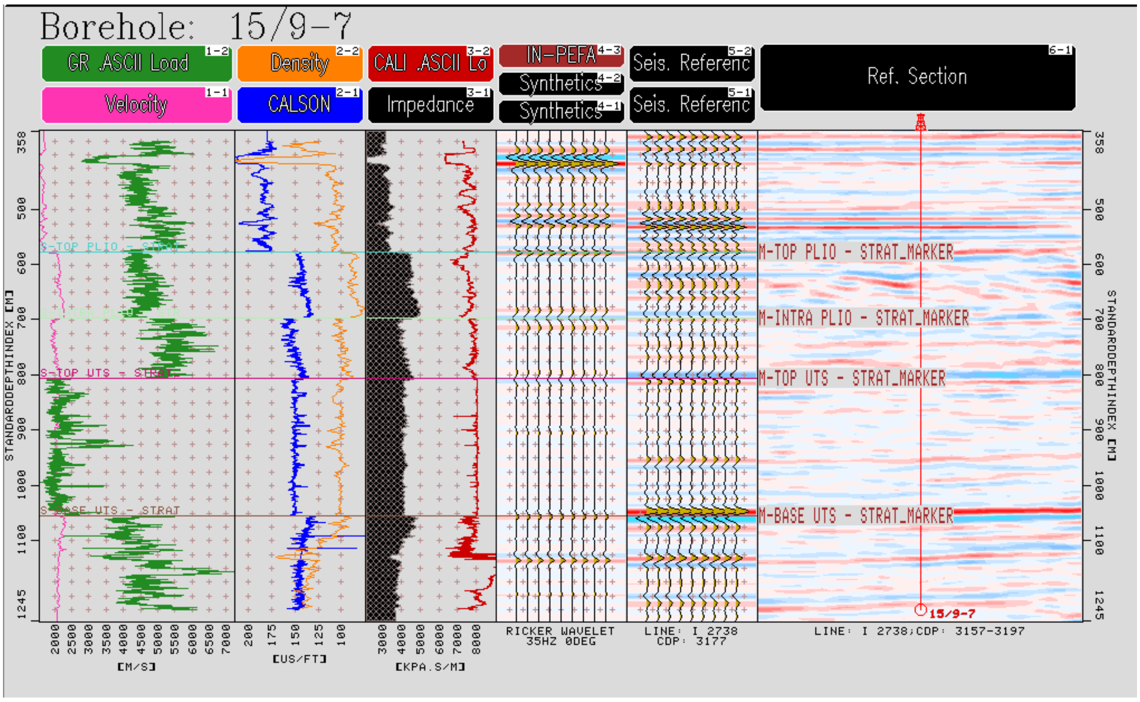
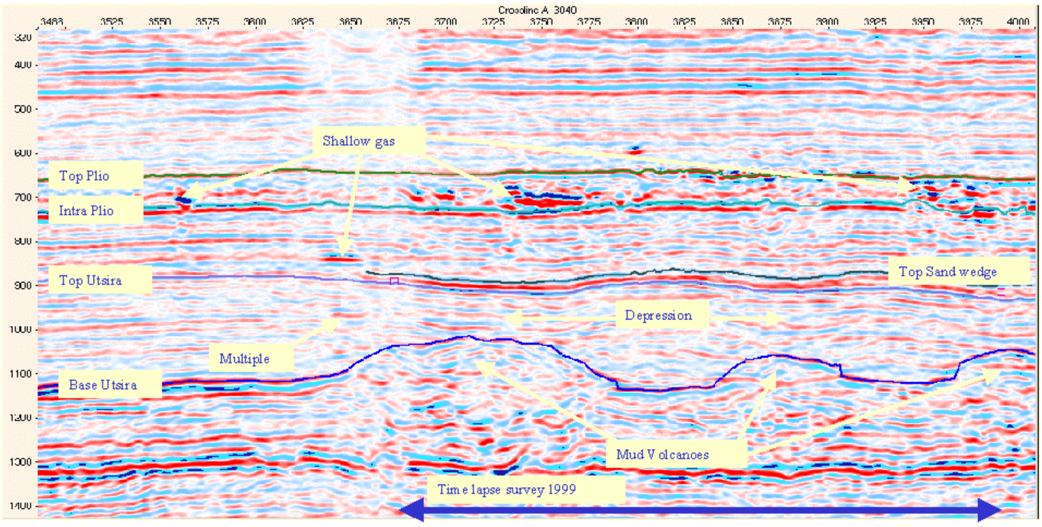


Figure 1.5: Synthetic seismograms derived from the well log data (Well 15/9-7) compared to the actual seismic data.



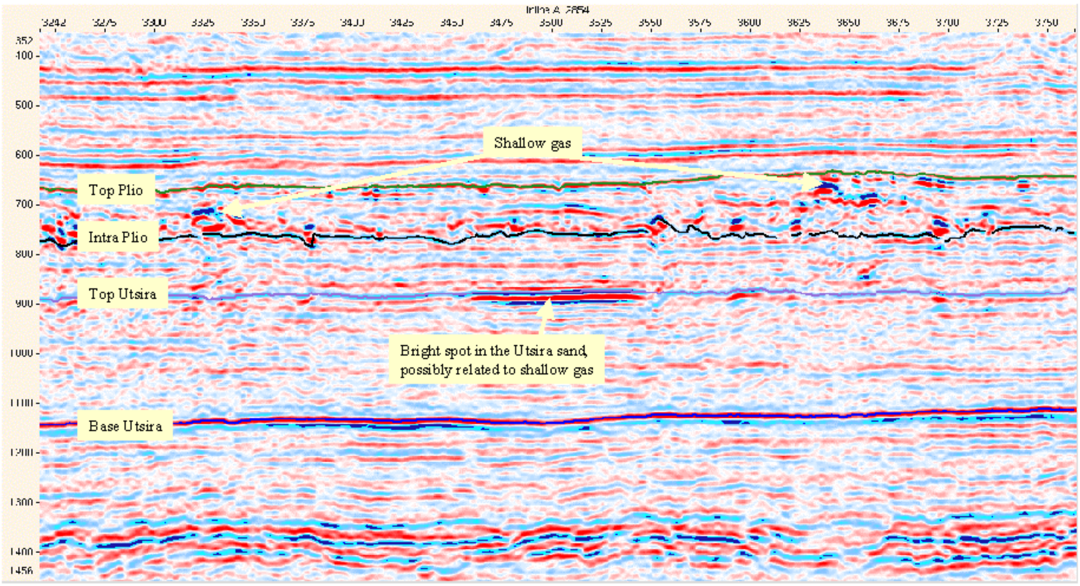


Figure 1.6: Seismic crossline (east to west)and inline (south to north) from the 3D seismic survey ST98M11. The 4 key horizons (from top to bottom Top Pliocene Prograding Unit, Intra-Pliocene, Top Utsira Sand and Base Utsira Sand) areidentified. Mud-volcanoes at the Base Utsira Sand are observed. Note the depressions just above them due to differential compaction. Amplitude anomalies possibly linked to the presence of shallow gas are observed in the thin shale drape just above the Top Utsira Sand in the lower Pliocene and also in the upper Pliocene. Note the difference in character between these different types of anomalies.

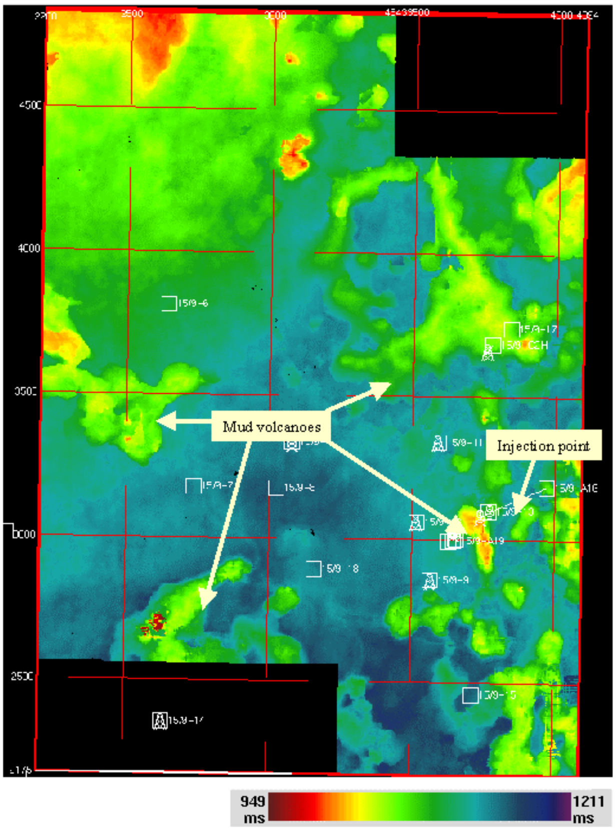


Figure 1.7: Structure map in TWT (ms) of the Base Utsira Sand showing the mud volcanoes.

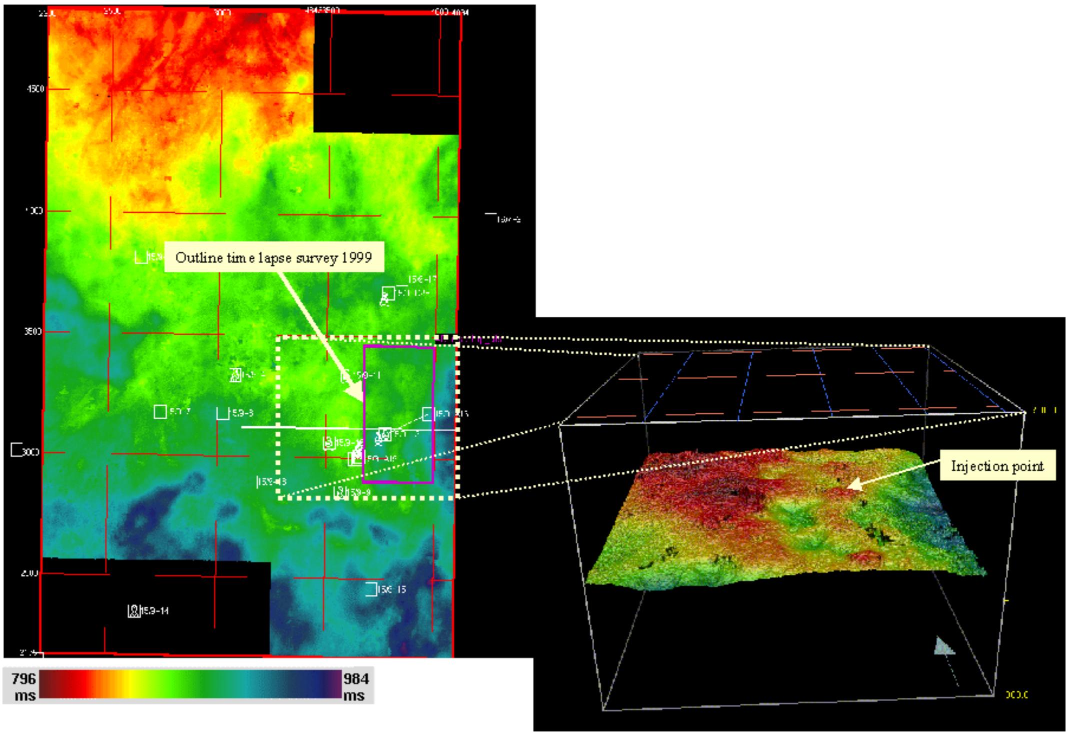
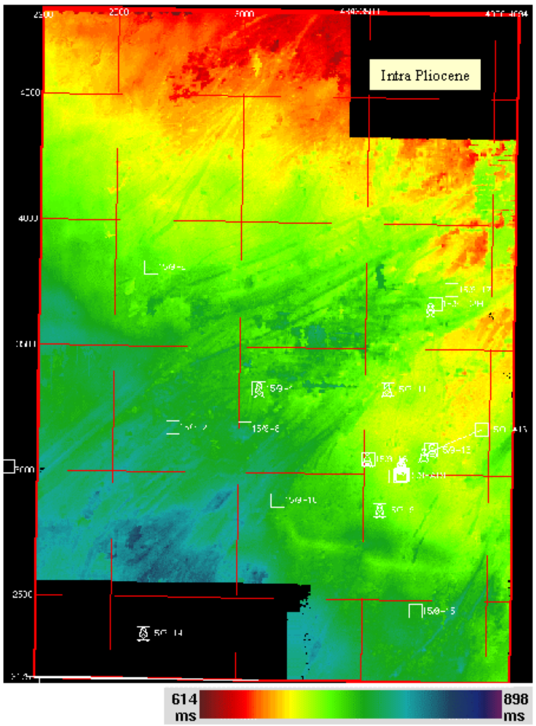


Figure 1.8: Structure map in TWT (ms) of the Top Utsira Sand, showing a general southerly dip and a more detailed 3D image of the Top Utsira horizon around the injection well in TWT (ms) showing the local domal and anticlinal structures caused by differential compaction.

Note: the purple square indicates the boundaries of the 1999 time-lapse seismic survey.



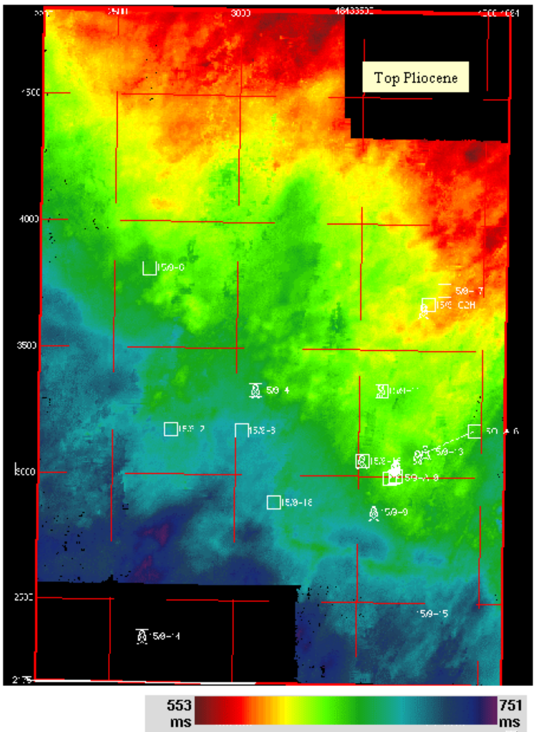


Figure 1.9: (a) Structure map in TWT (ms) of the Intra-Pliocene (left) and of the Top Pliocene Prograding Unit (right) horizons. Note the overall structural trend with a southwesterly dip.

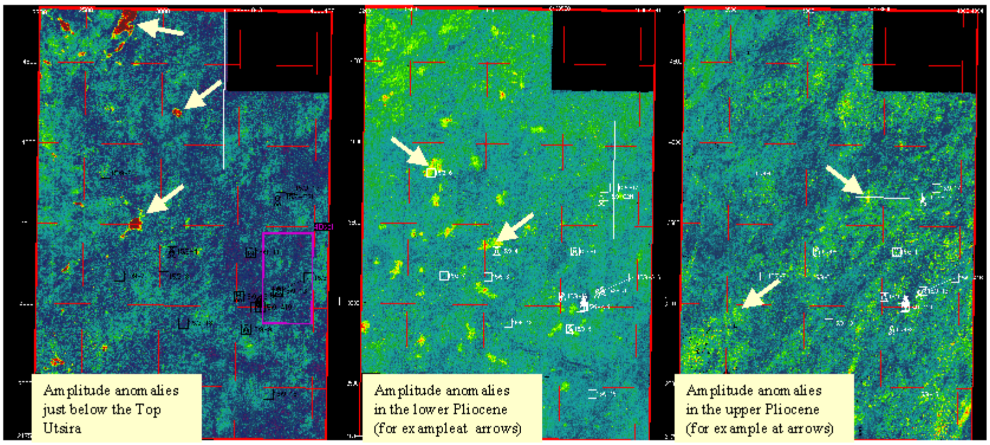


Figure 1.10: Attribute maps showing the occurrence of anomalously high amplitudes within the Utsira Sand just below the Top Utsira (left); within the lower Pliocene shale drape just above the Top Utsira Sand (middle); and within the upper Pliocene (right). The anomalies in the upper Pliocene show quite a chaotic character.

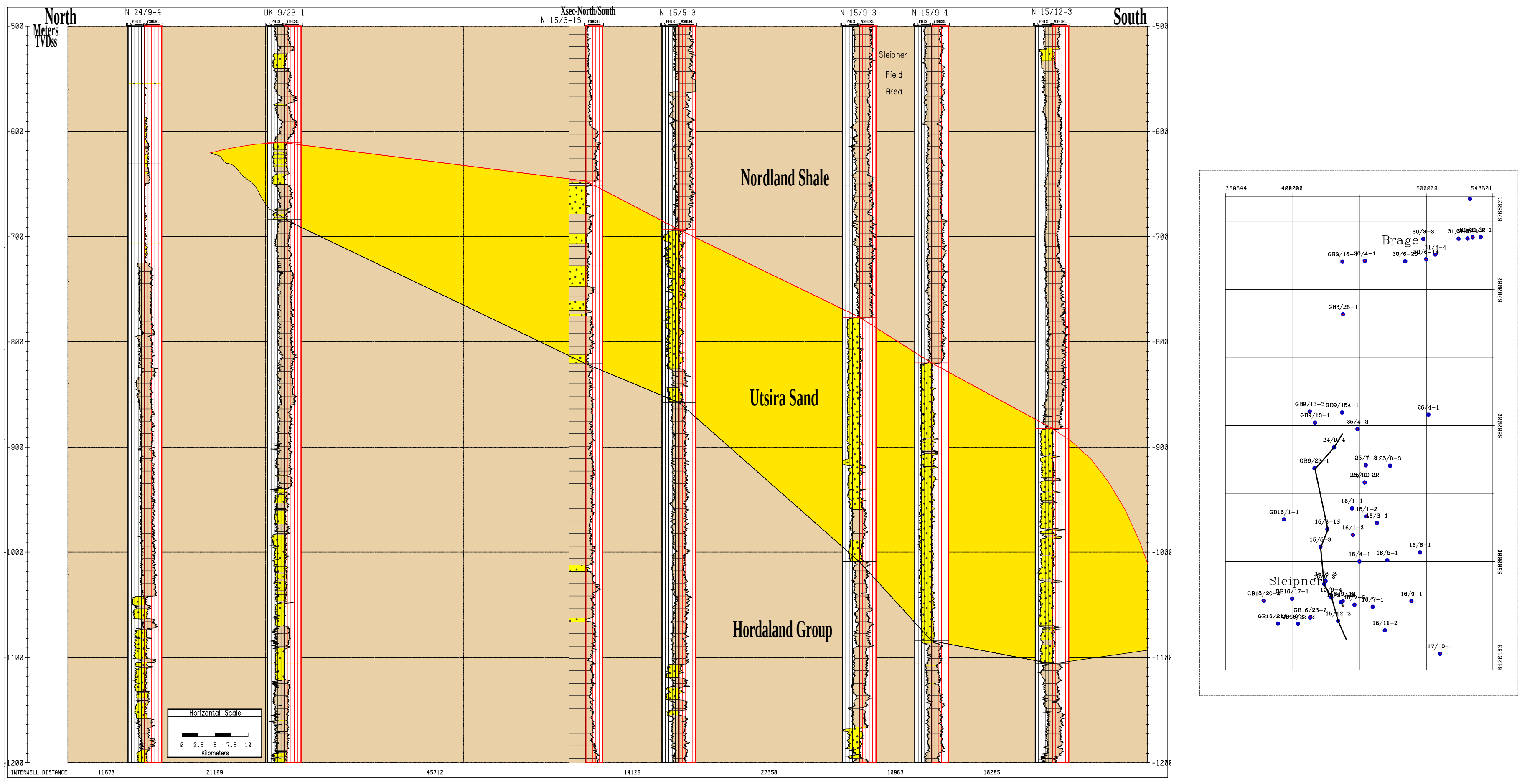


Figure 1.11 Correlation panel through wells in the Norwegian sector showing variation in shalyness of the Utsira Sand

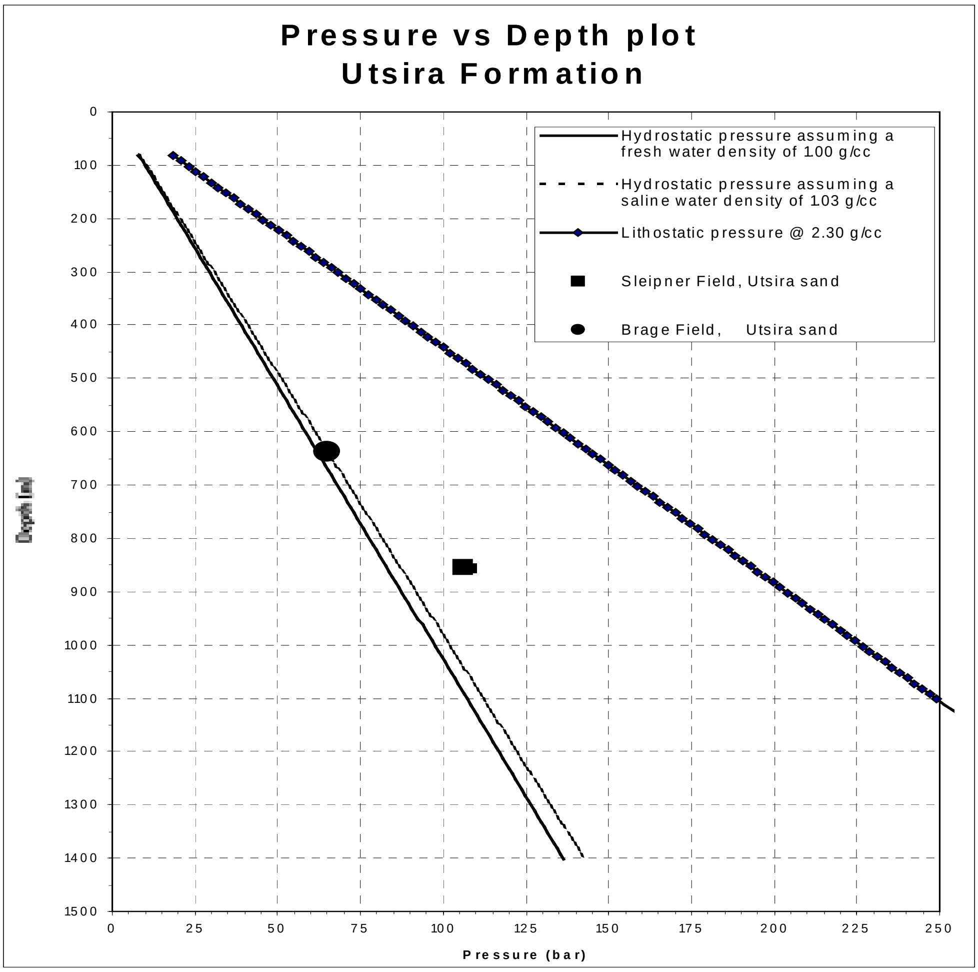


Figure 1.12 Pressure data in the Utsira Sand

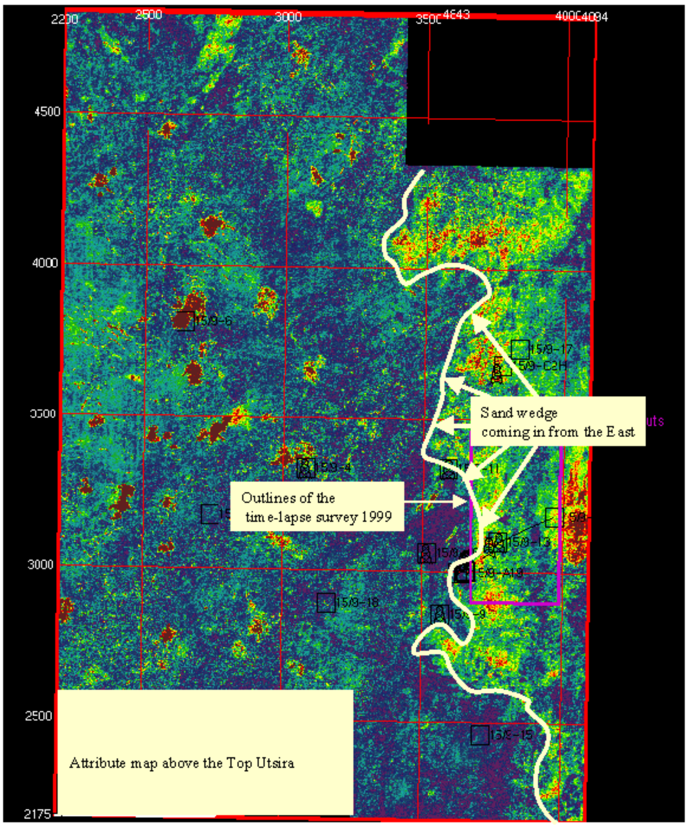


Figure 1.13: Attribute map showing the lateral extent of the sand wedge just above the Top Utsira Sand, downlapping from the east (and northeast).

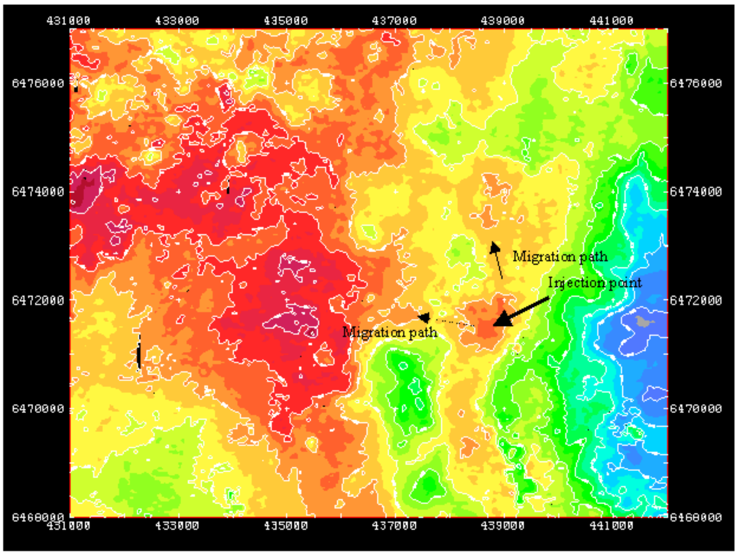


Figure 1.14 Depth map of the Top Utsira Sand covering the area close to the injection site. The spill points have been indicated (small arrows).