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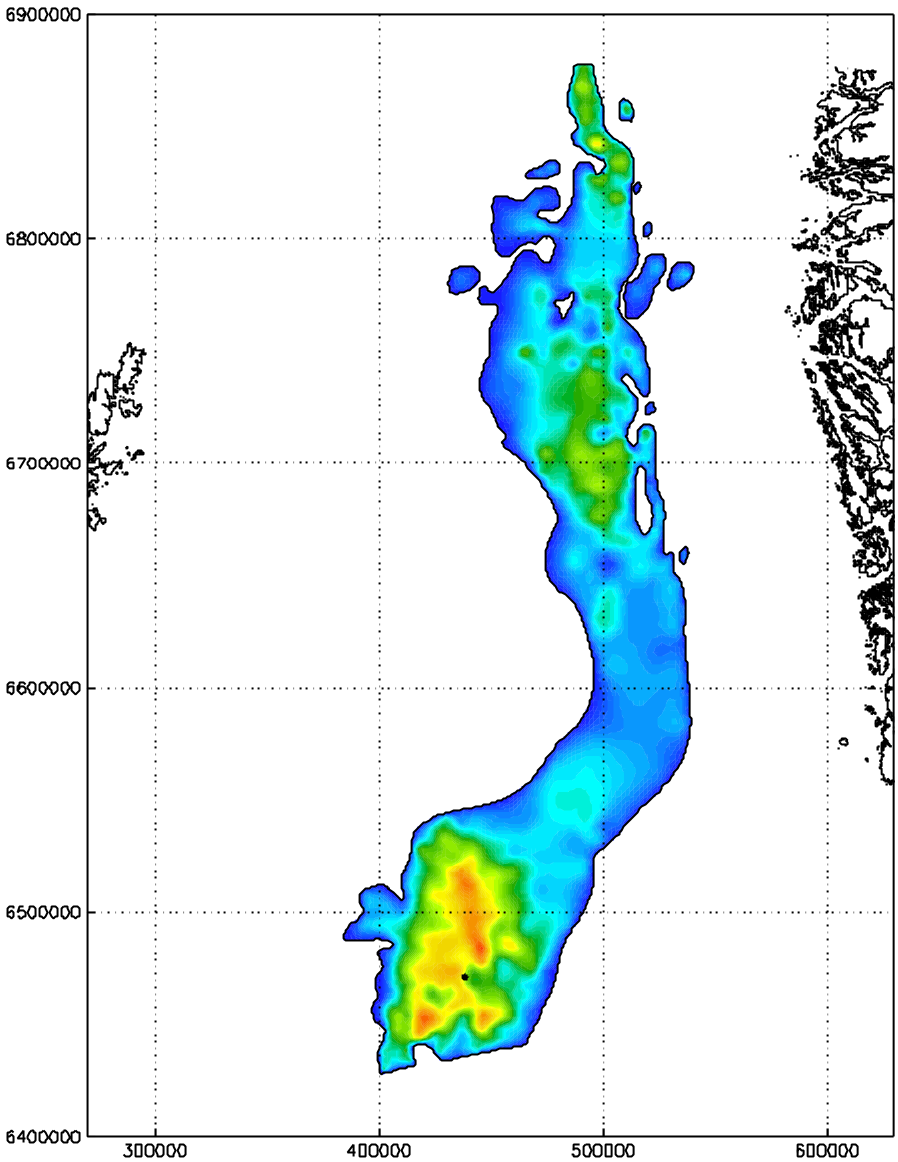
Depth Mapping and characterisation of the Utsira Sand Saline Aquifer, Central and Northern North Sea

Reservoir Geoscience Programme

Commissioned Report CR/01/218N Released 06/05/08



Depth mapping and characterisation of the Utsira Sand Saline Aquifer, Central and Northern North Sea

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Key words

CO2 storage, Seismic reflection data, well data, depth and isopach maps, porosity, sand proportion, pore volume, reservoir

Front cover: Isopach map of the Utsira Sand

Bibliographical reference

KIRBY, G. A.., CHADWICK, R. A. & HOLLOWAY, S. 2001. Depth mapping and characterisation of the Utsira Sand Saline Aquifer, Northern North Sea. *British Geological Survey Commissioned Report,* CR/01/218N. 26pp.

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Foreword

This report is a product of a study by the British Geological Survey (BGS) and forms part of the international SACS (Saline Aquifer CO_2 Storage) project. The project aims to monitor and predict the behaviour of injected CO_2 in the Utsira Sand reservoir at the Sleipner field in the central North Sea by methods including time-lapse geophysics, modelling its subsurface distribution and migration, and simulating likely chemical interactions with the host rock.

The report aims to provide information on the extents, depth, thickness and physical characteristics of the Utsira Sand reservoir as determined from an interpretation of seismic and well data. It outlines the datasets available and the methods used to interpret the data consistently and presents a summary of the results of that interpretation.

Acknowledgements

The authors would like to thank a number of GEUS and SINTEF colleagues whose work has contributed to the contents of this report namely Dr Ulrik Gregerson, Dr Peter Johanasson (GEUS), Dr Peter Zweigel (SINTEF) and Dr Rob Arts (NITG-TNO).

Contents

Summary

This report summarises the results of detailed mapping of the Utsira Sand in the central and northern North Sea utilising regional seismic reflection surveys combined with well data. It outlines the process of integration of these two datasets and conversion of the seismically-derived TWTT maps to depth. A series of contour maps illustrating the Utsira Sand in terms of porosity and proportion of clean sand are presented, based on determinations using available geophysical logs, and these are used to estimate the total pore volume of the reservoir.

The Utsira Sand is a basinally restricted Mio- Pliocene sand unit deposited in a N-S elongate area overlying the Viking Graben of the central and northern North Sea. Although dominated by sand, there are locally numerous shale interbeds. It has a maximum N-S extent of 400 km and E-W extent of up to 100 km. There are three depocentres, with maximum thicknesses in excess of 300 m occurring in the south, and ranging up to 200 m in the depocentres to the north. The depth to the top of the reservoir ranges from 550 to 1500 m and the base from 600 to 1700 m. The basal surface is more complex than the top, due to the presence of mud volcanoes combined with channelling and loading features. The form of the top surface suggests that long-term buoyancy-driven migration of injected CO_2 will be from the injection site towards to the north and then the northwest towards the margins of the reservoir.

Determinations of porosity from the Utsira core are in the range 30 – 42%; determinations from logs at the Sleipner field are in accord with this, averaging some 38%. However away from the Sleipner field there is substantial variation in porosity of the Sand unit, ranging from 30 to 40%. The proportion of clean sand in the Utsira Sand varies greatly, ranging from as low as 30% locally to 100%. Variations are due to both widespread thin shale interbeds and locally thick shale units.

An estimate of a total pore volume of 6.05×10^{11} m^3 was obtained by integrating the results of the above analyses. This is close to an earlier estimate made based on assumed porosity and thickness variations.

1 Introduction

Due to the global warming threat posed by man-made greenhouse gases there is an urgent need to develop ways of lowering industrial CO_2 emissions to the atmosphere. The world's first subsurface CO_2 sequestration operation is currently running at the Sleipner field in the central North Sea. Here, CO_2 extracted from the natural gas produced at Sleipner, is being injected into the Mio-Pliocene Utsira Sand, a subsurface saline sandstone aquifer, at a depth of about 1000 m below sea level. The injected CO_2 then migrates upwards but is trapped beneath the overlying, shale-dominated Nordland Group. The operation commenced in 1996, and is expected to last for 20 years, injecting at an average rate of about one million tonnes per year.

There is a need to understand the distribution and physical characteristics of the Utsira Sand reservoir so that predictions can be made of the likely total storage capacity available within the reservoir and the potential migration directions of the injected CO_2. This report details the work undertaken to provide this information.

2 Mapping the Utsira Sand Reservoir

The Utsira Sand reservoir was mapped using seismic and well data from both the UK and Norwegian sectors of the central and northern North Sea. Staff at both BGS and GEUS, using Geographix and Landmark workstations respectively performed this work. The initial products of this work were maps of the Two Way Travel Time (TWTT) to both the top and the base of the reservoir, presented in a number of reports and publications (Holloway et al. 2000, Chadwick et al. 2000).

2.1 UTSIRA SAND DEFINITION

The Utsira Sand, as mapped in this work package, corresponds to the thick Mio-Pliocene sand unit penetrated in wells at, and around the Sleipner field in the central North Sea e.g. well 15/8-1 from the Norwegian sector.

2.2 DATASETS

2.2.1 Seismic Data

Four regional seismic surveys were used to map the regional distribution of the Utsira Sand; the Central North Sea Tie (CNST-82), Viking Graben seismic traverse (VGST-89), Northern North Sea Traverse (NNST-84) and North Viking Graben Traverse (NVGT-88). The distribution of these surveys is shown in Figure 1. Data quality was variable, and varied from moderate (CNST-82) to very good (VGST-89).

2.2.2 Well Data

A total of 430 wells were loaded into the workstations to provide control on the seismic picks (Figure 1). Of these, 190 had well velocity surveys that improved the accuracy of the ties between the well and seismic data. 132 had provings of Utsira Sand. A total of 234 wells had associated geophysical log data loaded onto the workstation that aided in correlation of stratigraphic units and in characterisation of the physical properties; this included 49 wells that had provings of Utsira Sand. Well control for the Utsira Sand is better in the south than in the north.

2.3 INTERPRETATION METHODOLOGY

The Utsira Sand is a highly porous sandy unit that lies towards the base of the predominantly argillaceous rocks of the Nordland Shale. At the Sleipner field it is typically massive with a few thin internal shaly units. The velocity and density contrast with overlying and underlying shaly units is mostly small, but generally results in a lower acoustic impedance in the sand. Typically therefore, the top of the sand is represented on the seismic data by a black peak and the base by a white trough. Although some internal reflectors could be distinguished locally it was not possible to trace these extensively. Both the top and base of the sand unit were picked regionally on the seismic surveys and used to map the extents of the sand reservoir. In addition the seabed and several intermediate reflectors were mapped.

The initial top and base Utsira Sand picks were identified on the seismic data by tying in wells from the Sleipner field. All available velocity surveys were used so as to provide maximum confidence in the well to seismic ties. However, during this work it became evident by careful correlation of the seismic picks, that the sandy units labelled as Utsira Sand in some wells were not the stratigraphic equivalent of the true Utsira Sand proven in wells of the Sleipner field. Some ‘provings’ of Utsira Sand were entirely younger, others entirely older and several included the Utsira Sand as well as younger or older sands. The basic approach taken during this work was therefore to carefully use the seismic data to correlate picks away from the Sleipner field and to use these picks to confirm or otherwise, the presence of the reservoir unit in other wells. The ability of the seismic picks to distinguish between true correlative sand bodies and sand units falsely identified in the wells as Utsira Sand is illustrated by Figure 2. In this it can be seen that the sand unit in well 16/29-4 at this approximate stratigraphic level (highlighted in yellow) and originally identified as Utsira Sand, is not the equivalent of the seismically correlated Utsira Sand that pinches out either side of the well. The Utsira Sand picks were therefore deleted from this well. This process of reconciling well and seismic picks of the Utsira Sand was performed across the entire seismic and well datasets and ensured that there was consistency between well and seismic picks. This permitted depth conversion to be performed in a constrained manner.

Picks were initially made on the CNST-82 survey in the south and transferred onto the NNST-84 survey in the north and then onto the NVGT-88 survey. There was initially some uncertainty in this transfer of the picks between the CNST-82 and NNST-84 surveys because of the limited overlap between surveys and the thinness of the Utsira Sand at this locality. This uncertainty was eased however when the VGST-89 survey was later made available to the project, as this data was of high quality and also provided more overlap between the surveys.

The form of the base Utsira Sand is generally more complex than that of the top Utsira Sand, due to a combination of channelling, loading and shale diapirism. There is also commonly a correspondence between the downward concave features at the base, and upward convex features at the top Utsira Sand (e.g. Figure 2) suggestive of features formed by syn and post depositional loading (Zweigel et al 2000).

Careful mapping of the reflectors, paying particular attention to the lap out positions of the Utsira Sand enabled the precise limits of deposition of the reservoir to be determined. TWTT maps to the top and base Utsira Sand were constructed using EarthVision modelling software with a 250 m grid interval. These also incorporated the detailed seismic picks from the 3D survey in the Sleipner field area (Zweigel et al 2000). The resultant TWTT shaded contour map to the Top Utsira Sand is presented in Figure 3. It can be seen that the depositional extent of the Utsira Sand has a highly N-S elongated form, extending for greater than 400 km with a maximum east-west extent of roughly 100 km. Seismic stratigraphic relationships demonstrate that the Utsira Sand unit is basinally restricted. The limits in the east and west are defined by lap-out of the sand, as is the southeastern boundary. The limits of the reservoir are locally complex with some isolated depocentres and lesser areas of non-deposition within the main depocentre, particularly in the north. The southwest margin however, marks the lateral transition into shaly sediments and the northern boundary the limit of the seismic data available to this project.

Although the general form of the top and base surfaces can be discerned from the TWTT maps, depth conversion is necessary to give a structurally accurate picture that permits accurate prediction of migration paths and modelling of the 3D form of the reservoir.

3 Depth Conversion

Depth conversion of the TWTT maps utilised a simple interval velocity model with three layers: OD to seabed, seabed to top Utsira Sand and top to base Utsira Sand. It was not feasible to determine a more detailed model, as intermediate seismic picks did not extend over the entire area of Utsira Sand deposition. A velocity of 1480 ms^{-1} for OD to seabed was assumed and achieved a close match between depth converted seismic picks and well observations. The depths in wells and the corresponding TWTT on the seismic data at the well locations determined the spatially variable velocity grids for the two lower intervals, which were used to depth-convert the seismic picks. The resultant depths grids were then compared with the depths proven in wells and minor adjustments made to ensure consistency between the datasets. The resultant depth maps, produced from the grids using Earthvision software using a 250 m grid interval are presented in Figures 4 – 7.

Figure 4 shows the seabed depth over the area of extent of the Utsira Sand. It clearly shows the presence of the Norwegian trough in the east and north, where seabed depths range up to greater than 350 m. This contrasts strongly with the much of the remainder of the area where seabed occurs at depths of less than 150 m.

Figure 5 shows an isopach map of the Utsira Sand. There are three main depocentres, the principal one occurring in the south where thicknesses range up to greater than 300 m in a generally irregular pattern, although there is a significant north south trend. The second depocentre lies to the north and thicknesses here range up to 200m. It is separated from the depocentre in the south by a broad area of generally thin Utsira Sand. The third depocentre lies in the far north where the depositional extent is very narrow. Thicknesses range similarly up to 200 m locally. Thicknesses in the minor depositional protuberances and isolated outliers in the north are generally very low. The complex thickness variations result from the topography on both the top and base Utsira Sand surface, presented in Figures 6 and 7 respectively.

The top Utsira Sand surface generally varies relatively smoothly with a total depth range from 550 to 1500 m, but mostly from 700 to 1000 m. The topography of the top surface is particularly important to a consideration of the likely migration directions for the injected CO_2. Figure 6 shows that the top surface slopes northwards away from the injection site and then northwestward towards the margins of the reservoir. This map will permit determination of likely migration directions for any chosen injection site.

Figure 7 shows the depth to the base of the Utsira Sand. This shows more complex and detailed variations than the top surface, due principally to the channelling and mud volcano features than affect this boundary and are well imaged on seismic data. Depths vary from 600 to 1700 m although mostly lie between 700 and 1200 m.

4 Characterisation of the Utsira Sand

In order to assess the storage capacity and migration paths of CO_2 in the Utsira Sand it is necessary to assess the physical properties of the reservoir unit, and in particular the porosity of the sand and proportion of shale units within the reservoir. There is however, very limited core available from the Utsira Sand – a total of 9 m from one well at Sleipner. Measurements from this core suggest a porosity in the range 30 to 42% (e.g. Pearce et al. 1999, Lindberg et al 2000).

Geophysical logs through the Utsira Sand in wells provide an alternative means for determining physical properties. A summary of geophysical logs available to this project for wells that penetrate the Utsira Sand reservoir is presented below in Table 1.

Table 1

Logs	**Number of wells**
GR, Sonic, Density, Caliper	12
GR, Sonic Density	2
GR, Sonic, Caliper	8
GR, Sonic	23
A further 12 wells with logs were rejected as they had either no caliper or were washed out over the Utsira Sand interval	

There is a limited range of suitable logs. The density and sonic logs have the potential to provide estimates of the porosity of the sand, and the gamma ray log a measure of the thickness of any shale interbeds. The caliper log provides an indication of the integrity of the borehole walls; where deviations to large values occur, the borehole is washed out and the porosity values determined from other logs over this interval will likely be suspect.

A typical GR profile through the Utsira Sand in the vicinity of Sleipner in the southern depocentre is illustrated in Figure 8. Values are mostly low, with some higher peaks over a limited depth range, interpreted as shale interbeds. A GR cut-off was therefore used in all wells to distinguish sand from shale interbeds, although the absolute value of this cut-off varied from well to well. Within the sand units, the caliper log, where available, was used to define intervals where geophysical logs were considered to provide reliable readings.

Sand porosity determinations were first made using wells with density, sonic, GR and caliper logs to produce the best-constrained estimates, highlighted in Figure 8 by the blue columns. Estimates of porosity derived from the density log were close to those determined from the core, and taken therefore to be accurate. Values derived from the sonic log however were consistently higher, the mean ratio of density to sonic derived values being 0.88 (Figure 9). This relationship allowed the conversion of porosity estimates based on the sonic log alone (in those boreholes where the density log was not available), to the more realistic density derived value. The number and geographic spread of log derived porosity values was thereby increased and permitted the construction of a contour map of Utsira Sand porosity (Figure 10). This shows a range of porosity from just above 30% to locally near 40%, most areas having values in the range 37 to 39%.

In each well, a GR cut-off was determined that most effectively separated sand from shale interbeds. Values ranged from 26 to 98 api, with a mode of 38 api. Using these cut-offs the proportion of clean sand in each well was determined and the resulting values contoured to produce the map presented in Figure 11. There is a significant variation in the proportion of clean sand, from 30 to 100%, variations often occurring over short distances as in the southern depocentre. Figure 12 is a well correlation diagram that illustrates this change in the proportion of shale interbeds in an E-W section across the southern depocentre. There is a steady eastwards increase in the proportion of sand and a corresponding decrease in the ‘rattiness’ of the GR signature. Figure 13 is a well correlation diagram from N to S across this depocentre. It can be seen that the localised low sand proportion in the south is due to a thick shale unit within the Utsira Sand whereas the low values in the north are due to the abundant thin shale units dispersed throughout the Utsira Sand.

5 Volumetrics

The total porespace within the Utsira Sand can be calculated by multiplying the Utsira Sand isopach by the porosity and the proportion of clean sand. A map showing the total porespace thickness variation for the Utsira Sand is presented in Figure 14. By integrating this with the area of Utsira Sand deposition, a figure for the total pore volume of 6.05×10^{11} m^3 is obtained. This compares with an earlier estimate based on assumed porosities and approximate depth conversion, of 5.5×10^{11} m^3 (Chadwick et al. 2000).

6 References

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Zweigel, P., Lothe, A.E, Arts, R. & Hamborg, M. 2000. Reservoir geology of the storage units in the Sleipner CO_2-injection case. A contribution to the Saline Aquifer CO_2 Storage project (SACS). Sintef Petroleum Research Confidential Report 523.4285.00/02/00. (CD-ROM).

Figure 1: Seismic and well data available to this study

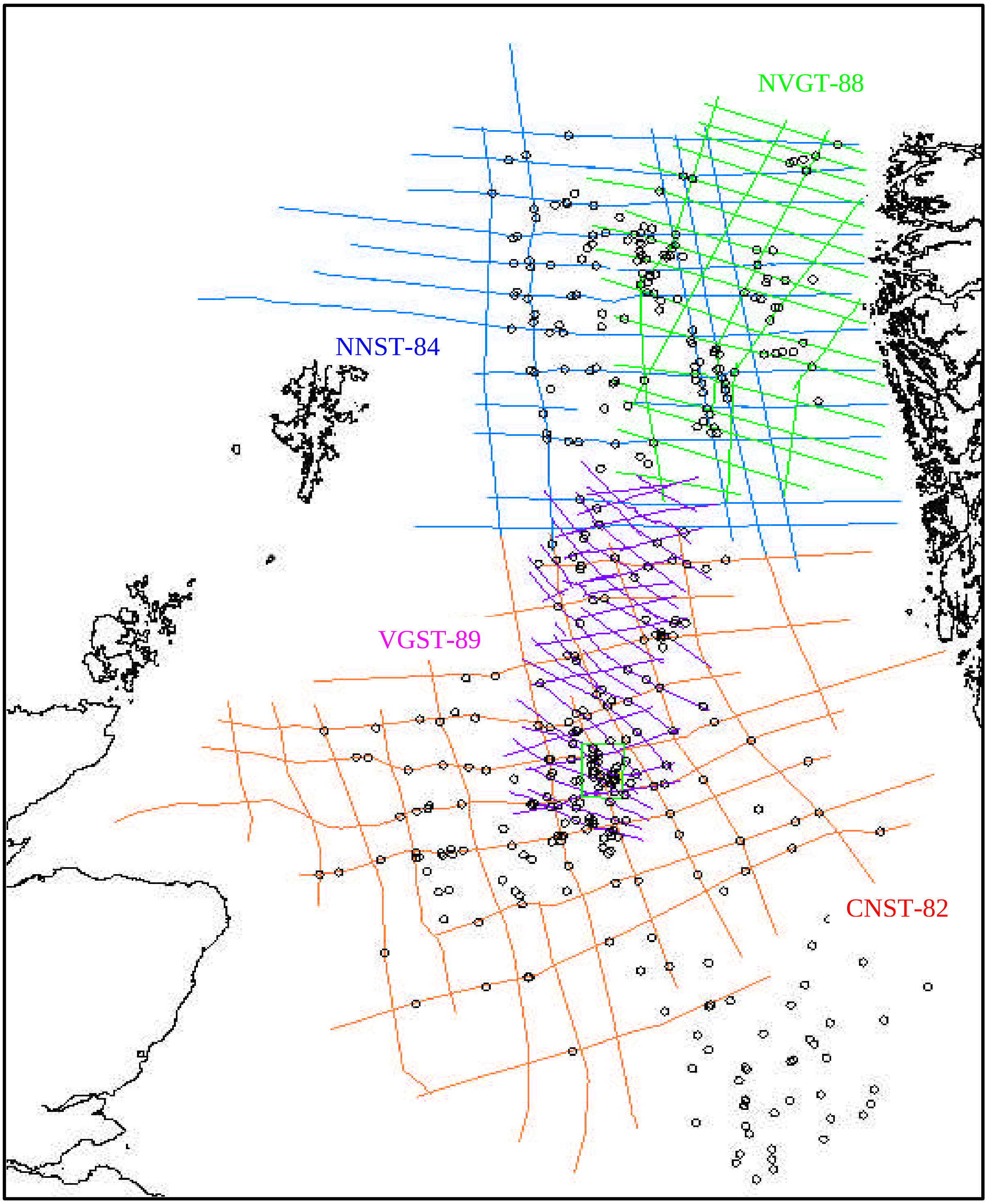


Figure 2: Distinguishing Utsira Sand from other sand bodies

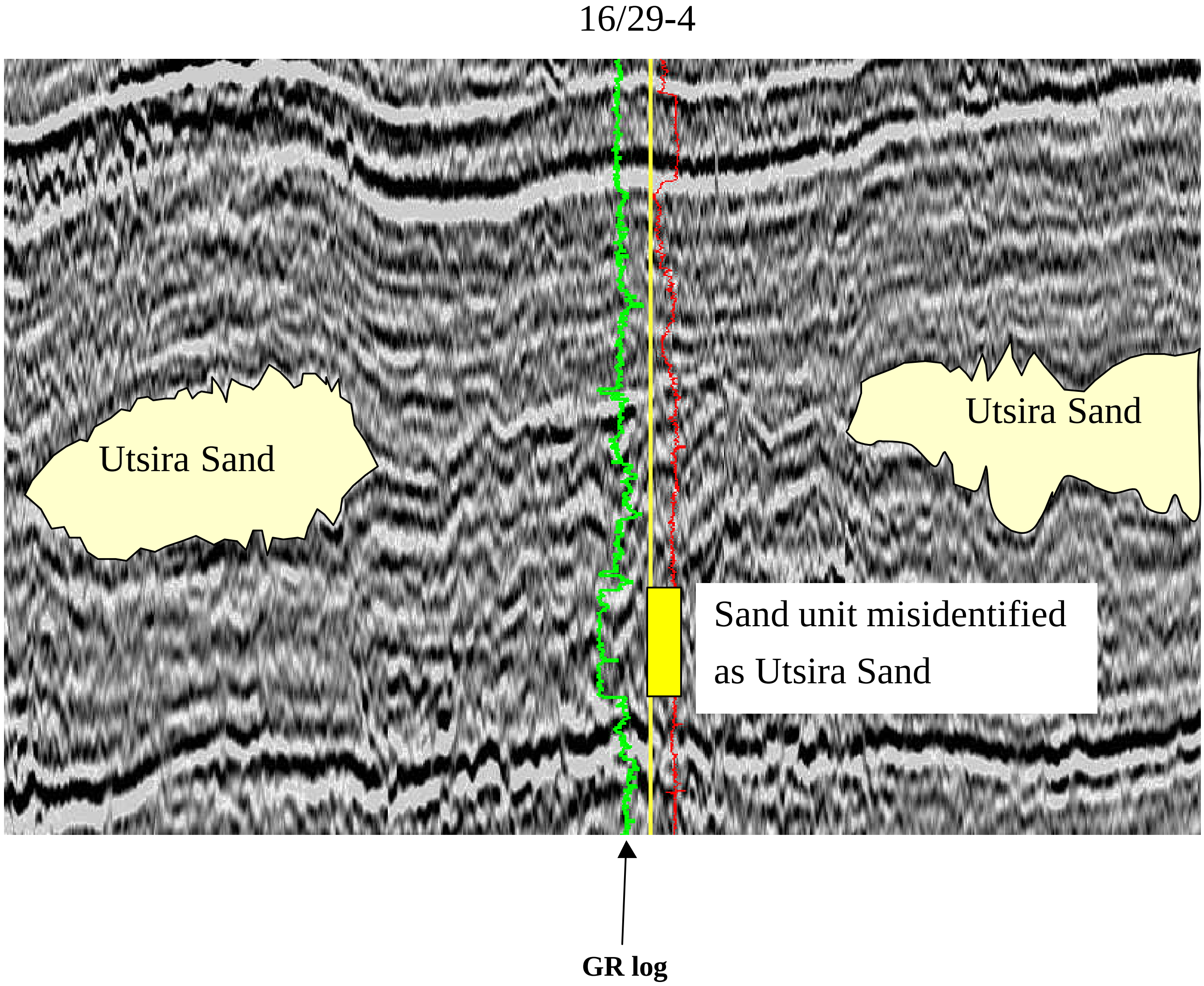


Figure 3: Two Way Travel Time to top Utsira Sand (seconds)

CO_2 injection point marked by black dot

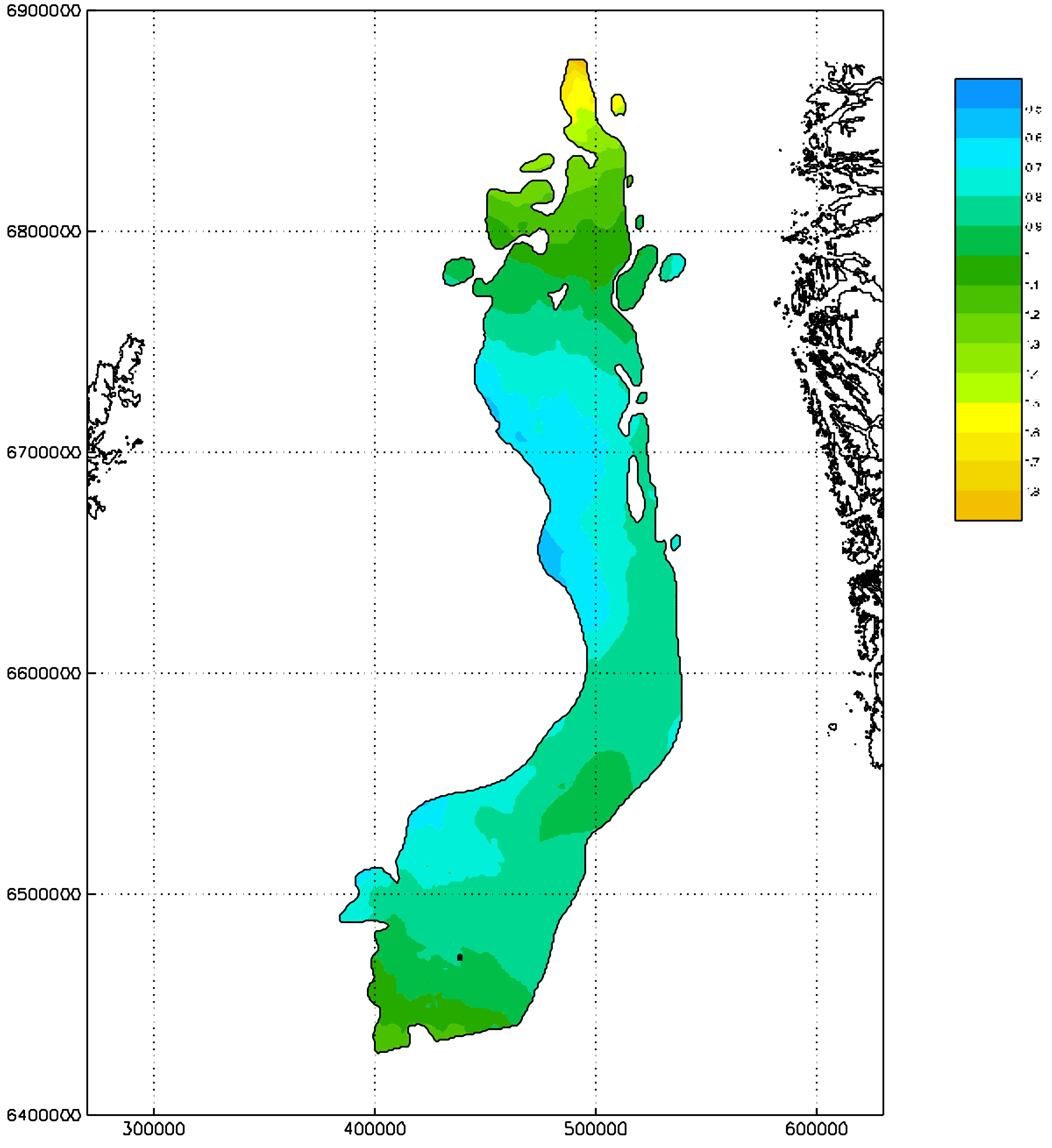


Figure 4: Water depth over area of extent of Utsira Sand (metres)
CO_2 injection point marked by black dot

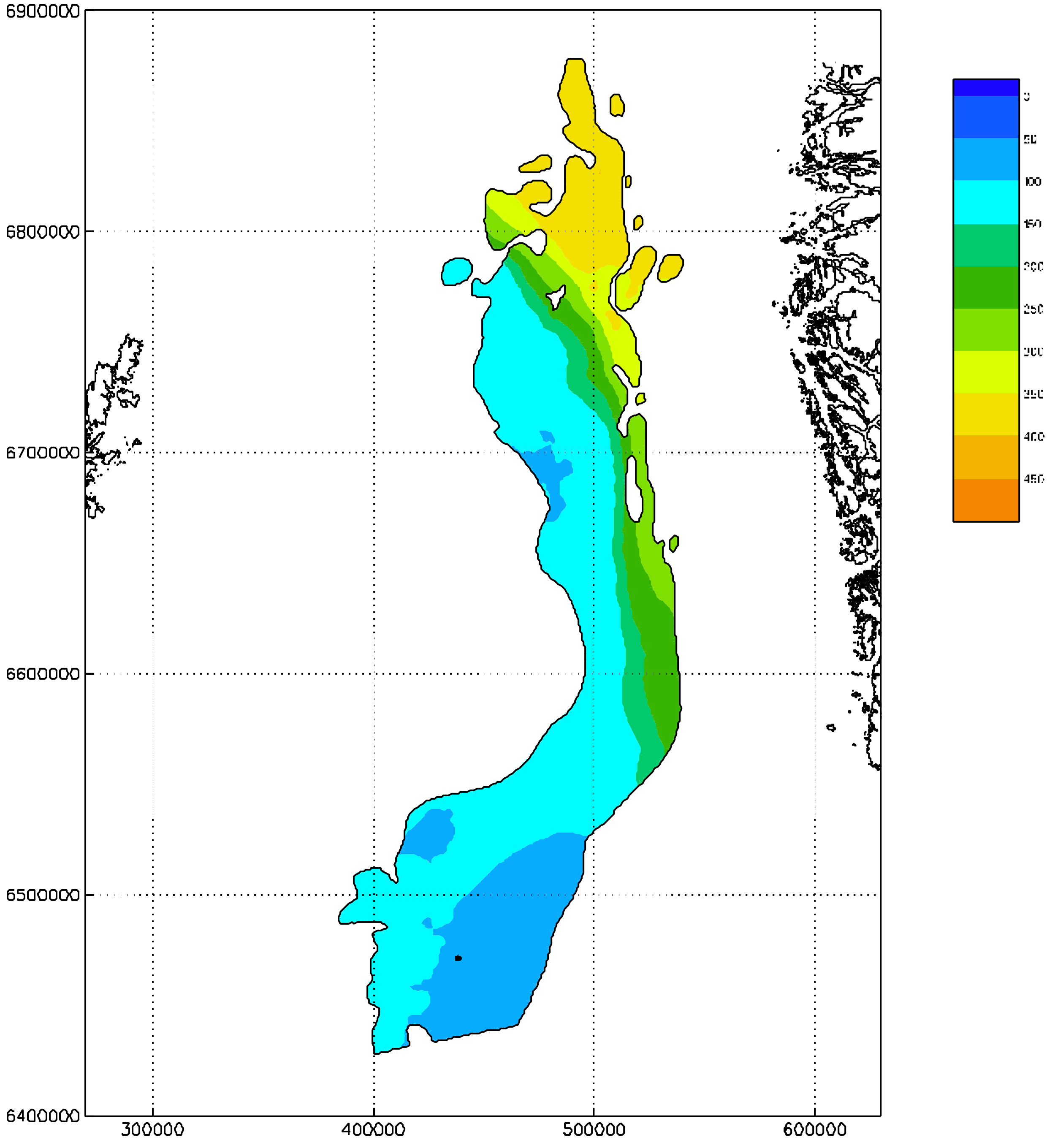


Figure 5: Utsira Sand Isopach (metres)

CO_2 injection point marked by black dot

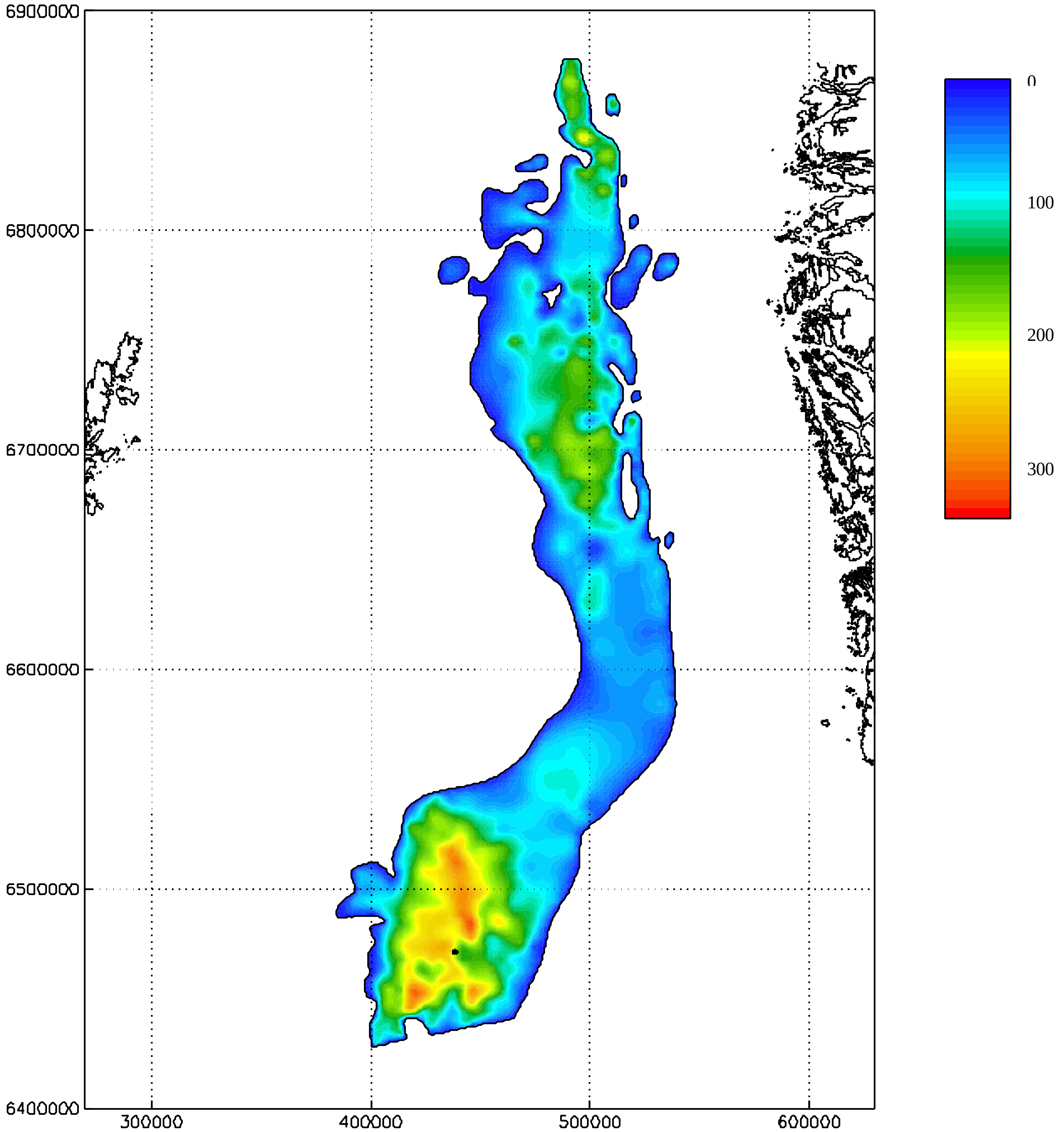


Figure 6: Depth to top Utsira Sand (metres)

CO_2 injection point marked by black dot

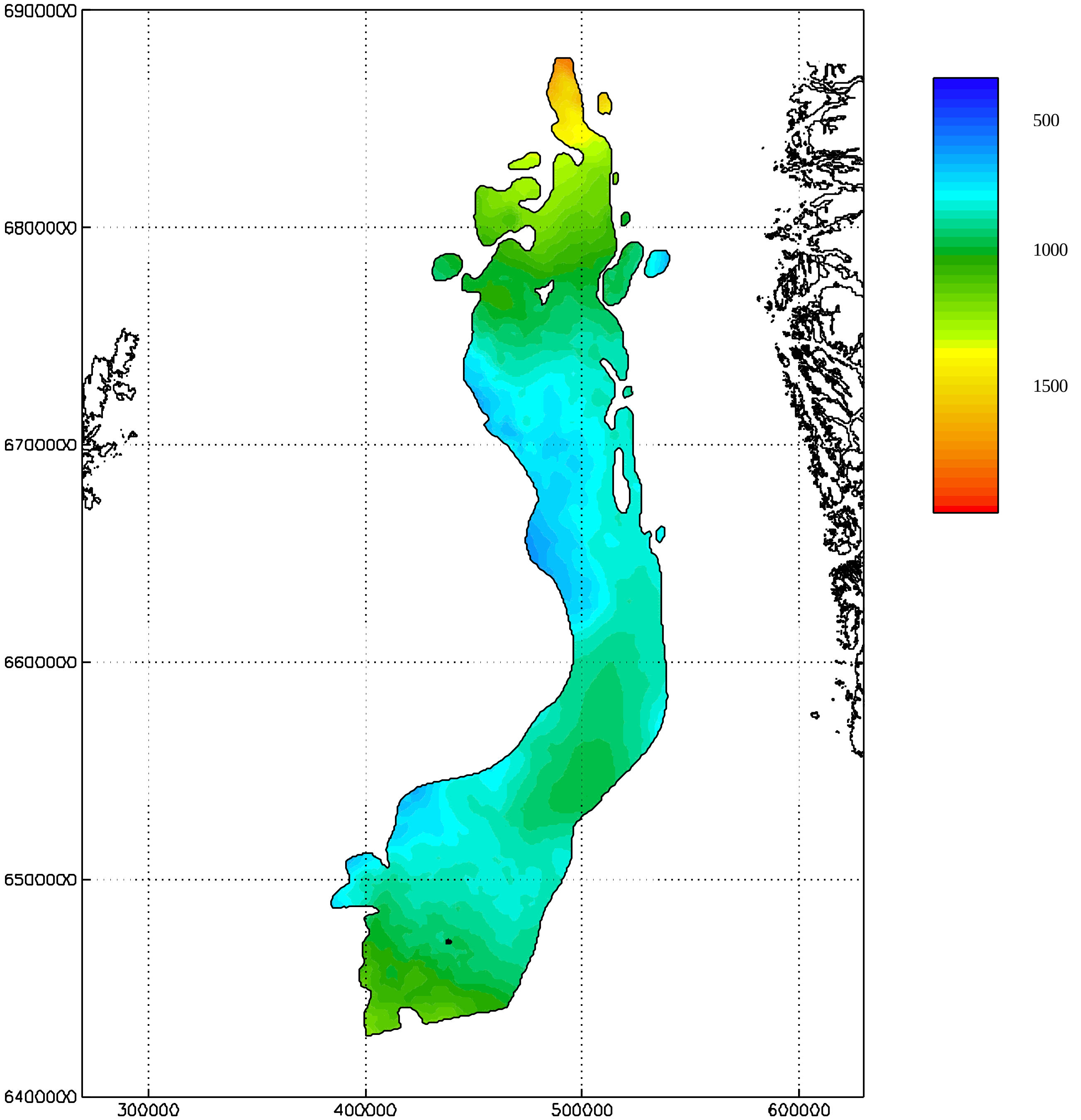


Figure 7: Depth to base Utsira Sand (metres)
CO_2 injection point marked by black dot

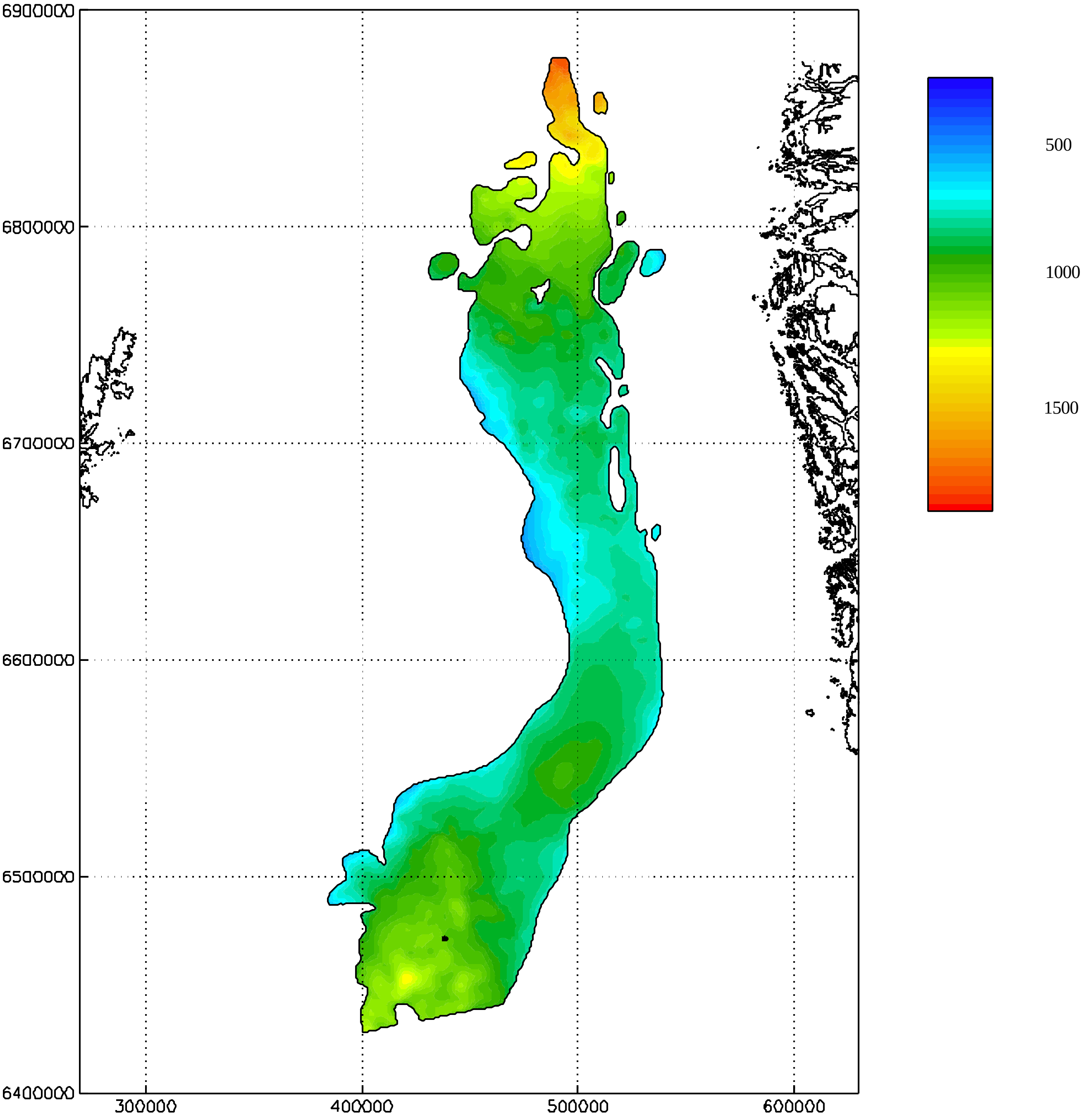
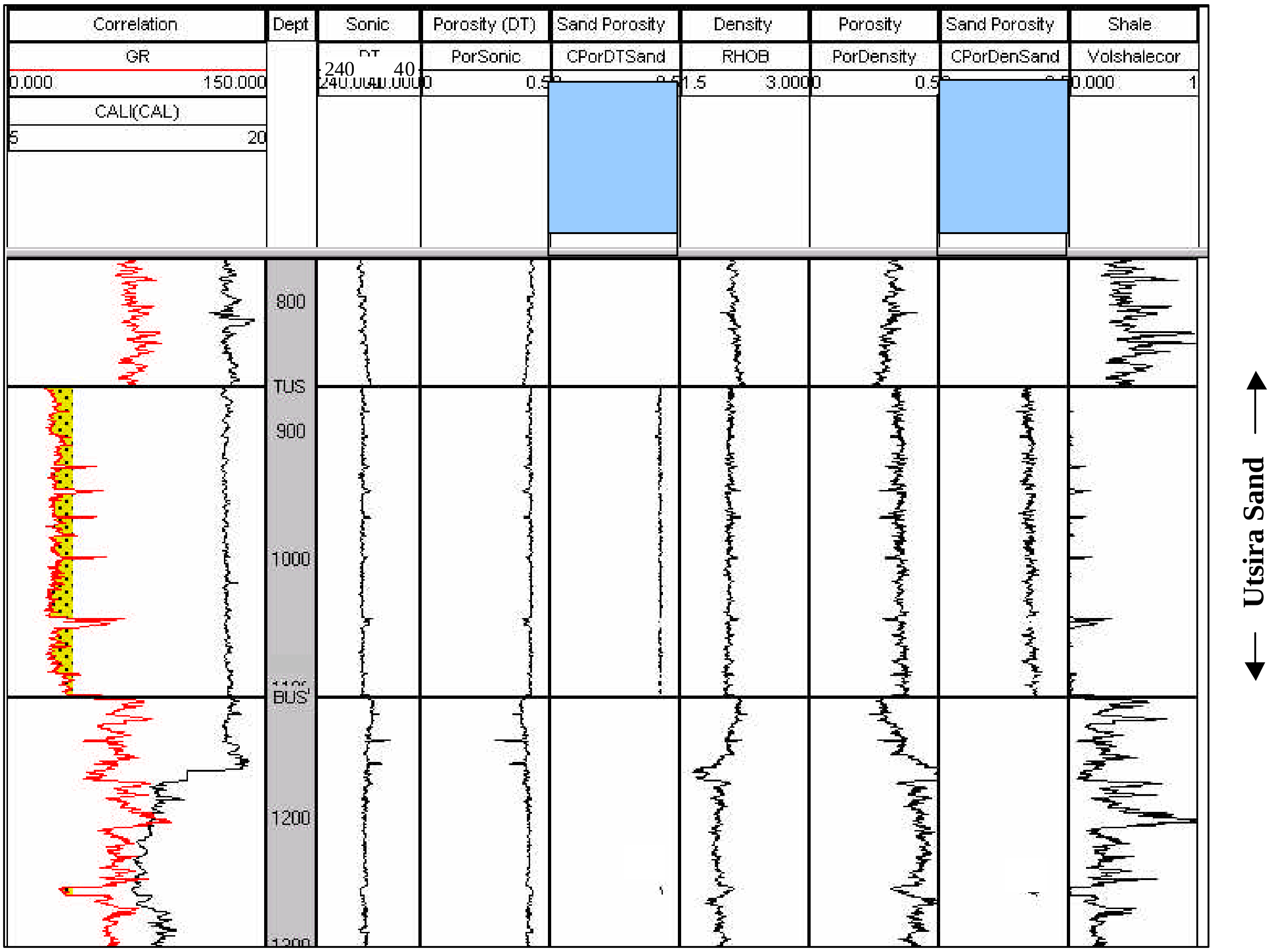


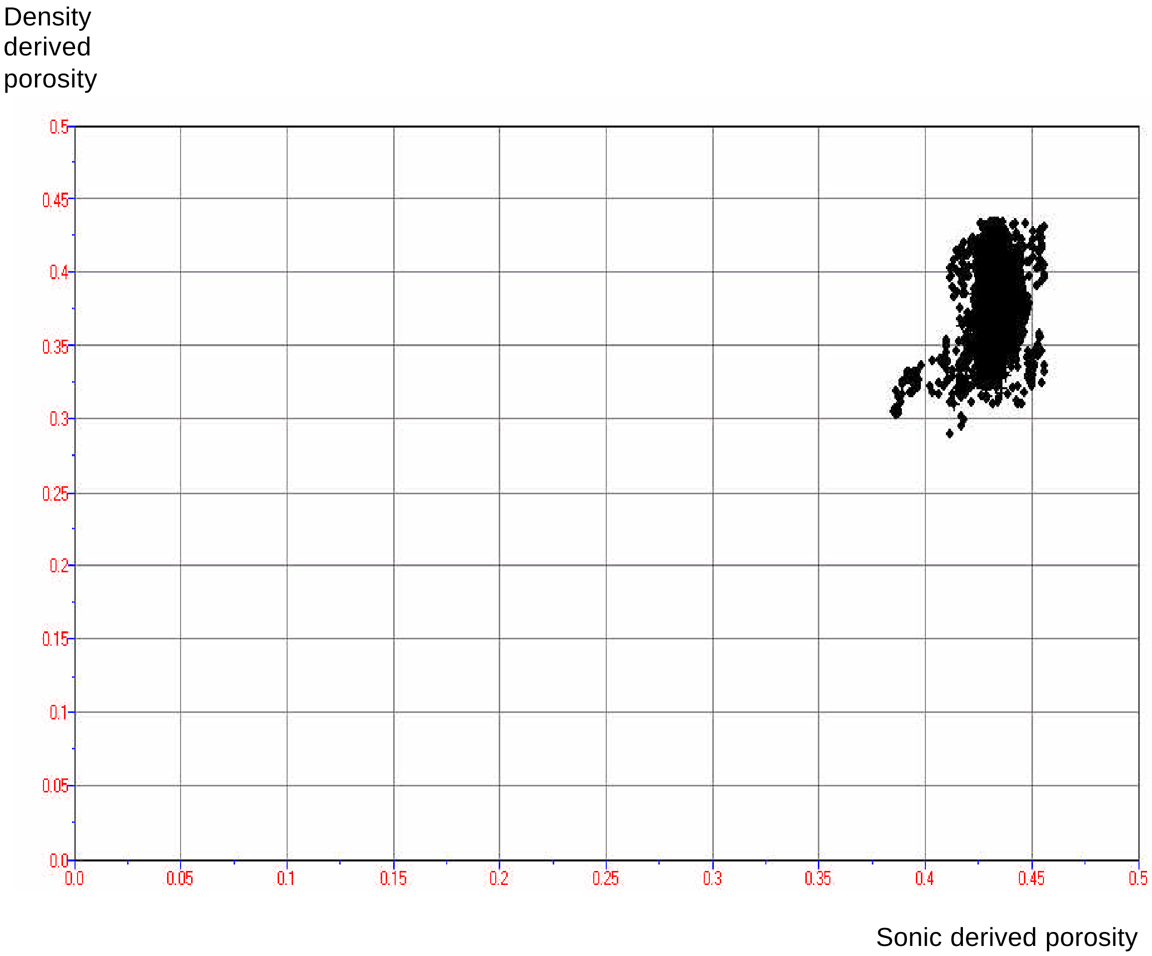
Figure 8: Log response across Utsira Sand



TUS = Top Utsira Sand

BUS = Base Utsira Sand

Figure 9: Relationship between density and sonic log derived porosity estimates



Density derived porosity: Sonic derived porosity = 0.88

Figure 10: Variation in porosity of clean sands of the Utsira Sand (%)

CO_2 injection point marked by black dot

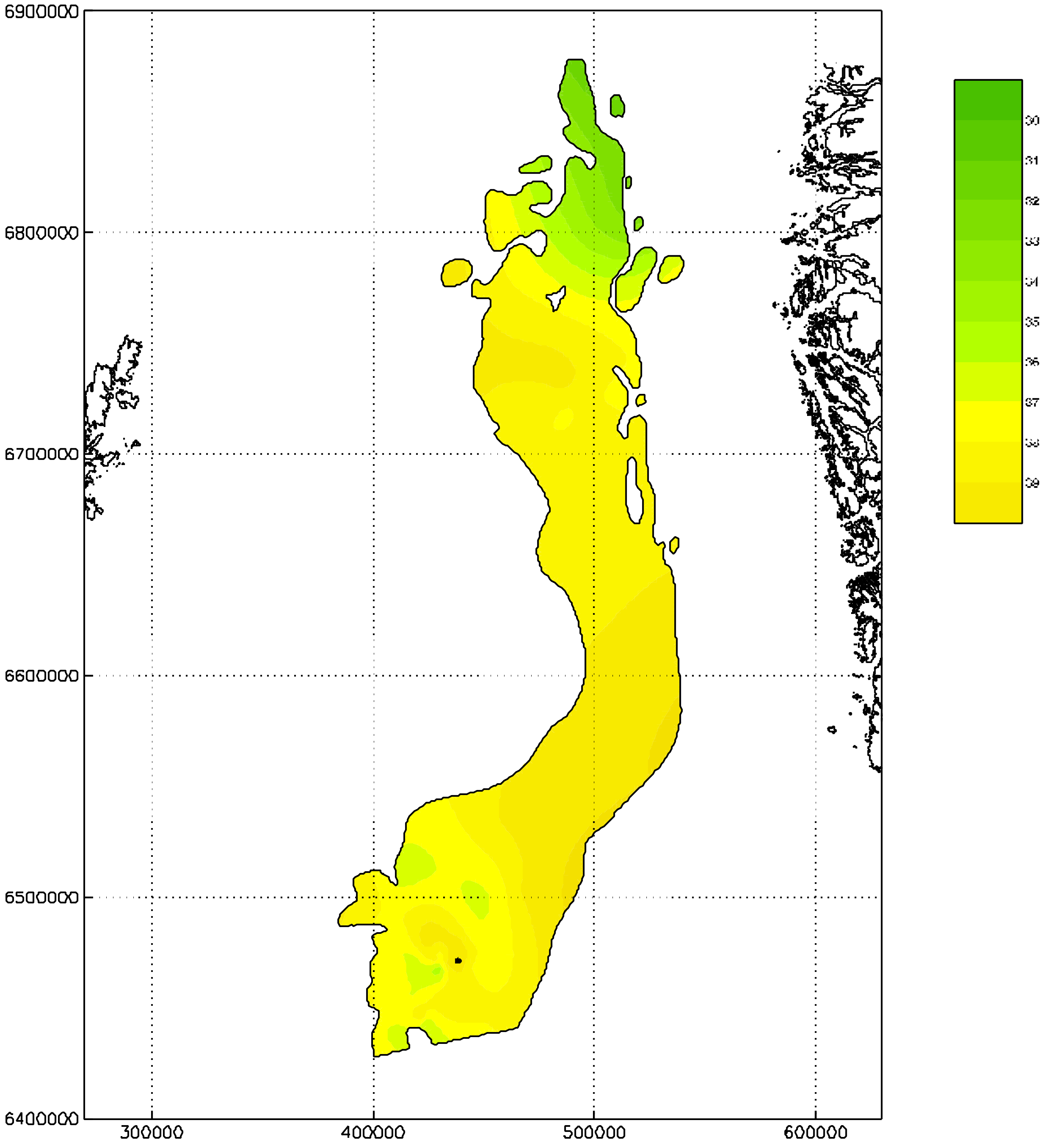


Figure 11: Proportion of clean sand in Utsira Sand interval

CO_2 injection point marked by black dot

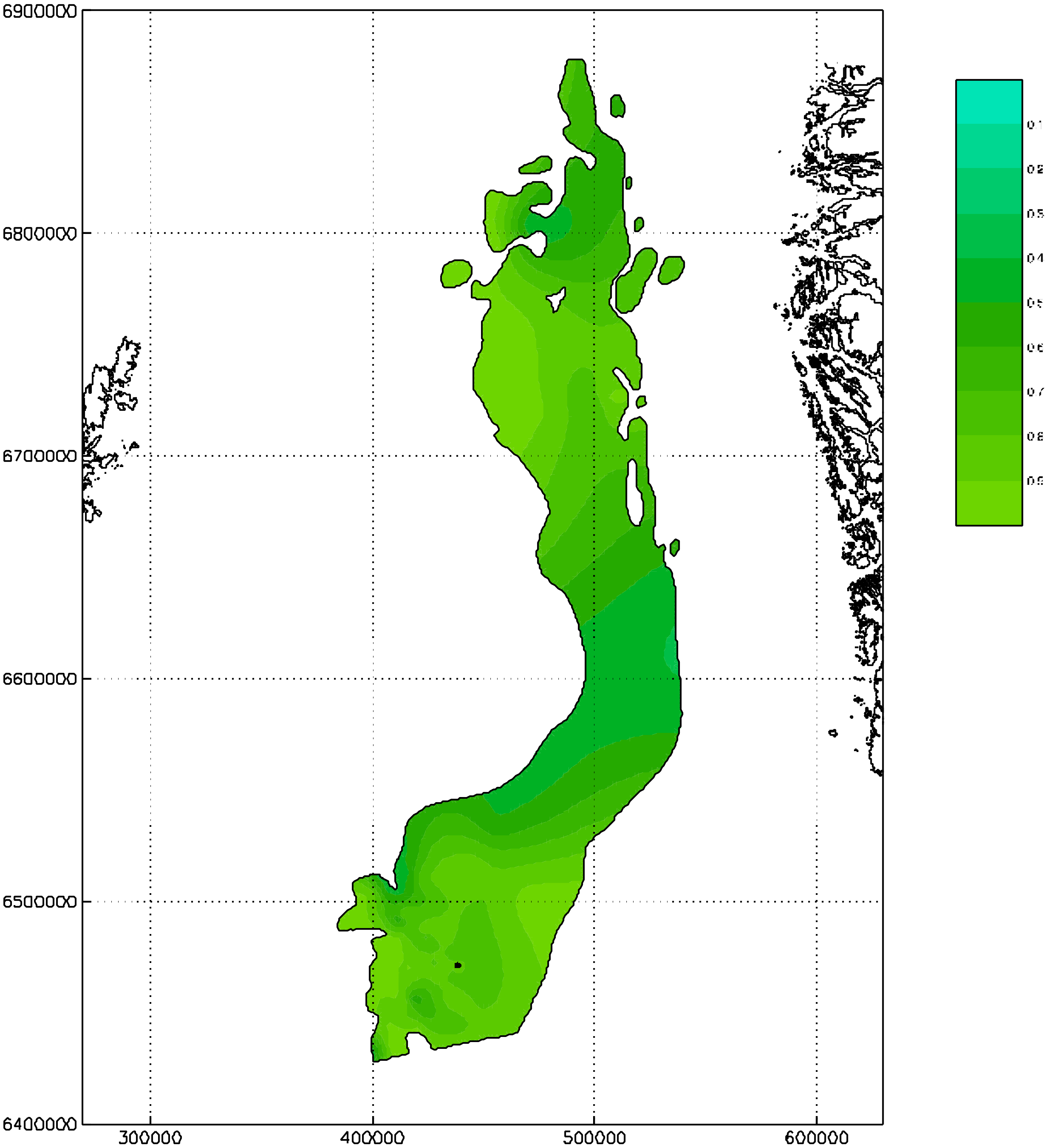
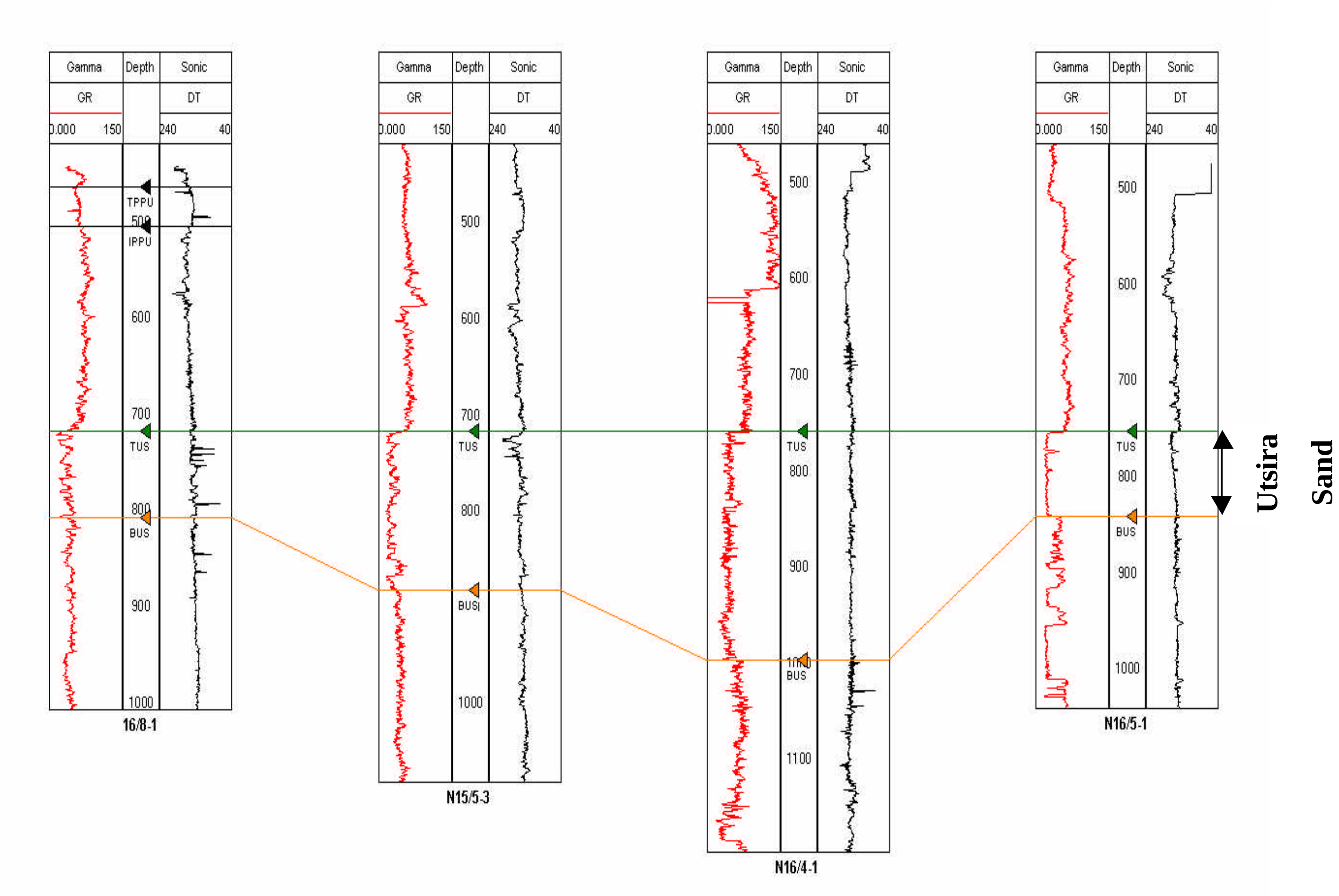


Figure 12: Stratigraphic correlation of the Utsira Sand: E-W profile



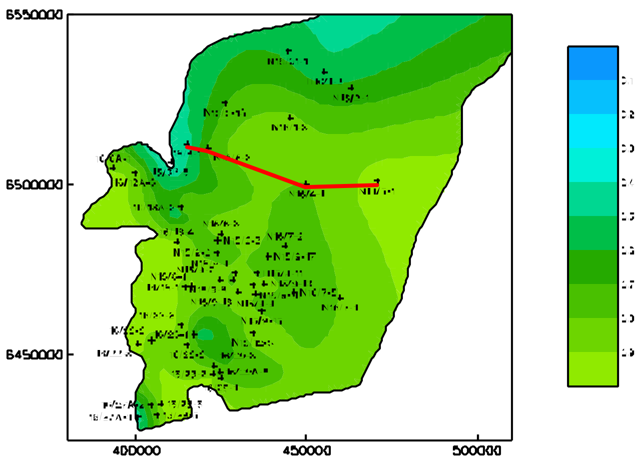
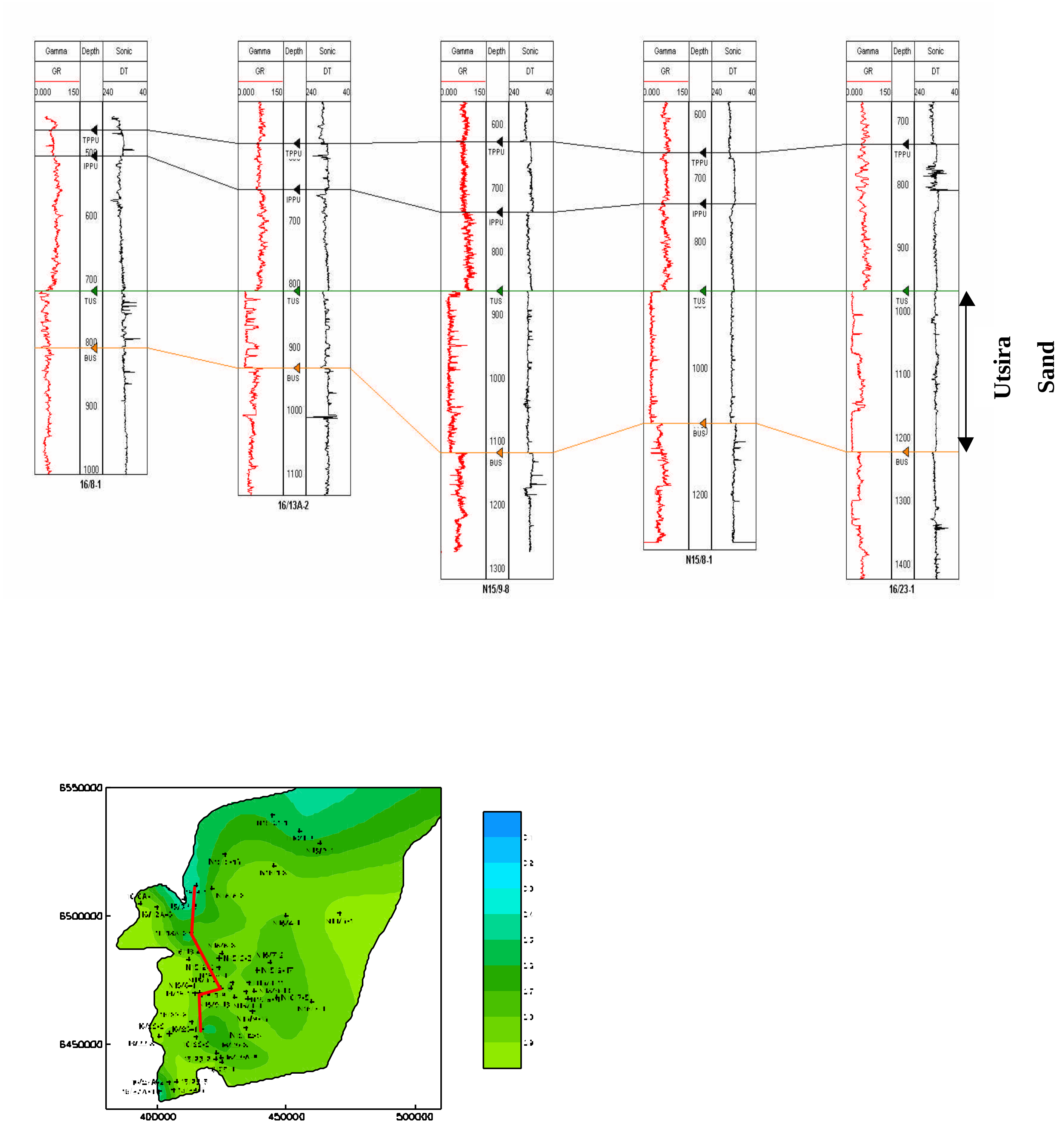


Figure 13: Stratigraphic correlation of the Utsira Sand: N-S profile



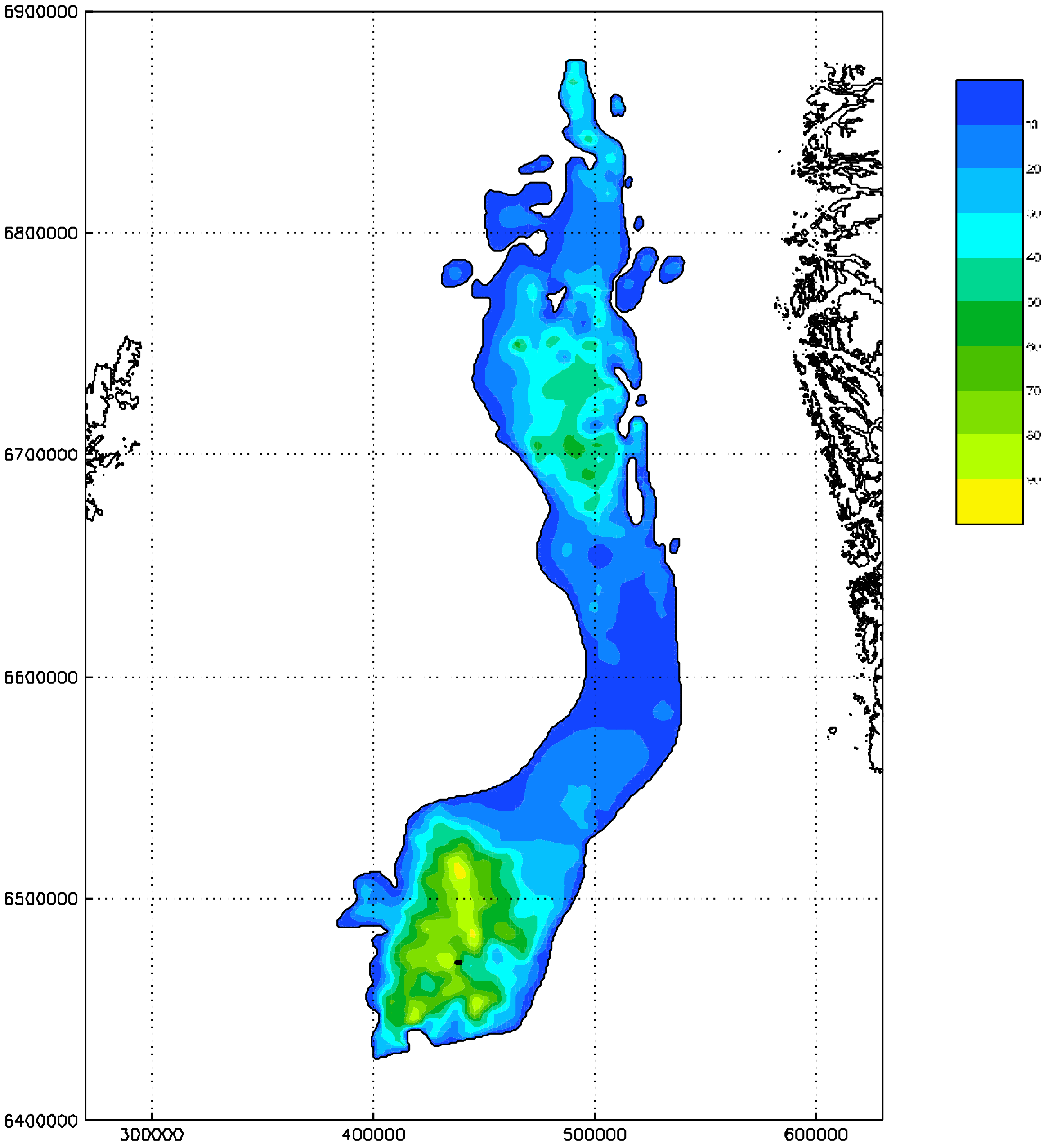


Figure 14: Total pore space thickness: Utsira Sand (metres)
CO_2 injection point marked by black dot