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Date	Authors	Authors signatures
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Document summary:
The document lists the work performed in the Troll Kystnær area over two periods; 2009-10 and 2012 following acquisition of additional seismic.

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1 EXECUTIVE SUMMARY

This report presents the evaluation of the Troll Kystnær area as a potential storage site for CO_2 captured at Mongstad. The location is one of three areas evaluated during a screening phase where the aim was to find alternatives to the Johansen storage site. This study was performed for Gassnova SF as part of the work done to mature a storage location for the Mongstad Capture site.

.The work was performed over two periods:

- Q4/2009 – Q3/2010: focused on the mapping of the storage complex within the Troll Kystnær area, mainly based on 2D seismic. Construction of geological and reservoir model with simplistic property modelling, for general pressure build-up and plume migration analysis. It was also used as basis for suggested seismic acquisition during 2011.

- Q1/2012 focused on interpreting new 3D seismic covering the injection sites, plume extension area, in particular the Øygarden Fault Complex (ØFC). High level petrophysical evaluation and geomechanical assessment was performed with the aim to give an indication of safe pressure build-up. External study performed at NORSAR regarding seismic activity in area near ØFC.

The Troll Kystnær storage site is located on the Horda Platform east of the Troll East Gas Field (Figure 1-1), with a distance to Mongstad of approximately 50 km a water depth ranging from 300m to 350m. The aim of the study was to map and assess the extent of the potential storage formations (Upper Jurassic Sognefjord, Fensfjord and Krossfjord formations) and the cap rock formation (Draupne) in the area.

The area is partly covered by one Production license. PL577 operated by Wintershall (40%), Talisman (30%) and Spring Energy (30%) and is valid to 04.02.2018. The plume spread is not expected to affect the PL577 license with the proposed injection location (see Figure 1-1).

<u>Storage Complex Definition</u>
The Troll Kystnær storage complex is identified as a fault block bounded by major faults to the north, east and west, where the faults system in the east is the Øygarden Fault Complex and the fault to the west and north is the Vette Fault (Figure 1-1). The storage formations have been found to die out towards the south. Seismic mapping together with well observations suggests good reservoir properties and extensive pore volume connectivity. The depth to the storage formation varies between 890m to 1300m in the plume migration area.

<u>Storage Formation – presence and quality</u>
Within the Troll Kystnær area two wells have been drilled penetrating the potential storage formation. Well 32/4-1 penetrated approximately 70m of Sognefjord Formation, 230m of Fensfjord Formation and 45m of Krossfjord Formation, while well 32/2-1 had 114m of Sognefjord, 103m of Fensfjord Formation and 70m of Krossfjord Formation. The Sognefjord Formation is the main reservoir unit in the Troll Field and its reservoir presence and quality is proven by several of the Troll Field wells. The storage formation is interpreted to be present all over the Troll Kystnær fault block. The total storage formation thickness is interpreted to reach up to 700m in the mapped area and between 310m to 450m in the CO_2 plume migration area.

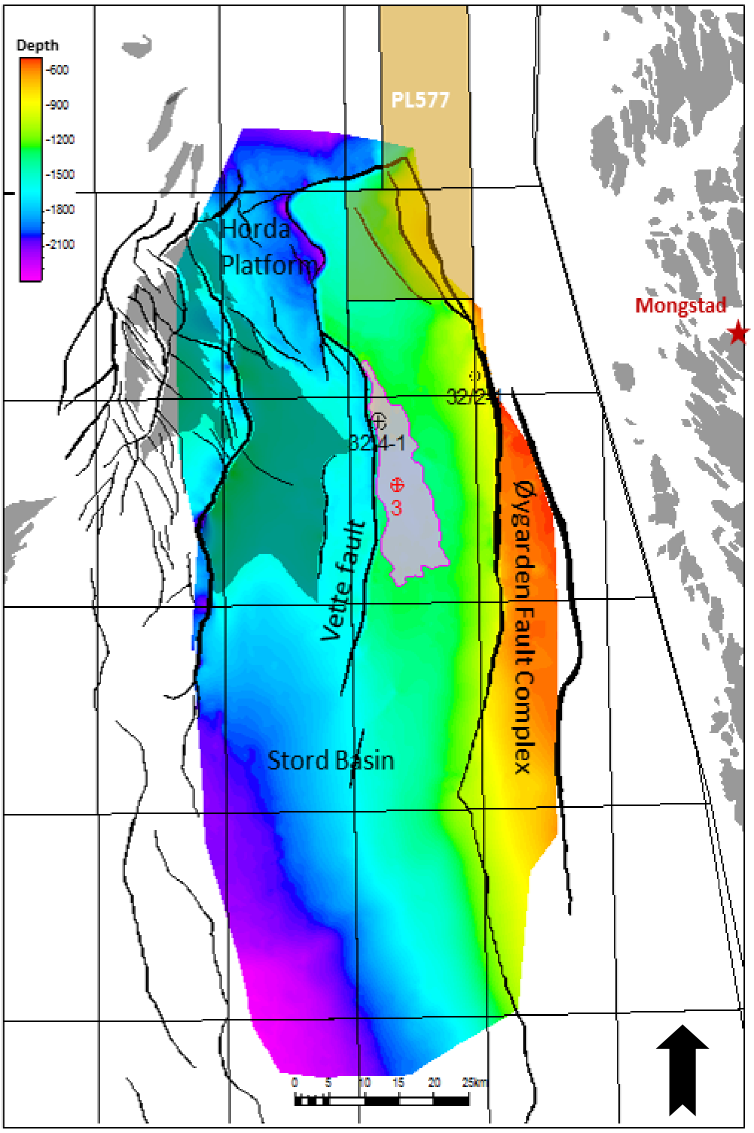

Figure 1-1 Top Sognefjord Formation depth and structural map with the suggested injection location (#3) and plume migration after approximately 500 years (purple polygon).

Storage Formation Seal

The Cap rock covering the Sognefjord formation is the upper Jurassic Draupne Formation which is a marine, organic rich, impermeable claystone. Secondary seal units are present in the form of cretaceous limestone and shales belonging to the Shetland and Cromer Knoll groups. Tertiary and Quaternary deposits are also assumed to have sealing capacity. The total seal present is approximately between 500m and 1200m in CO_2 plume migration area. The eastern boundary for the storage complex is the ØFC and it is assumed that this fault zone is sealing the storage formation towards east. This assumption seems valid based on interpretation of newly acquired 3D seismic and earlier independent fault seal analysis of the fault zone. In addition an evaluation has been done by NORSAR where the seismicity of the fault zone was studied. This study further validates the above assumption.

Storage Performance
Based on the geophysical and geological interpretations made, a reservoir model of the Troll Kystnær area was created. The model comprises the Sognefjord, Fensfjord and Krossfjord formations. Preliminary estimations of pressure build-up and estimations of safe pressure at shallowest point of plume migration, indicates that the area will have capacity for the required Mongstad volume. This based on preliminary simulations of 3.2MT/yr for 50 years which gives a pressure build-up of 25 bars for the Base case pore volume. Several injection points have been simulated and the most promising is presented in this report.

Well data from the Troll area, including exploration well 31/8-1, and Troll Kystnær indicates that there is depletion in the Troll Kystnær storage complex. This confirms extensive communicating porevolume and may give larger storage capacity.

Extensive primary and secondary seals are identified with sufficient thicknesses for safe subsurface storage of CO_2. There are, however, uncertainties regarding the estimation of “safe pressure build-up” which need to be addressed in future work. Also a deepest ultimate migration point for the plume will be more favourable. Alternative injection points may be investigated.

Uncertainty and integrity
In order to assure long term safe storage of CO_2 the main uncertainties and risk factors have been assessed: Presence and quality of storage formation, quality and thickness of cap rock, and number and properties of faults in the area of interest.

The uncertainty regarding the presence and quality of the storage formation is considered low to moderate. The main uncertainty is its southward extension which is difficult to accurately predict due to lack of suitable seismic data, and the actual quality of the formation in the injection location due to lack of core data.

The uncertainty regarding seal integrity is considered moderate to low as the total thickness of seal units over the area is between 500 and 1200m. Lack of cores and dedicated minifrac data makes the assessment of safe pressure build-up uncertain.

Nothing has been found indication that the integrity of the Øygarden Faults Zone is questionable. There is minor tectonic activity, and no seismic anomalies indicate a leaking fault. There are no signs of pockmarks above the zone. The Vette fault defining the western boundary of the Storage Complex is also found to have good sealing properties with no sand/sand juxtapositions.

The current injection location exposes the legacy well 32/4-1 to CO_2. The well has questionable well integrity and requires a plan for minimising leakage risk.

The depth of the storage formation lends itself well to 4D seismic monitoring of the CO_2 plume

Conclusions and recommendations for further work
It is believed that it is feasible to develop a CO2 storage complex in Troll Kystnær. The main risk which is the seal of the Øygarden Fault Zone have been considerably reduced by the work performed in 2012. Further work is however required for the purpose of documenting the storage complex properties, Need for data and work is identified. The quality of storage formation and cap rock is well documented.

A Storage Formation geo-model has been developed and one injection site is suggested. Plume migration and pressure development has been simulated. The results show that the Troll Kystnær storage complex has a possible large storage potential and can be recommended for further work.

The following work is recommended in order to reduce the main uncertainties and risk towards DG2:

- Storage formation presence and quality are proven by 2 wells. The uncertainty associated with presence and quality is hence considered low to moderate. The volumetric risk is higher both regarding rock compressibility and extension of the hydraulic unit. This need to be narrowed down through more detailed mapping of sand extension, faults and core testing to assess rock compressibility.
- The interpretation of the 3D seismic cube, GN1101, performed Q1 2012 and the seismicity study performed by NORSAR has reduced the risk from high (in the first assessment period) to moderate with regard to the Øygarden Fault Complex sealing capacity and associated thinning of overburden. Additional assessment of e.g. stress effects on the Øygarden Fault Complex and e.g. overburden strength related to burial history will further reduce these uncertainties.
- Optimization of injection point in order to achieve the deepest possible plume migration point. This increases storage efficiency and integrity
- Well data from the Troll area, including exploration well 31/8-1, and Troll Kystnær indicates that there is depletion in the Troll Kystnær area. An extensive study on well data is needed to verify the degree of depletion.
- An overburden model should be constructed as basis for a migration path analysis. This would also be part of the monitoring plan.
- To fully characterize the Troll Kystnær Storage Complex according to EU requirements, a verification well is needed. This well should have a full suite of formation evaluation, including cores and fluid samples. This will also confirm the degree of depletion in the storage formations. The data collection programme should have at least the same focus on the cap rock as for the storage formation.
- In order to make a decision regarding need for verification well before investment decision, more work needs to be done with existing data.

Development cost has not been included in this report as it was outside the scope of work.

2 INTRODUCTION

During the course of maturing a base case storage site for the Mongstad Carbon Capture project (CCM), Ross Offshore, in its role as Gassnova's Owner Engineer, recommended to look for alternative storage locations offshore Mongstad. In cooperation with NPD, three areas were selected for further evaluation; Utsira Central, Stord Basin and Troll Kystnær. While the Utsira Central area lacked the sufficient depth and seal for safe storage, the Stord Basin seems to offer great potential, but was concluded too immature to be an alternative for DG2 in October 2012. Troll Kystnær on the other hand seemed to offer the correct balance between storage potential and maturity to be a viable alternative.

The work on Troll Kystnær has been done in two phases where the first was a screening phase based on existing data. This evaluation was done during 2009 – 2010 and consisted of main evaluations regarding suitability, model building and reservoir simulations. The main conclusion on the suitability of the Troll Kystnær area as a potential storage site and the recommendation to collect addition 3D seismic over the Øygarden Fault Zone as this represented the largest uncertainty regarding leakage risk. This was documented in the report "Trollkjerring Preliminary Development Report (Doc no: TL02-ROS-Z-RA-0005). The additional seismic was collected during summer of 2011 and was briefly interpreted in Q1 of 2012 to better understand the Øygarden Faults Zone. Further was a study issued to NORSAR were the seismic activity related to the Horda Platform and Øygarden Fault zone was investigated. Some additional simulation work has also been done during 2011 both to investigate effect of depletion in the area, and as a basis for location of 3D seismic. The result from all this work is reported in this updated report which is a re-issue of the Preliminary Development Report, updated with work performed during 2011 and 2012.

2.1 Work objective

As the work summarised in this report spans two work periods, the objectives of the work can be described as twofold:

- First phase was to perform a screening of the area to assess suitability as a potential storage site, identify the highest risk/ uncertainties and recommend further work.

- Second phase was to perform a more detailed investigation of the Øygarden fault zone in an attempt to de-risk this feature as a potential threat to storage site integrity.

The objective of the second phase was originally more extensive. For reasons outside this project, the priorities changes during 2011 and it was decided to do minimal interpretation of the newly collected seismic. The scope of the second phase was therefore reduced.

2.2 Capacity requirements

A capacity requirement of 3.2Mt/y over a period of 50 years was set by Gassnova as the desired capacity. This was based on 2.1Mt/y from Mongstad Power Station and Cracker with an extra 50% capacity.

2.3 Location and license information

The Troll Kystnær fault block is located on the north-eastern flank of the Horda Platform in Northern North Sea, mainly in quadrant 32 (Figure 1-1).

The following license is rewarded in the area:

- PL577 operated by Wintershall (40%), Talisman (40%) and Spring Energy (30%) and is valid to 04.02.2018, and awarded in APA2010.
- Several APA2012 announced blocks.

The reservoir target for the above mentioned licenses is thought to be Cretaceous as the Sognefjord system is proven non-hydrocarbon bearing in the area. This should not cause any conflicts with possible CO2 storage.

2.4 Storage Site description

The Troll Kystnær Storage Complex is a saline aquifer with the Sognefjord Formation as the main storage formation. Additional volume is found in the Fensfjord and Krossfjord formations. Within the storage complex fingers of the Heather formation (named Heather A,B and C) are recognized, however due to low permeability they are not included as a storage volume contributors. The Storage Complex is bounded by the Vette fault to the west and north and the Øygarden Fault Complex to the east, while a pinch out of the Sognefjord Formation defines the southern limit. The storage complex is capped by the Draupne Formation; which is defined as the primary seal.

2.5 Work structure

As there still is no guideline presented by the Norwegian Authorities, international recommendations or best practices for the maturation of storages were used. Both the EU directive 2009/31/EC/ (Storage Directive) and the DnV CO2QUALSTORE guidelines have been followed during the work. The EU directive does not deal with screening criteria, but rather a stepwise approach to how the work should be performed and what ultimately shall be documented for the selected site in a Storage Permit Application. The work follows the stepwise process outlined in the Directive, but the CO2QUALSTORE Guideline was used as screening criteria during the first phase.

The following screening criteria were used:

- The target formation should have adequate porosity and thickness (for storage capacity) and permeability (for injectivity) at sufficient depth to achieve dense phase conditions (> approx. 700 m TVD).
- The storage formation should be capped by extensive confining low permeable units (such as shale, mudstones, salt or anhydrite beds) to diminish the probability of CO_2 migration out of the defined storage complex.
- The geological environment shall be sufficiently stable to avoid compromising storage integrity. This means that extensively faulted areas may require more careful characterisation to assess their suitability.
- Sites should not be in conflict with other natural resources, ie underlying or overlying hydrocarbon reservoirs.

The work process is according to the Storage Directive. This involves a 3 step process.

- Step 1 Data collection:
  Sufficient data shall be accumulated to build a three-dimensional static earth model for the storage site and the storage complex, including the caprock, and the surrounding area, including the hydraulically connected areas.
- Step 2 Building the three dimensional static geological earth model.
  Using the data collected in step 1, a three-dimensional static geological earth model, of the candidate storage complex, including the caprock and the hydraulically connected areas and fluids shall be built using computer reservoir simulator
- Step 3 Characterisation of the storage dynamic behaviour, sensitivity characterisation, risk assessment
  The characterisations and assessment shall be based on dynamic modelling, comprising a variety of time-step simulations of the CO2 injection into the storage site using the three-dimensional static geological earth model(s) in the computerised storage complex simulator constructed under Step 2.

This is largely the same work process as outlined in the QUALSTORE Guideline:

- Review data and identify potential sites
- Estimate capacity and uncertainty

Under each of the 3 steps listed above, the Storage Directive list characteristics which, as a minimum, shall be covered and documented in a Storage Permit Application. The CO2QULASTORE gives guidance on how to structure the information in an application for a storage permit. It is important to keep in mind that this report summarises the work performed primarily as a screening process. The focus has therefore been more on the screening criteria associated with storage integrity and risk of leakage on a broad scale, and less on issues like geochemistry, reactive processes, and other sensitivities regarding plume migration and the ultimate fate of the injected CO_2 in a 10000 year perspective. Further has a full assessment of volumetric uncertainty and hence storage capacity not been within the project scope.

As part of the work performed by the group on maturing the Johansen storage complex a guideline for storage site qualification was developed. Although the reporting format developed for this guideline is used for this report, the majority of work performed for Troll Kystnær was performed before the guideline was developed.

2.6 Report structure

The report layout follows the recommended structure developed as part of the internal guideline. The main sections are as follows:

- **Data collection and assessment** lists all the data the evaluation is based on, and any special studies that have been performed. These include a high level Petrophysical study and assessment of safe pressure build-up, and a assessment on the seismicity of the Horda platform. These data are used both in construction of the static 3D geological model and in the dynamic model.

The chapter also indicates the additional data needed for a complete storage application.

- **Storage complex description** describes how the static geological 3D model was constructed using the data collected. The chapter includes seismic interpretation, development of depositional model, description of storage formation(s) and cap rock and an assessment of safe pressure build-up. An explanation of the volumetric uncertainty in the area is also given. The geological model constructed forms the basis for the dynamic model used to simulate plume movement.
- **Dynamic storage behaviour and predictions** looks at plume migration for the suggested injection point and the associated pressure build-up of the reference case model. The dynamic model used is based on the geological model.
- **Storage site uncertainty and integrity** details the main uncertainties and risk factors in order to assure long term and safe subsurface storage of CO_2 in the Troll Kystnær storage complex and the integrity of the storage formation and seal.

A first version of this report was issued in 2010 as a result of the study performed during 2009-2010. After the short study in Q1 2012, an updated report was created to include additional results and findings.

3 DATA COLLECTION AND ASSESSMENT

This section contains an overview of the databases used for both phases of the project. In addition a petrophysical evaluation of available data and a seismicity study (NORSAR) were conducted in Q1 2012.

3.1 Well database

The well database comprises released wells within the study area, with time/depth relationship and lithostratigraphic tops. Wells have been used in order to recognize storage formation rocks and cap rocks. All wells used for well calibration and seismic tie are listed in Table 3-1 and shown in Figure 3-1.

Table 3-1 Key well database

Well name	Year drilled	Gamma Ray log	Depth to Sognefjord Fm (m)
31/2-1	1979	x	1440
31/3-1	1983	x	1352
31/3-2	1984	x	1567
31/3-3	1984	x	1753
31/6-1	1983	x	1352
31/6-2R	1984	x	1460
31/6-3	1983	x	1511
31/6-5	1984	x	1518
31/6-6	1984	x	1561
31/6-8	1985	x	1507
32/2-1	2008	x	910
32/4-1	1996	x	1238

Petrophysical data, check shots, GR logs, velocity logs and markers provided by NPD have been used in the evaluation. A total of 23 m core was cut in well 32/4-1 covering both the first Heather shale and the Sognefjord sand system. Core analysis reports are available. No cores were cut in 32/2-1, but a petrophysical evaluation was performed.

Figure 3-2 shows the development of the Troll Kystnær storage complex with key horizons, which constitutes the primary seal and storage formation units.

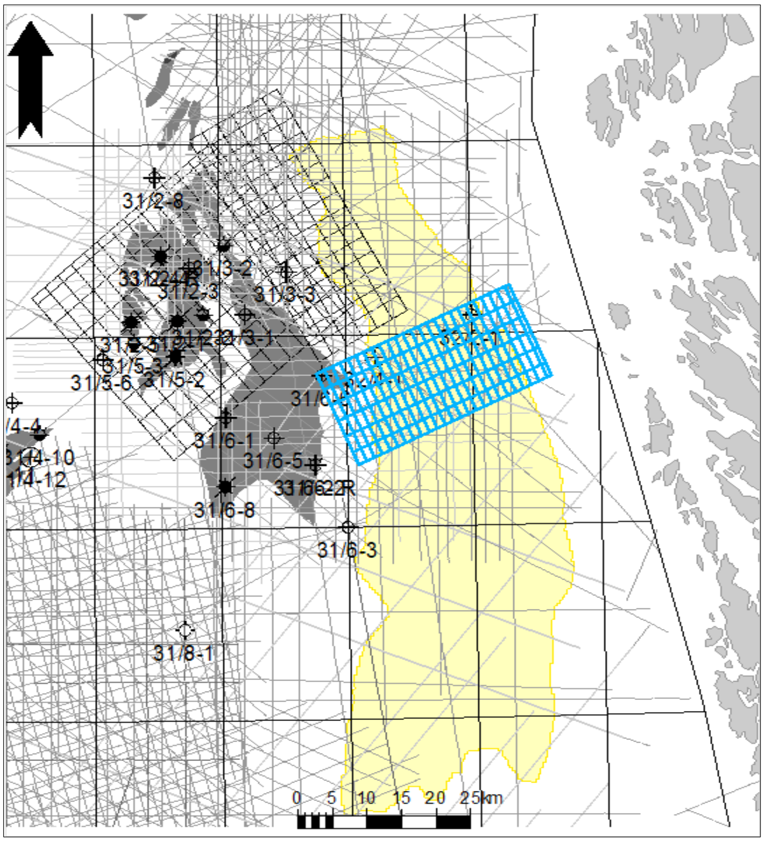

Figure 3-1 The map displays the wells and the 3D and 2D seismic data used in the Troll Kystnær storage complex evaluation. The black grid intersecting the yellow polygon marks the TNE01 3D survey and the blue grid marks the GN1101 3D survey (used in the Q1 2012 study). The yellow polygon represents the outline of the Troll Kystnær base case geo-model generated for the reservoir simulations.

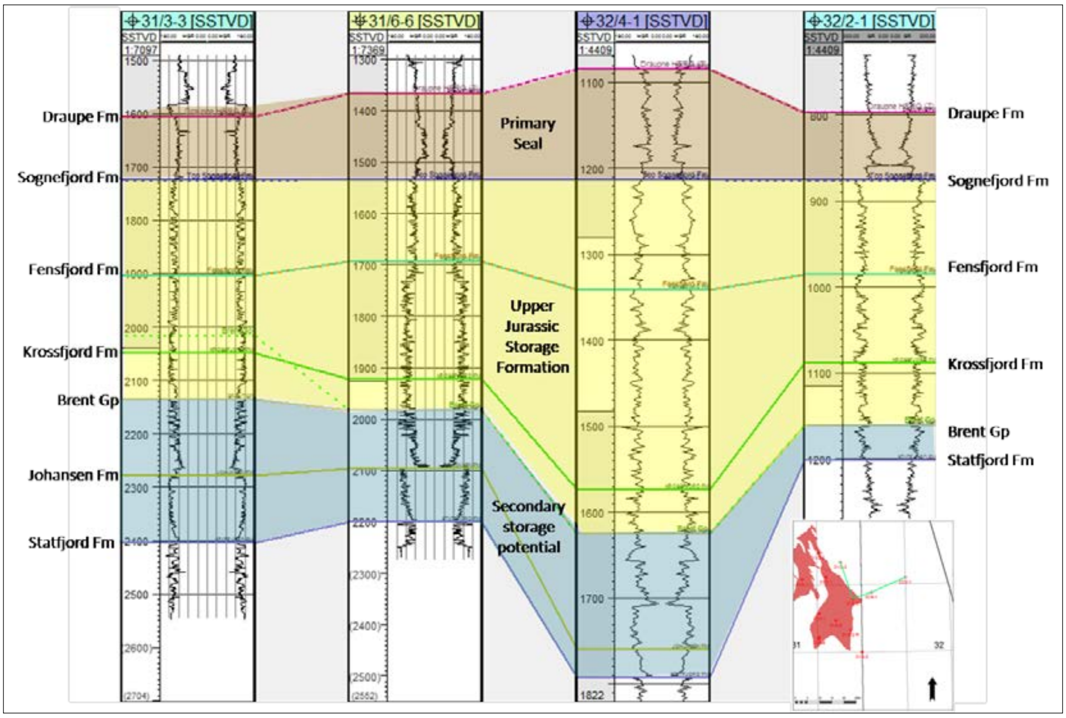

Figure 3-2 Correlation of the wells on the Troll East fault block to the wells on the Troll Kystnær fault block.

3.2 Seismic Database

The seismic database used in the evaluation is shown in Figure 3-1 and Table 3-2. The database consists of public 2D and 3D seismic of various vintages and quality. The storage site area is mainly covered by 2D seismic in a varying grid, only a small part of the storage site area is covered by 3D (TNE01 and GN1101).

The 3D seismic survey (GN1101; see Figure 3-1) was collected by Gassnova in 2011 based on the recommendations given in the first phase of this evaluation (2009-2010). The placement of the GN1101 3D cube was decided on the following criteria; the 3D cube needs to cover the suggested injection site and large areas of the expected CO_2 plume. It must also include parts of the ØFC and the Vette fault.

Table 3-2 Seismic database.

Survey name	Survey Year	Type	Shot for	Quality
BPN88	1988	2D	BP	Low
GSB-85R97	1997	2D	GECO	Low
HRTRE00	2000	2D	GEOTEAM	Medium
HT91	1991	2D	GEOTEAM	Medium
MN88	1988	2D	MOBIL	Low-Medium
MN89	1989	2D	MOBIL	Low
MN9001	1991	2D	MOBIL	Low
MN9102	1991	2D	HYDRO	Low-Medium
MN9103	1991	2D	MOBIL	Low-Medium
MN9201	1992	2D	HYDRO	Low
NPD-KYST	1996	2D	NPD	Low
NSR	2006	2D	NOPEC	Good
SBGS-RE-94	1994	2D	NOPEC	Medium
SG8043	1980	2D	SAGA	Medium
SG8970	1989	2D	SAGA	Medium-Low
SG9206	1992	2D	SAGA	Low-Medium
SH8001	1980	2D	SHELL	Low
SH8102	1981	2D	SHELL	Medium
SH8203	1982	2D	SHELL	Low
SH8401	1984	2D	SHELL	Medium
ST8201	1982	2D	STATOIL	Low
ST8301	1083	2D	STATOIL	Low
ST8618	1986	2D	STATOIL	Low
TE93	1993	2D	GEOTEAM	Low
TNE01	2001	3D	HYDRO	Medium
TT98	1998	2D	NOPEC	Low
TW91	1991	2D	NOPEC	Medium

3.3 Petrophysical Evaluation

A petrophysical evaluation has been made to evaluate:

- The storage formation which include all formations from the Middle Jurassic formations to the Upper Jurassic Sognefjord Formation
- The primary cap rock which is the Draupne Formation
- The secondary seal including all formations from the top of the Draupne Formation to the sea floor

Seven wells were incorporated into the analysis; the two wells in the Troll Kystær region, 32/2-1 and 32/4-1, four wells at the eastern edge of Troll Øst and the recent Breiflabb well, 31/8-1. The well locations are identified in Figure 3-3. The petrophysical interpretations are based on the general suite of logs including Gamma Ray, Resistivity, Sonic, and Density/Neutron.

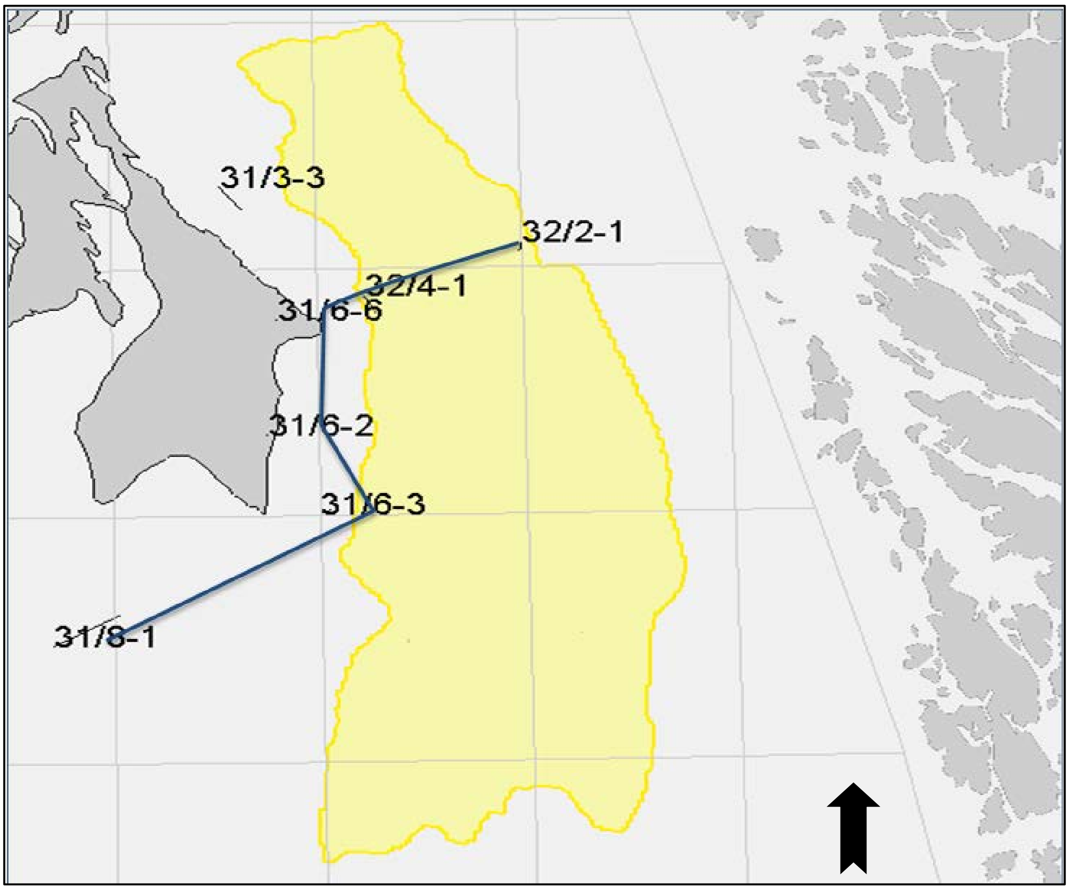

Figure 3-3 Map showing wells incorporated in the Troll Kystnær petrophysics evaluation.

The formations considered to be present within the storage complex, from oldest to youngest, include Heather A Formation, Krossfjord Formation, Fensfjord Formation, Heather B formation, Sognefjord Formation, and Heather C Formation. The Heather A and B Formations are not always present and generally have lower porosity and permeability than the main storage volumes of Sognefjord, Fensfjord and Krossfjord formations. As such they may act as barriers to CO_2 flow. The Heather C Formation, in particular, which comprises a relatively thin (~20m), milliDarcy permeability sequence above the Sognefjord Formation is present in all wells analysed, and may act as a relative barrier to CO_2 flow.

The primary cap rock formation is the Draupne Formation. The secondary seal is made up of all formations above top Draupne Formation, and are referred to as the overburden sequence. The overburden sequence varies across the region. In the storage region it is considered to include the Lower Cretaceous Cromer Knoll Group and the Nordland Group of sediments. The stratigraphic zonations used are those from the NPD. The volume of clay (VCl), porosity (PHIE) and permeability results for the storage formations and the primary cap rock formations are shown in Table 3-3. Owing to the lack of petrophysical data available, porosity and permeability models of the overburden sequence were not made. VCl models were made and the results are shown as lithology interpretations in Figure 3-4. Note that the storage formation average values of VCl, Phie and permeability in Table 3-3 are averaged from Heather A, Krossfjord, Fensfjord, Heather B and Sognefjord formations, excluding the Heather C Formation.

Table 3-3 Summary of average volume of clay (VCl), porosity (PHIE), and base case permeability results for storage formations and primary cap rock. The main storage formation average excludes Heather C and Draupne formations.

Results: Volume of Clay

	Volume of Clay							
	32/4-1	32/2-1	31/6-6	31/6-3	31/6-2	31/3-3	31/8-1	Formation Average
Draupne	*0,61*	*0,59*	*0,57*	*0,69*	*0,60*	*0,56*	*0,58*	*0,60*
HeatherC	0,30	0,40	0,33	0,31	0,42		0,36	0,35
Sognefjord	0,08	0,12	0,07	0,19	0,12	0,16	0,20	0,13
HeatherB	0,13		0,16		0,27	0,26	0,47	0,26
Fensfjord	0,10	0,10	0,14	0,22	0,13	0,17	0,19	0,15
Krossfjord	0,08	0,31	0,15	0,16	0,07	0,06	0,18	0,14
HeatherA	0,17		0,21		0,20	0,27	0,25	0,22
Main Storage Formation Average	0,11	0,18	0,14	0,19	0,16	0,18	0,26	

Results: Porosity (PHIE) Base Case

	Porosity (PHIE)							
	32/4-1	32/2-1	31/6-6	31/6-3	31/6-2	31/3-3	31/8-1	Formation Average
Draupne	*0,14*	*0,11*	*0,19*	*0,09*	*0,12*	*0,16*	*0,05*	*0,12*
HeatherC	0,18	0,17	0,16	0,16	0,14		0,14	0,16
Sognefjord	0,30	0,27	0,24	0,21	0,26	0,22	0,22	0,25
HeatherB	0,27		0,19		0,17	0,17	0,12	0,18
Fensfjord	0,25	0,25	0,21	0,19	0,21	0,21	0,20	0,22
Krossfjord	0,22	0,19	0,18	0,20	0,21	0,22	0,20	0,20
HeatherA	0,17		0,14		0,16	0,13	0,03	0,13
Main Storage Formation Average	0,24	0,24	0,19	0,20	0,20	0,19	0,15	

Results: Permeability (Kh) (Base Case)

	Permeability (Base Case) mD							
	32/4-1	32/2-1	31/6-6	31/6-3	31/6-2	31/3-3	31/8-1	Formation Average
Draupne								
HeatherC	7,08	1,60	2,90	3,40	0,26		0,33	*2,59*
Sognefjord	2478,89	1194,08	110,58	34,27	827,60	79,92	58,82	683,45
HeatherB	565,04		4,40		0,89	1,46	0,22	114,40
Fensfjord	1275,29	410,61	45,88	17,72	10,58	26,39	38,07	260,65
Krossfjord	33,96	91,10	2,32	8,69	7,36	19,83	31,58	27,83
HeatherA	3,63		0,62		0,64	0,14	0,07	1,02
Main Storage Formation Average	871	565	33	20	169	26	26	

3.3.1 Methodology and Modelling

The Jurassic sequence consists of a number of predominantly sandstone units including Sognefjord Formation, Fensfjord Formation, and Krossfjord Formation, interbedded with the locally more silty Heather B and Heather C formations. The upper part of the Upper Jurassic sequence includes the Heather C Formation and the Draupne Formation. Draupne Formation is generally a claystone acting as the regional seal to the hydrocarbon bearing Sognefjord Formation and is considered the primary seal for CO_2 storage. Heather C may also be considered to have sealing properties (Table 3-3). However, for this petrophysical discussion it is presented as part of the storage formation. The Jurassic sands are often micaceous, with tight calcareous streaks. The calcareous streaks are considered to be discontinuous regionally (refs. Walderhaug et al, 1989 and Gibbons et al, 1993) and are thus not absolute barriers to CO_2 flow. The petrophysical zonation used is the NPD zonation. Additional zones were also added to separate gas and oil zones where needed.

3.3.2 Log Data and Quality Check

All log data was loaded into the log analysis tool “Interactive Petrophysics” (IP) and quality checked to assure logs were on-depth and for other log effects due to hole problems. The IP model in each well was set up according to recommendations from logging tool vendor to ensure correct tool calibrations.

3.3.3 Volume of Clay Analysis (VCl)

A number of different volume of clay (VCl) analysis methods were used, using Density and Neutron and Gamma Ray logs. The VCl analysis was calibrated to lithology descriptions from various sources including lithology summaries in Monaghan & Iskander (2009), wellsite lithology descriptions from Completion Reports and core descriptions.

3.3.4 Porosity and Water Saturation Analysis

Porosity: Effective porosity, PHIE, was determined from the Density/Neutron model. Total porosity, PHIT, was corrected for volume of clay. Calculated PHIE was multiplied by 0.974 to correct the PHIE to reservoir stress conditions at an approximate depth of 900mTVDmsl, in accordance with laboratory data from Sognefjord Formation in 31/5-3.

Water saturation: For the evaluation the Indonesian equation has been used. Saturation parameters and water resistivity, Rw, were determined using Pickett Plots in the clean (VCl < 0.15) sands. Saturation parameters varied between wells and formations and ranged between m = 1.95-2.2, n = 2 – 2.2 and a = 1.

Reservoir temperature: For each well a generic temperature gradient of 3.46°C/100m was used (ref. Millennium Atlas) assuming a mudline temperature of 3.88°C.

True Formation Resistivity: Rt, was determined from cross plots of VCl vs deep resistivity.

Shale and Matrix Parameters: Shale and matrix parameters were derived from logs, histograms and cross plots. Generally a matrix density of 2.67 g/cc was used to account for the presence of mica through much of the Jurassic sequence.

3.3.5 Permeability Analysis

Laboratory core porosities and permeabilities are available in several of the Middle and Upper Jurassic formations including Heather C, Sognefjord, Fensfjord, Heather B and Krossfjord formations in a number of wells including 32/4-1, 31/6-6, 31/3-3 and 31/3-3. No core data was available for the 32/2-1 well. To derive porosity-permeability correlations, core helium porosity and ambient pressure Klinkenberg-corrected horizontal permeability were cross-plotted for each well, and for each formation type. The porosity-permeability relationships vary for each formation, and also between the different wells. From the range of available data in the different wells, three porosity-permeability trends were identified for porosities above 17%, based on all available storage formation data for 31/3-3, 31/6-6 and 31/3-1, defining high, base and low case porosity-permeability relationships, respectively. For porosities below 17% a single porosity-permeability trend was used, based on core data from 31/6-6. In addition, to account for in-situ stress effects on permeability, the permeability derived from the above correlations was corrected by the following factors of 0.93, 0.87 and 0.76 for high, base and low case correlations, respectively. This according to permeability reduction factors established from cores tested from ambient conditions up to storage formation depth equivalent stresses in 31/5-3. No core data is available for the Draupne Formation. Porosity and permeability for the Draupne Formation from several tests (ref. Okiongbo, 2011) was used as a generic representation of the Draupne Formation properties. The average reported Draupne Formation horizontal permeability is 7 x 10^{-5}mD (70 nanoDarcy), and the average vertical permeability is 6 x 10^{-6}mD (6 nanoDarcy). No further permeability modelling has been conducted for Draupne Formation.

3.3.6 Lithology Analysis

As a result of the petrophysics modelling, a lithology zonation was defined, based primarily on the VCl. Criteria were defined for clean sand, shaly sand, siltstone, shale and claystone for the storage formations, and the primary and secondary seal formations (Table 3-4).

Table 3-4 Lithology zonation according toVCl.

Lithology	Volume of Clay (VCl)
Clean Sand	<0.15
Shaly Sand	0.15 – 0.3
Siltstone	0.3 – 0.4
Shale	>0.4
Claystone	>0.5

Carbonates, occurring as calcite stringers in the storage formations, and massive limestones or marls in the secondary seal formations were identified based on lithology reports in the Completion Reports and using a combination of GR, resistivity, sonic, and density/neutron logs. The calcite-cemented zones in the storage formation are generally several tens of centimetres to 2-3 meters in thickness. They are reported to be tens of meters to a few kilometres in lateral extent (refs. Walderhaug et al. 1989 and Gibbons et al. 1993). An example of the lithology model for 32/2-1 and 32/4-1 is shown in Figure 3-4.

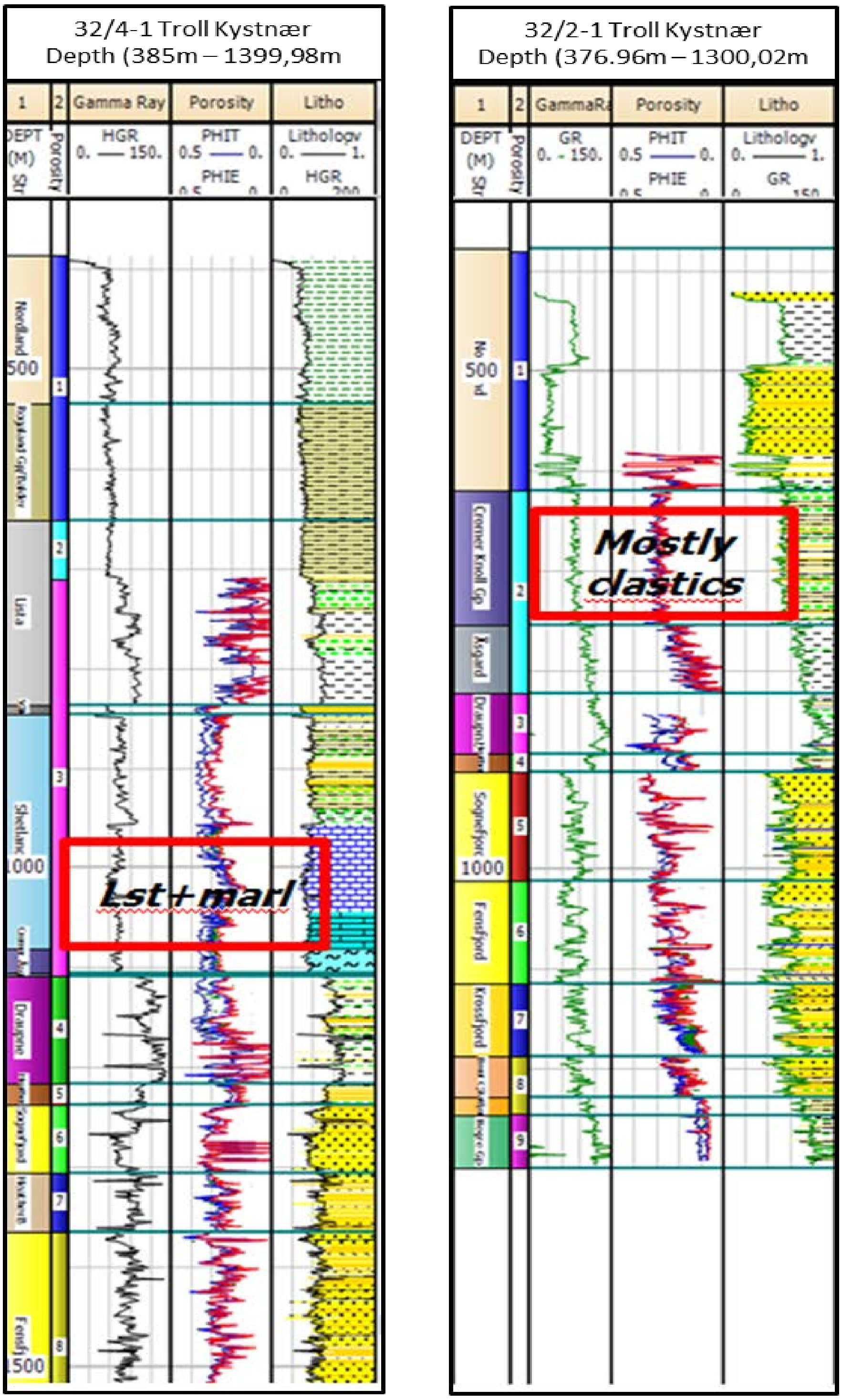

Figure 3-4 Results of the lithology zonation in 32/2-1 and 32/4-1 wells. Well correlation flattened on seafloor. The expected geological sequence in the storage area is likely to be similar to 32/2-1.

3.3.7 Evaluation of pressure gradients

Figure 3-5 shows pressure points for Eastern Troll wells (31/6-3, 31/6-6, 31/3-3, 31/6-2), Troll Kystnær wells (32/2-1 and 32/4-1), and Breiflabb well (31/8-1). There are different pressure gradients reported in several wells where the solid curves represents the range of virgin pressures in any given well for the range of possible pressure gradients. The Breiflabb well (31/8-1) was drilled in 2011 and have pressure points well below the virgin pressure trend.

From one of the Troll Kystnær wells (32/2-1) the final well report shows that one LWD pressure point was measured in the Brent Group at 1194.9mTVDrkb. This value is 118.556bars which is 1.01sg equivalent mud weight. The normal/virgin pressure should be 1.03sg so this measurement represents a small depletion – approximately 2-3bars within Brent. No pressure points were made in Sognefjord, Fensfjord and Krossfjord formations from this well. If extrapolating the observed depletion (using the trends from the other wells) into overlying formations it seems possible that the Sognefjord-Krossfjord formations are depleted with up to 10-20bars. It is recommended to do a more thorough comparison of regional pressure data to obtain a better understanding of depletion in this region.

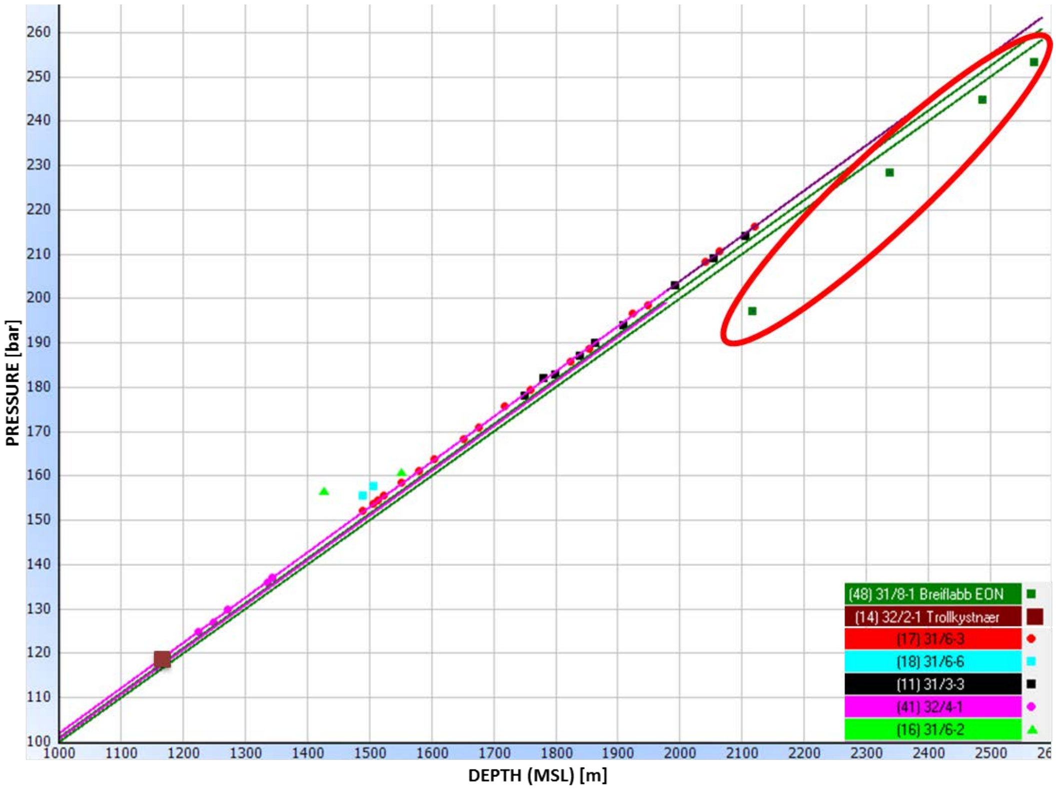

Figure 3-5 The lines represent virgin pressure gradients obtained in Eastern Troll wells (31/6-3, 31/6-6, 31/3-3, 31/6-2), Troll Kystnær wells (32/2-1 and 32/4-1), and Breiflabb well (31/8-1). Red circle highlights depleted pressure points from well 31/8-1. The brown square (lower left corner) indicates the datapoint from well 32/2-11. This datapoint is 2-3bars lower than the trend.

3.3.8 Seal Analysis and Safe Pressure Evaluation

Two aspects of the sealing potential of the primary cap rock, Draupne Formation, have been evaluated. These are:

- Petrophysical properties of Draupne Formation (thickness, VCl, porosity, permeability).

- Geomechanical parameters to estimate allowable CO_2 injection pressure at base Draupne Formation, according to estimates of minimum stress and fracture initiation stress.

Processes of fault sealing and fault reactivation have not been evaluated as part of this analysis.

3.3.9 Petrophysical Properties of Draupne Formation

For the 7 wells analysed, the average thickness of Draupne Formation is 108m, ranging from 61m to 125m. In several of the wells log quality was low throughout the Draupne Formation, owing to the setting of casing shoes, rathole effects and hole size changes. Petrophysical properties were derived from density/neutron and gamma ray, where available. From the analysis documented above, the average VCl for Draupne Formation is 60%, ranging from a minimum of 56% to a maximum of 69% for the 7 wells evaluated. Generally most of the Draupne Formation is claystone (VCl>50%) or shale (VCl>40%), particularly in the lower part of the formation. The upper section may be shale or grade to silt. Porosities (PHIE) for Draupne Formation average 12%, ranging from 9% - 18%. Permeability for intact Draupne Formation was estimated to be between 70 nanoDarcy and 0.001mD for horizontal permeability and approximately 6 nanoDarcy for vertical permeability (ref. Okiongbo, 2011).

3.4 Seismicity

A study was performed by NORSAR to investigate the seismicity of the Hordaplatform and seismic activity related to the Øygarden Faults Zone and potential leakage of CO2 (Norsar 2012).

The seismotectonic of the North Sea, the Norwegian continental margin and the surrounding regions have been studied extensively over the last 30 years. Some studies show that the Horda Platform is an area with quite anomalous stress, with strike-slip faulting, in a region transitional between normal and reverse faulting. The studies also clearly identified the Horda Platform (see Figure 3-6, Figure 3-7and Figure 3-8) as an aseismic region separating the Viking Graben. There are indications of extension and normal faulting where the coastal areas in the east, and the complex areas north of 61^{o}N, merge. While the focal mechanisms to the east and north are more mixed, the inferred stress directions are still dominantly NW-SE. Along the margin further north the mechanisms are more consistently reverse.

The study done by Møllegård (2000), who also reviewed in detail all available earthquake focal mechanisms, indicates a complexity of sources of stress, at plate wide, regional and local scales, together with a heavily fractured crust (especially around 61^{o}N where the number of mapped faults is also very high).

There is an indication from Figure 3-7 that the earthquakes are quite deep and that they terminate at the top of the (high-velocity) lower crustal body (LCB), which should be expected.

Around the southern transect (Figure 3-8) the seismicity is significantly lower and even more inconclusive, except that the hypocentres also seem to be quite deep here. This is expected to have minimal impact on storage site integrity.

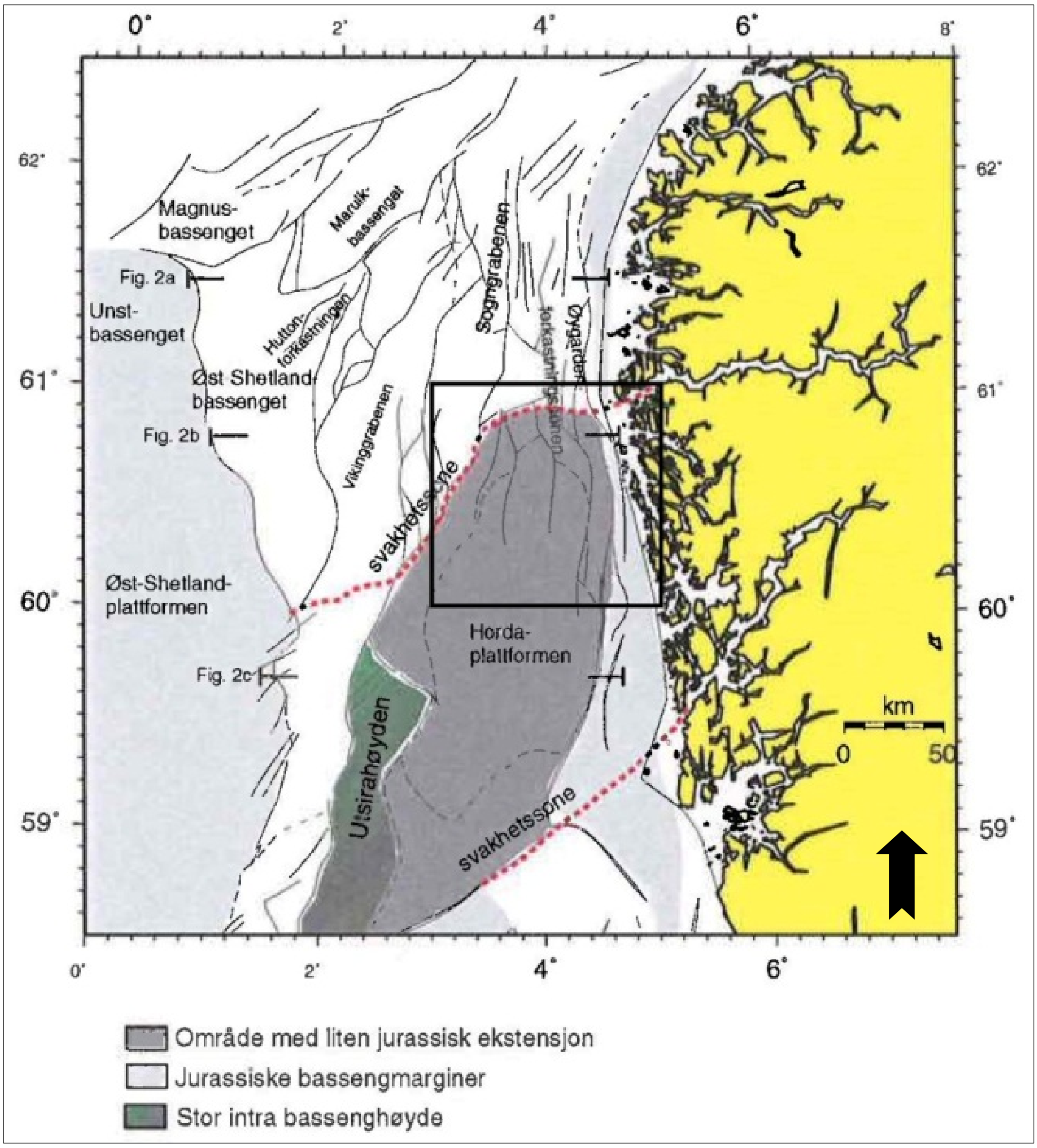

Figure 3-6 Overview of the Jurassic rift zone in the northern North Sea modified from Møllegård (2000). The shaded area is the Horda Platform and the black box in the centre is the study region, covering 3-5°E and 60-61°N.

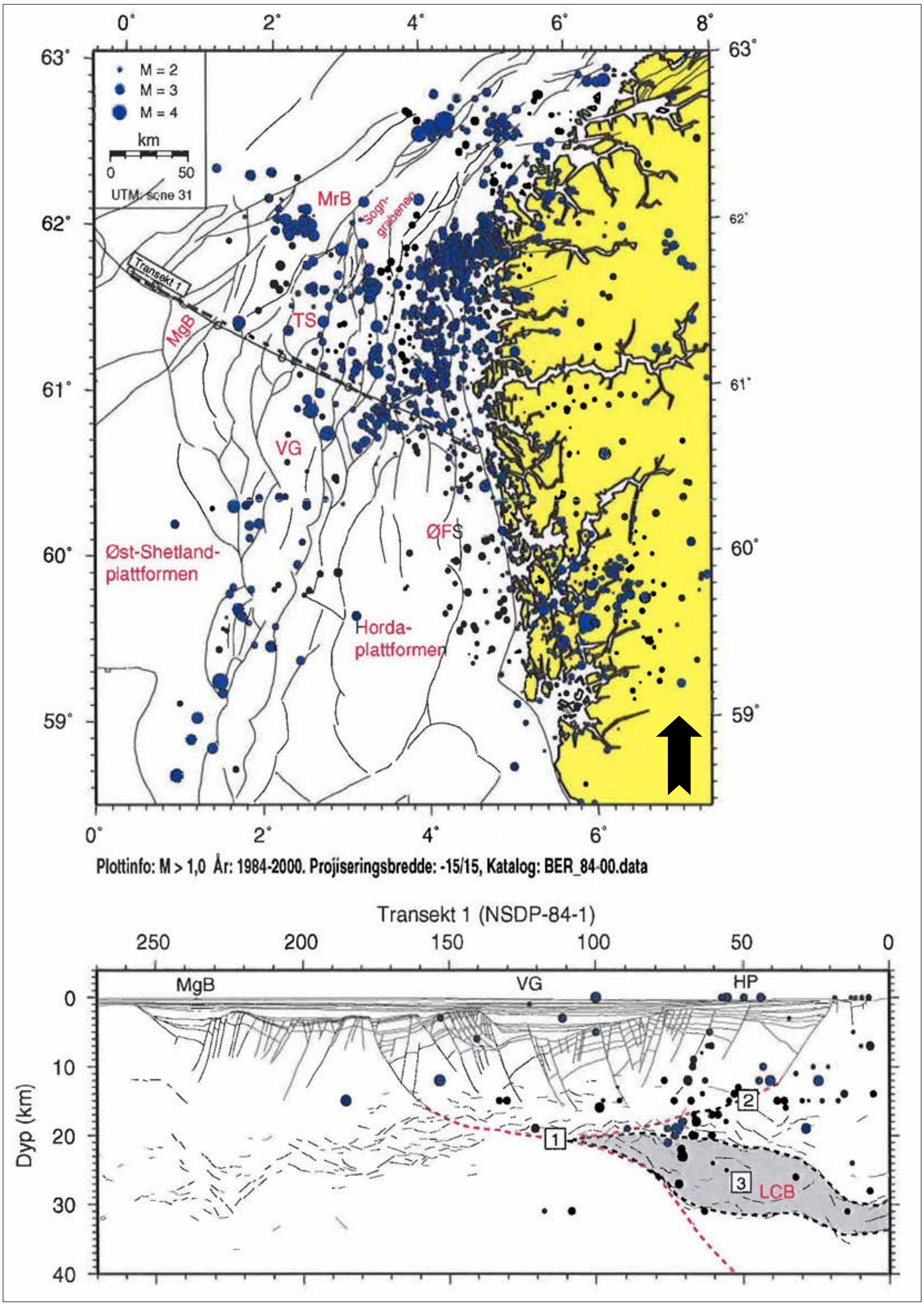

Figure 3-7 Earthquake distribution along profile NSP-84-1, projecting events from 15km on both sides of the line (Møllegård 2000). Line 1 indicates the continuation of a basement fault down to an old shear zone, whole Line 2 indicates the continuation of the Øygarden Fault zone terminating on top of a lower crustal body (LCB, indicated by 3).

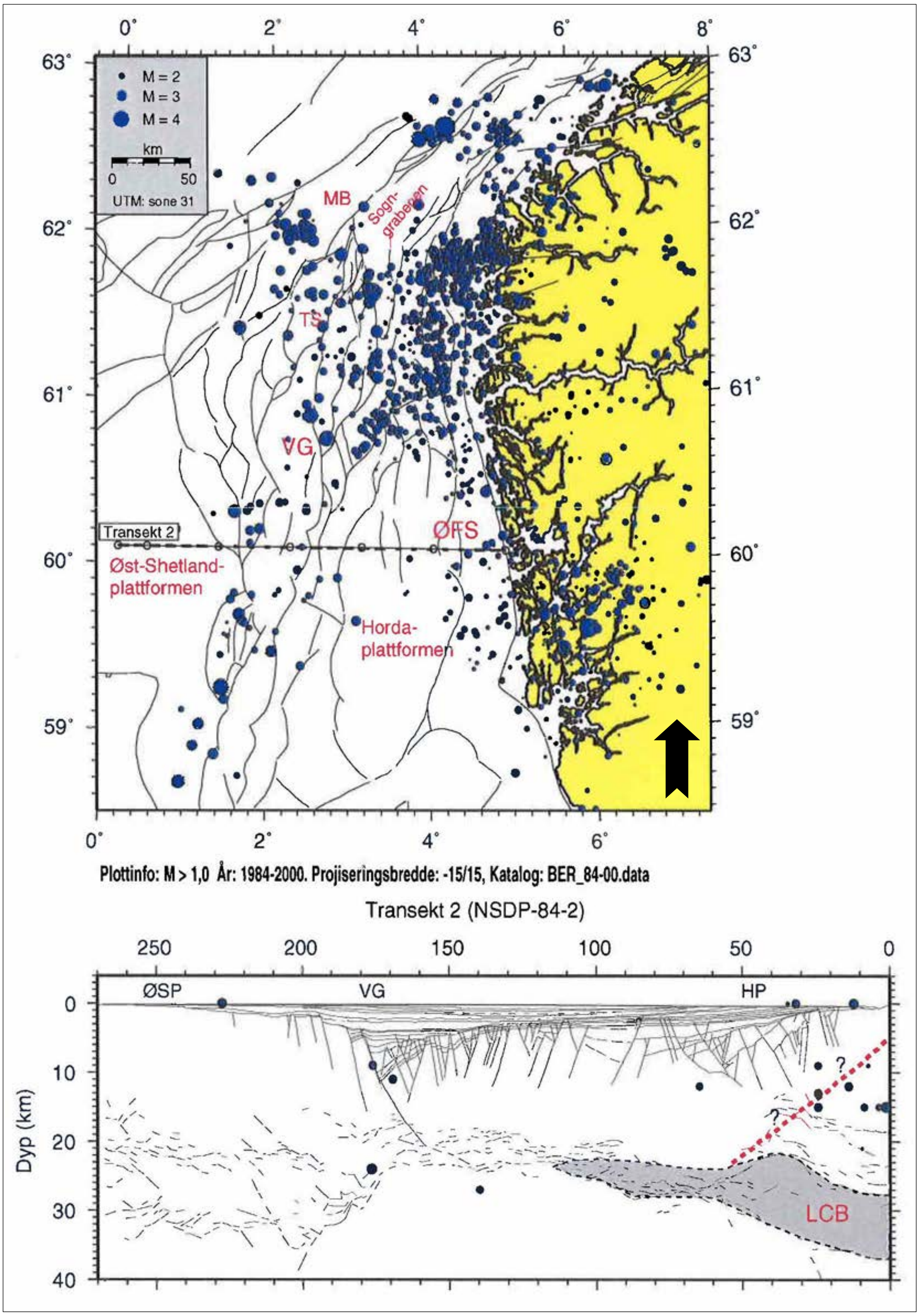

Figure 3-8 Earthquake distribution along profile NSP-84-2, projecting events from 15km on both sides of the line (Møllegård 2000).

3.5 Further data collection and assessment

To fully characterize the Troll Kystnær Storage Complex according to EU requirements, a verification well is needed. This will provide both confirmation of formation presence and quality, and also give an opportunity to collect fresh core samples from both storage formation and cap rock. A well will further give the opportunity to provide in-situ stress data using a mini-frac as well as FIT/LOT. Reservoir properties in the near wellbore region and in a reasonable radius from the well should be investigated using a “dual packer” test.

The fresh core and fluid samples should be used to perform a full suite of geochemical analysis to determine the long term fate of CO_2 and fully describe the trapping potential. It should further be used to narrow the uncertainties related to safe-pressure build-up.

4 STORAGE COMPLEX DESCRIPTION

This section outlines the steps performed in order to build a three dimensional earth model of the storage complex. The description covers work performed both on 2009-2010 and work done in 2012. The geo model was built in 2009-2010 and no findings during the 2012 seismic interpretations indicated that this model needed to be updated. The simplistic property model was not updated although a petrophysical study was performed in 2012. This was not considered a priority given the limited time available, as the effect of other uncertainties in the model would have bigger influence on the final result.

The geophysical work performed in 2012 was geared towards a stratigraphic/structural reconstruction of the Øygarden Fault Zone with the aim to better assess the leakage risk of this structure. This work is included in this section.

4.1 Introduction

The Upper Jurassic Sognefjord, Fensfjord and Krossfjord formations represent the primary storage formations for the Troll Kystnær area. The Sognefjord Formation is the main reservoir unit in the Troll Field and its reservoir presence and quality is proven and tested by several of the Troll Field wells. The storage formation varies in depth from approximately 900 – 1300m in the proposed injection area (Figure 4-1). Additional storage formation targets could be present in the older strata but were not evaluated.

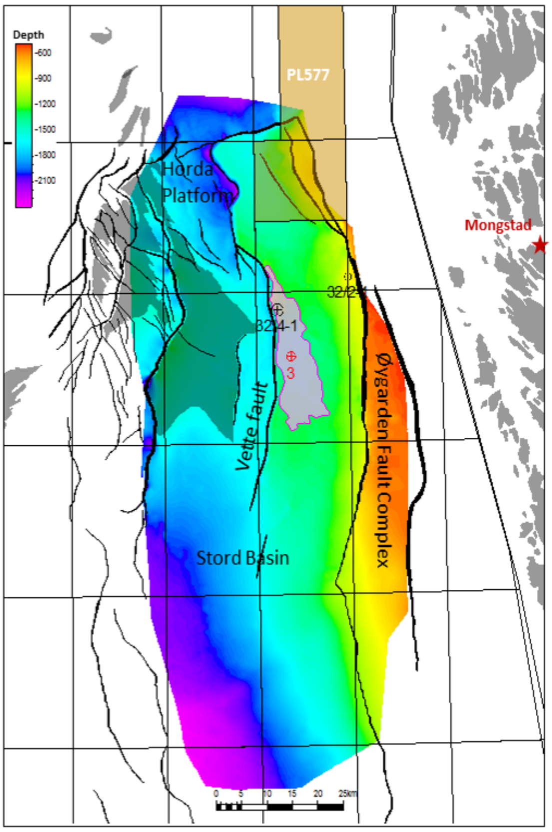

Figure 4-1 Storage formation and suggested injection location.

4.2 Seismic analysis

One of the main tasks in storage complex description is the interpretation and analysis of seismic data. The purpose is to establish the stratigraphic and structural framework for the Troll Kystnær Storage Complex. The Petrel E&P software platform (Schlumberger) is the main tool used in the analysis.

The main activities in the seismic analysis are;

- well to seismic calibration
- interpretation of faults/horizons
- depth conversion

The Q1 2012 interpretation was performed to more thoroughly inspect the injection area and the nearby major faults.

4.2.1 Well to seismic calibration

The seismic interpretation is based on one well to seismic calibration (Figure 4-2) and seismic ties to key wells (Figure 4-3).

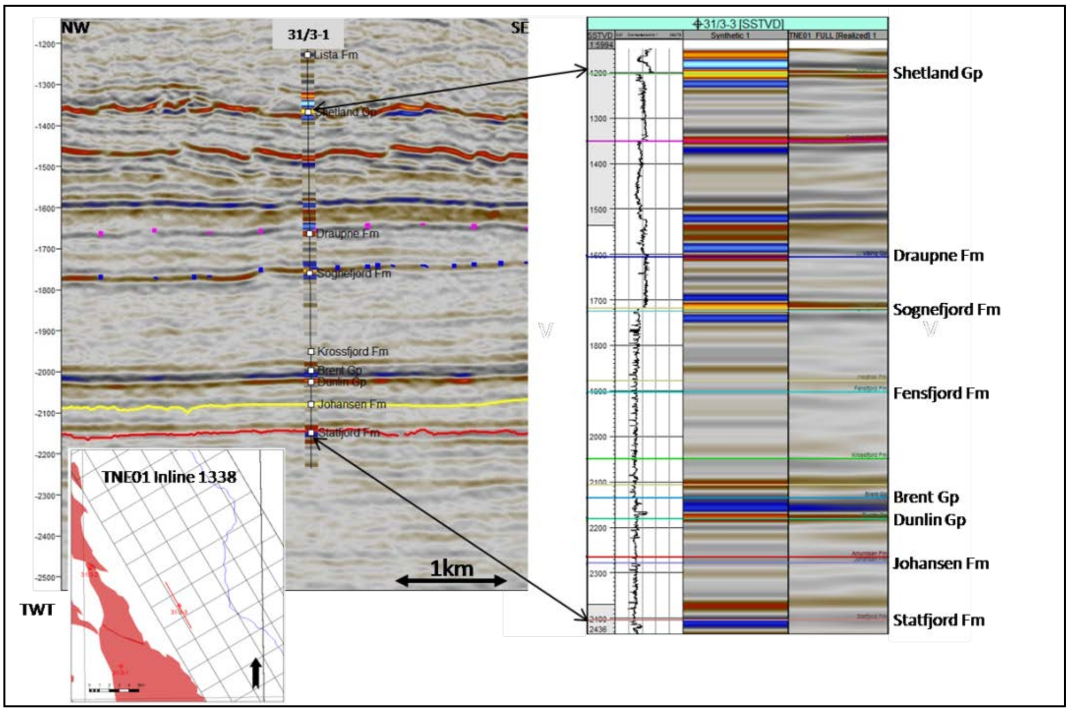

Figure 4-2 Well to seismic calibration between well 31/3-1 and seismic line TNE01 inline 1338.

A simple well calibration between well 31/3-1 and the TNE01 3D survey (inline 338) using a Ricker wavelet was performed. The sonic log was calibrated using check shot data from well 31/3-1. The seismic calibration shows acceptable correlation between the seismic data and the synthetics (Figure 4-2). A small shift of -5ms is observed in the TNE01 3D survey.

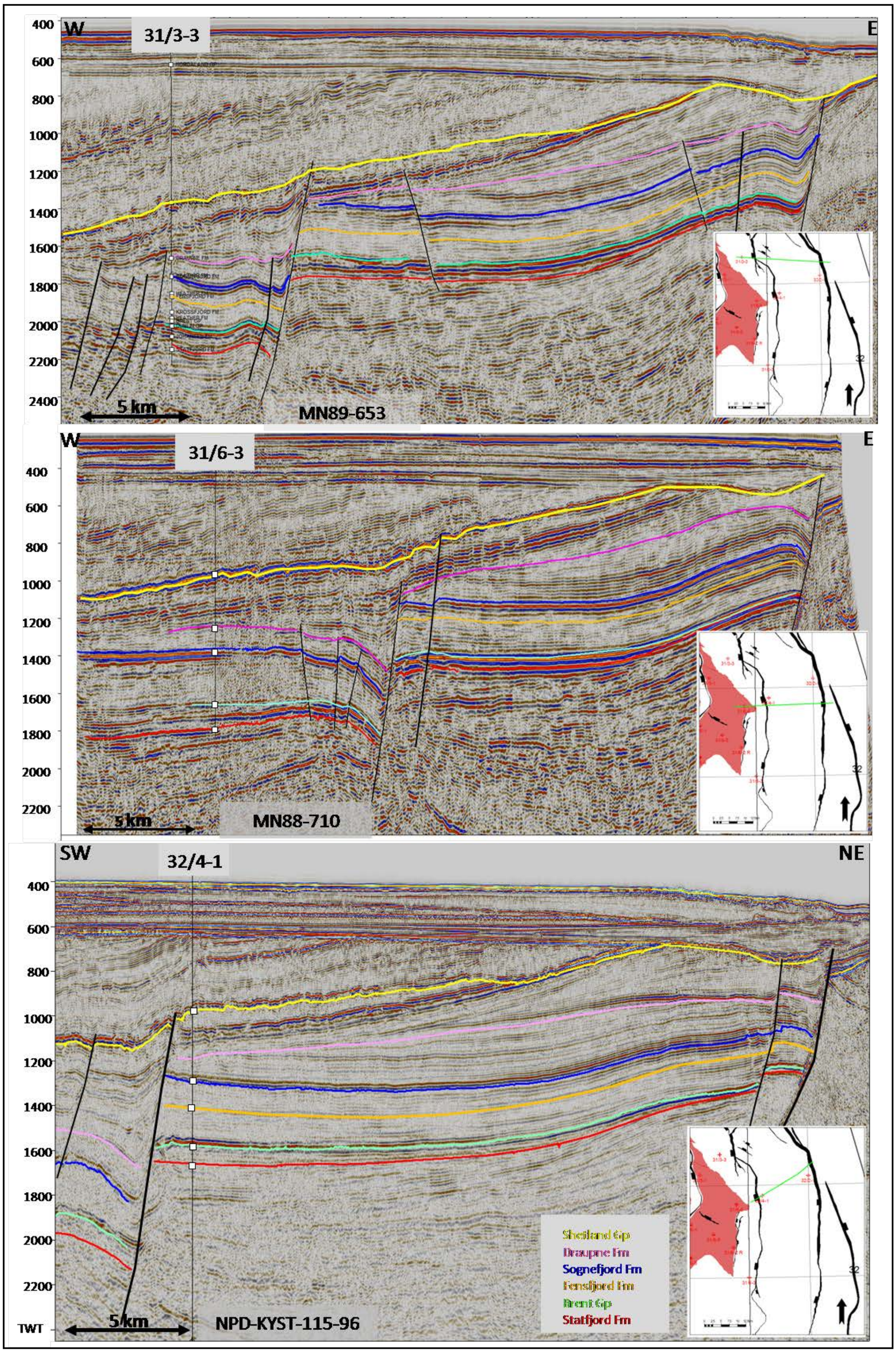

Figure 4-3 Seismic well ties.

4.2.2 Seismic Horizon Interpretation

To obtain a consistent interpretation of the Troll Kystnær storage formation, seal units and faults, the following horizons were interpreted. Interpretations were done in both phases of the assessment of Troll Kystnær, but in some cases different reflectors than the ones interpreted in the 2009-2010 study were used in the Q1 2012 assessment. The reason is explained in the horizon description below:

Horizon	Interpreted 2009	2012
Seabed	X	X
Base Quaternary		X
Top Shetland Group	X	X
Top Draupne Formation	X	X
Top Sognefjord Formation	X	X
Top Heather Formation 2		X
Top Fensfjord Formation	X	X
Top Krossfjord Formation		X
Top Dunlin Group		X
Top Brent Group	X	
Top Johansen Formation	X	
Top Statfjord Formation	X	

A time shift of -20ms was applied to the TNE013D survey to obtain interpretation consistency with the 2D data. Time, depth and thickness maps from the first assessment phase are enclosed in the appendices.

Top Shetland Group
The Shetland Group is a low velocity, low density layer. Based on reflector continuity a peak was chosen for the interpretation. This Upper Cretaceous group consists mainly of the chalk facies of chalky limestones, marls, and calcareous shales and mudstones. It is considered part of the secondary seal.

Top Draupne Formation
The Draupne Formation is an anomalously low velocity formation, low density and high resistivity layer and subsequently the Top Draupne Formation reflector should be interpreted on a trough. The top Draupne reflector is strong and easily recognized. However, the trough is sometimes very wide and therefore the interpretation of top Draupne was performed on the zero crossing at top of the trough in the 2009-2010 -interpretation, while it was performed on the peak below for the Q1 2012-interpretation. The Draupne Formation consists primarily of impermeable claystones and is considered the primary seal.

Top Sognefjord Formation
The Sognefjord Formation is a continuous and well-defined low velocity sand and is defined as a trough (decrease in acoustic impedance at the boundary with higher velocity Draupne claystones). The 2009-2010- interpretation was performed on the zero crossing since the trough was weak in some areas. The Q1 2012-interpretations were conducted on the peak below. The Sognefjord Formation comprises medium to coarse grained, well sorted and friable to unconsolidated sandstone and is considered as the upper part of the primary storage formation. The southernmost limit of the Sognefjord Formation has been identified as a pinch out.

Top Heather Formation 2
The Heather Formation consists mainly of grey silty claystone with thin streaks of limestone. From well-tie it was decided to perform interpretation on the trough.

Top Fensfjord Formation
The Fensfjord Formation is defined by a decrease in acoustic impedance (higher velocity Heather Formation) and interpreted as a trough. It was very difficult to follow this reflector. The formation consists of well sorted, fine to medium grained sandstones. Calcite cemented sandstones occur in bands and minor shale intercalations occur throughout the formation. In general, the formation has higher gamma ray intensity than the underlying Krossfjord Formation. It has been clearly identified in the Troll Field area.

Top Krossfjord Formation
The base of the formation is shown by the underlying reduction in gamma-ray intensity. The top is characterized by a change in the serrate gamma ray log motif of the overlying Fensfjord Formation, as well as an overall upward increase in gamma ray intensity. Interpretation was performed on a peak and the reflector was very difficult to follow.

Top Brent Group
The interpretation has been made on a trough due to the decrease in acoustic impedance from the higher velocity Heather Formation. The Brent Group consists of grey to brown sandstones, siltstones and shales with minor coal beds and conglomerates. It is recognizable over most of the northern part of the Horda Platform, and southwards it passes into the Vestland Group. Developed sand systems in the Brent Group could represent potential storage formations.

Top Dunlin Group
The group consists mainly of marine sediments however in marginal areas of the basin marine sandstones are well developed at several stratigraphic levels. The interpretation was performed on a trough.

Top Johansen Formation
The Johansen Formation is a low velocity, low density unit and is interpreted as a trough. It consists of sandstones which grades downwards into silty claystone. This formation could represent a potential storage formation.

Top Statfjord Formation
The Statfjord Formation is a low velocity layer, interpreted on a trough. It consists of grey, green and sometimes red shale inter-bedded with thin siltstones, sandstones and dolomitic limestones.

4.2.3 Seismic Fault Interpretation

Fault Interpretation has been conducted in both phases of the Troll Kystnær investigation. While the initial interpretation focused on the overall storage complex, the recent work did more detailed investigation regarding the Vette fault and in particular the Øygarden Fault Zone.

The focus of the fault interpretation has been the Triassic-Jurassic fault system cutting through the storage formation. The fault interpretation is the main input in the development of the structural model for the Troll Kystnær storage complex (Figure 4-4).

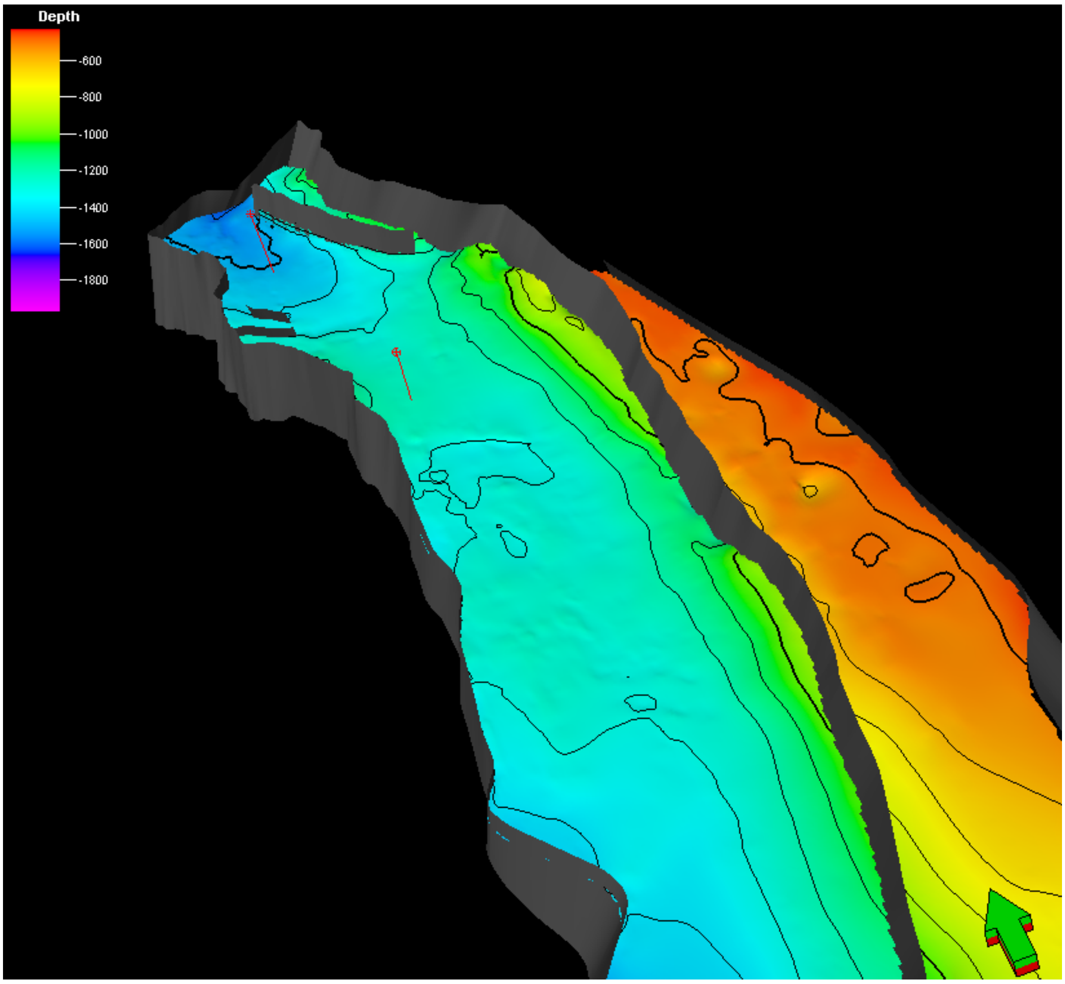

Figure 4-4 Modelled fault planes on Sognefjord Formation level based on seismic fault interpretations.

The main faults within the 3D cube (GN1101) are the Vette fault (west) and ØFC (east). The ØFC and large parts of the Vette fault are NS (NNW-SSE) trending. The throw along these faults is very large, with displacements ranging up to the order of kilometres. Faults within the storage complex are mainly NW-SE trending, but some NNW-SSE oriented faults can be observed as well. The displacement along these faults is minor and none of the faults in the area extend past the base quaternary erosional surface (Figure 4-5).

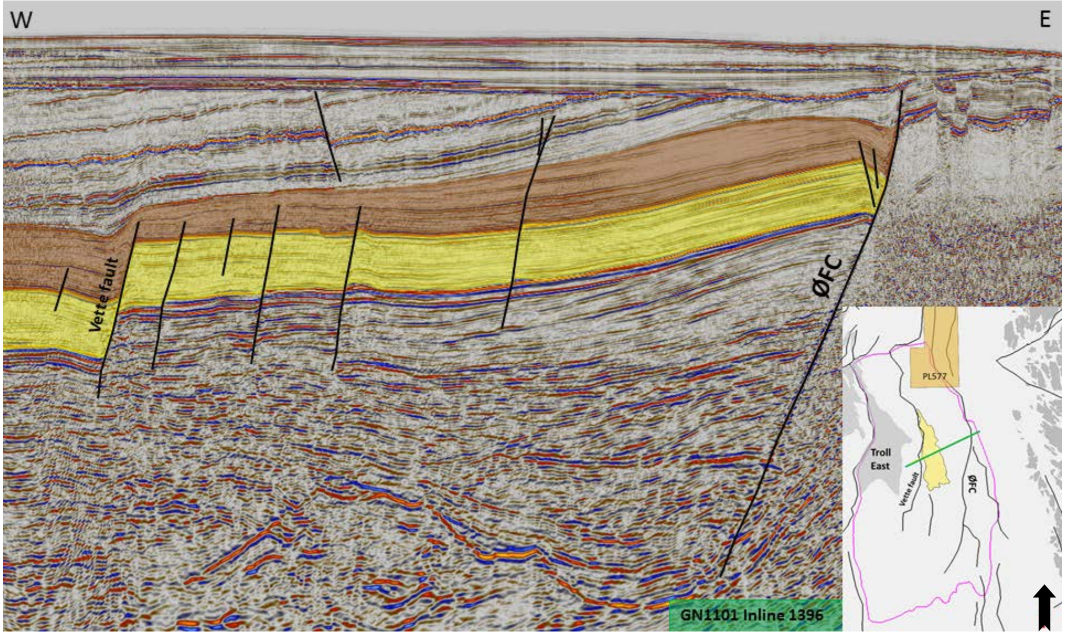

Figure 4-5 Faults within the Troll Kystnær Fault Block.

A thorough investigation of the movements along ØFC and the syn-fault sedimentation is described in section 4.4.1.

4.2.4 Depth conversion

To depth convert time horizons, a layer cake depth conversion method using the Petrel software was employed (Figure 4-6). Well data from three wells (32/2-1, 32/4-1 and 31/6-6) were used in the depth conversion. No stacking velocity data has been available and consequently the velocity model comprises velocity data from wells only.

Base		Correction		Model			
Surface	Top Shetland Gp	Well tops	SHETLAND GP (NPD Well Tops)	V=V0+K*Z	V0: Well TDR - Surface		K: Well TDR - Surface
Surface	Top Draupne Fm	Well tops	DRAUPNE FM (NPD Well Tops)	V=V0=Vint	V0: Constant	2600	
Surface	Top Sognefjord F	Well tops	SOGNEFJORD FM (NPD Well Tops)	V=V0=Vint	V0: Constant	2200	
Surface	Top Fensfjord Fm	Well tops	FENSFJORD FM (NPD Well Tops)	V=V0=Vint	V0: Constant	2900	
Surface	Top Brent Gp	Well tops	BRENT GP (NPD Well Tops)	V=V0=Vint	V0: Constant	3000	

Figure 4-6 Velocity model used for depth conversion of the Troll Kystnær time interpretation

The first layer in the velocity model was chosen from sea level to the Top Shetland Group. This interval is relative constant, and no large velocity anomalies are expected within this interval. A potential westward velocity increase caused by increasing Tertiary thickness is probably accounted for by the Middle Tertiary large eastward burial, uplifted and eroded in late Tertiary time.

The second and third velocity layers are the Shetland Group and Draupne Formation. The units were chosen as separate interval velocity layers due to both the large velocity difference between them, and the thickness increase towards the down faulted side (ØFC; Figure 4-7). The velocities used for each layer are the average velocities from the three wells.

For the Sognefjord and Fensfjord/Krossfjord/Lower Heather formations depth dependent interval velocities were constructed. The following formula was applied for both formations:

$V_{int} = 2*TWT - 800$

For the Sognefjord Formation the TWT is the two-way-time to the Top Fensfjord Formation and for the Fensfjord /Krossfjord/Lower Heather formations the TWT is the two-way-time to the Top Brent Group. The different horizons were automatically corrected in Petrel against at the three wells used.

The effect of depth conversion in relation to the CO_2 migration will be investigated further. Studies have shown (ref.. Zweigel & Hamborg, 2002) that very small differences in regional dip have strong effects on CO_2 migration.

4.3 Geological Development of Storage Formation

The Troll Kystnær storage formation (Figure 4-7 and Figure 4-8) has reservoirs formed during Callovian to Volgian, they are shallow-marine to shelf sandstones (Figure 4-9), each unit being in the form of a forestepping-to-backstepping, rift-marginal wedge. The formations belong to the Viking Group (ref. Vollset and Dore, 1984), which is typically represented by shales and claystones with locally developed sandstones.

The late Jurassic (Oxfordian-Kimmeridgian/Volgian) Sognefjord Formation (Figure 4-9) defines the upper part of the storage formation. The formation was deposited in a coastal-shelf to shallow-marine environment and forms a stacked series of sandstone and siltstone units which wedges out westward in to Heather Formation shelf mudstones (ref. Dreyer et al., 2005). In this evaluation the upper part of the storage formation also includes the Middle Heather Formation which represents finer grained silt/sand deposits compared to the Sognefjord Formation.

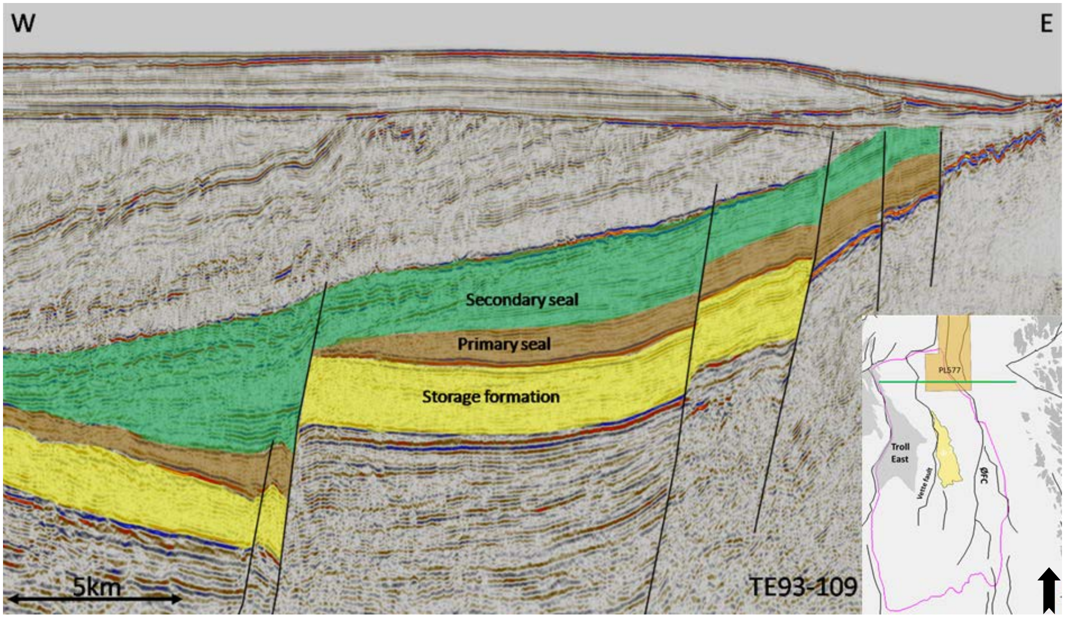

Figure 4-7 East-west trending seismic line showing the geological setting over the Troll Kystnær storage site.

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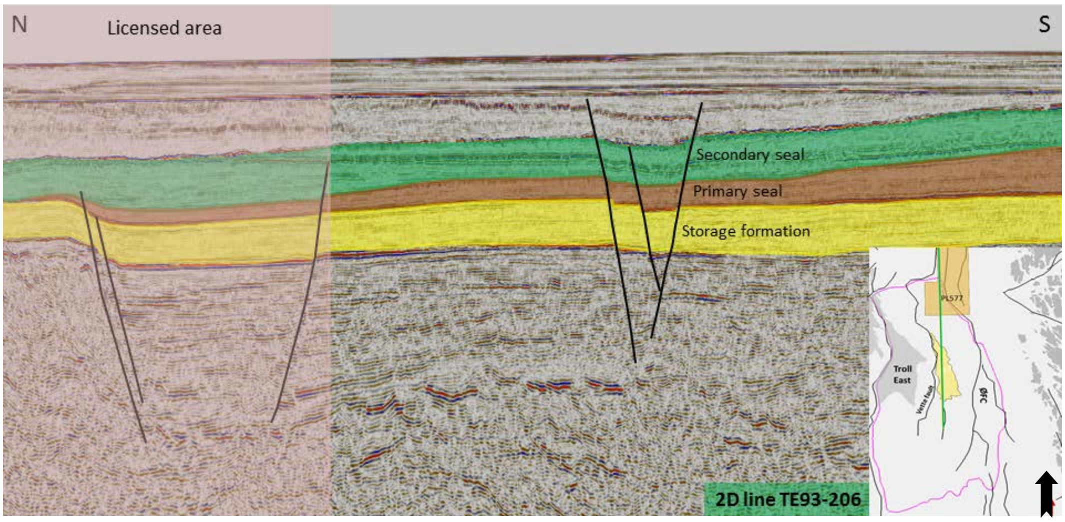

Figure 4-8 North-south trending seismic line showing the geological setting over the Troll Kystnær storage site.

The late Bathonian to Callovian Fensfjord Formation (Figure 4-9) represents extensive westward progradational shoreline sand deposits which interfingers basinward with shelf mudstones of the Heather formation (ref. Steward et al., 1995). The Fensfjord Formation lies on top of the Bathonian aged Krossfjord Formation which consists of sandstone with occasional calcite cemented streaks (ref. Vollset & Dore, 1984). Being the first continuous sandstone unit above the Brent Group the Krossfjord Formation represent the lowest part of the Troll Kystnær storage formation.

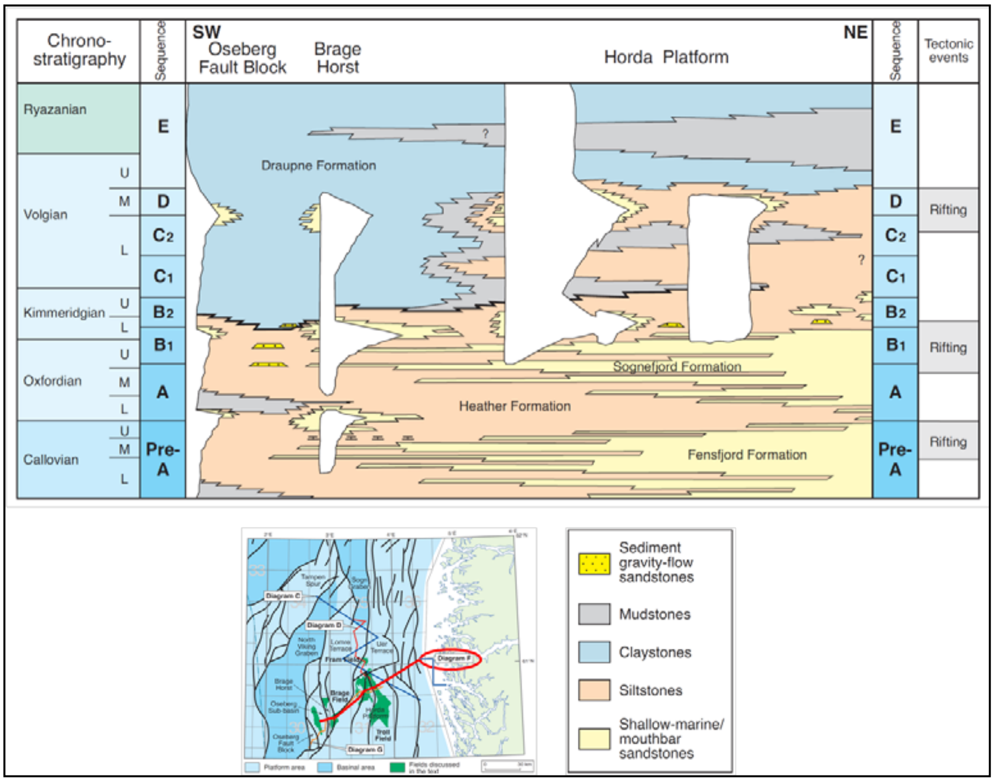

Figure 4-9 Chart showing chronostratigraphic and lithostratigraphic relationships from the Oseberg Field towards the Norwegian coast (modified from ref. Fraser et al. (2002)).

4.3.1 Storage Formation Presence

The presence of the storage formation has been confirmed by a number of wells in the evaluation area. Generalised depositional maps of Sognefjord and Fensfjod/Krossfjord formations can be seen in Figure 4-10. These are based on well observations and seismic interpretations.

The 32/4-1 and 32/2-1 wells penetrate the Troll Kystnær fault block which constitutes the Troll Kystnær storage complex (Figure 4-11). Well 32/4-1 penetrated approximately 70m of Sognefjord Formation, 230m of Fensfjord Formation sand deposits with minor beds of clay-, silt and limestones and 45m of Krossfjord Formation. In well 32/2-1 approximately 100m of both Sognefjord (114m) and Fensfjord (103m) formations were penetrated and 70m of Krossfjord Formation. The deposits consist of interbedded sand- and claystones and appear to represent the same facies as the offset wells to the west.

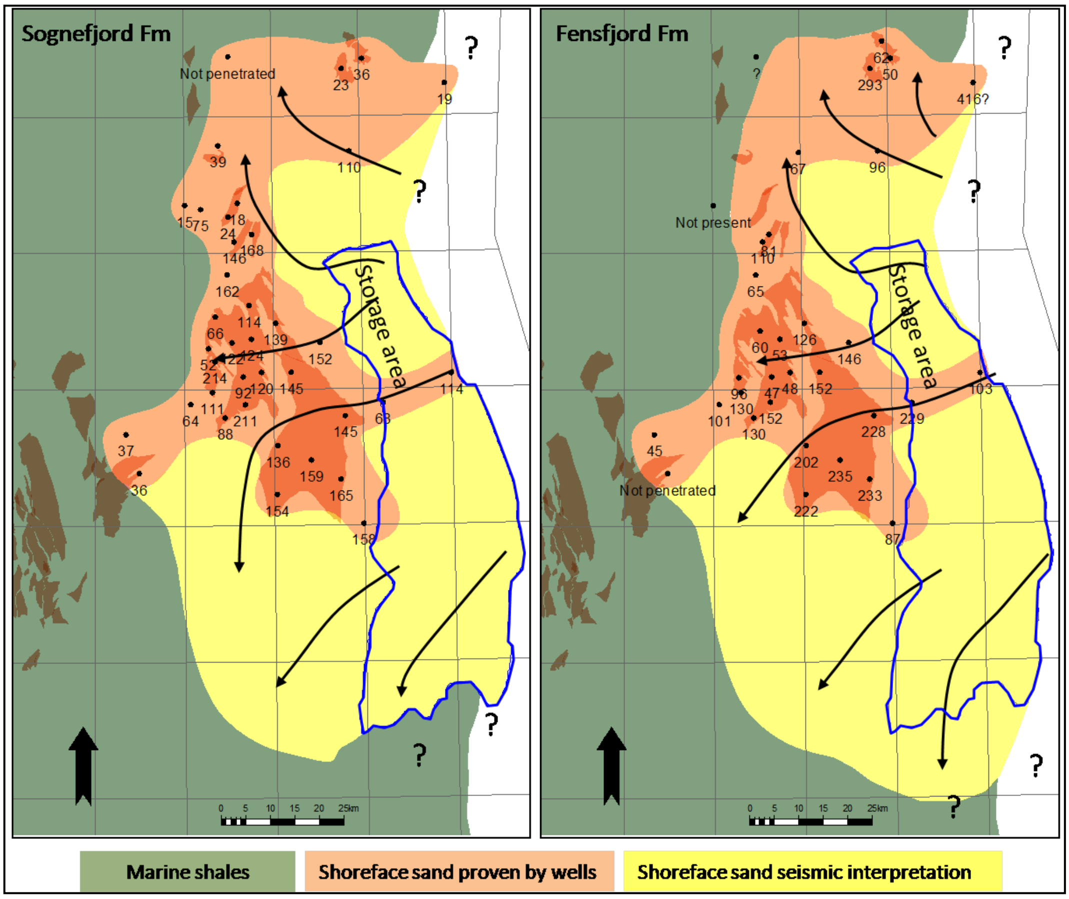

Figure 4-10 Generalised distribution of the Sognefjord and Fensfjord formations. Formation thicknesses (m) are shown at well locations. The blue polygon represents Troll Kystnær base case geo-model. Breiflabb well 31/8-1 not included in map.

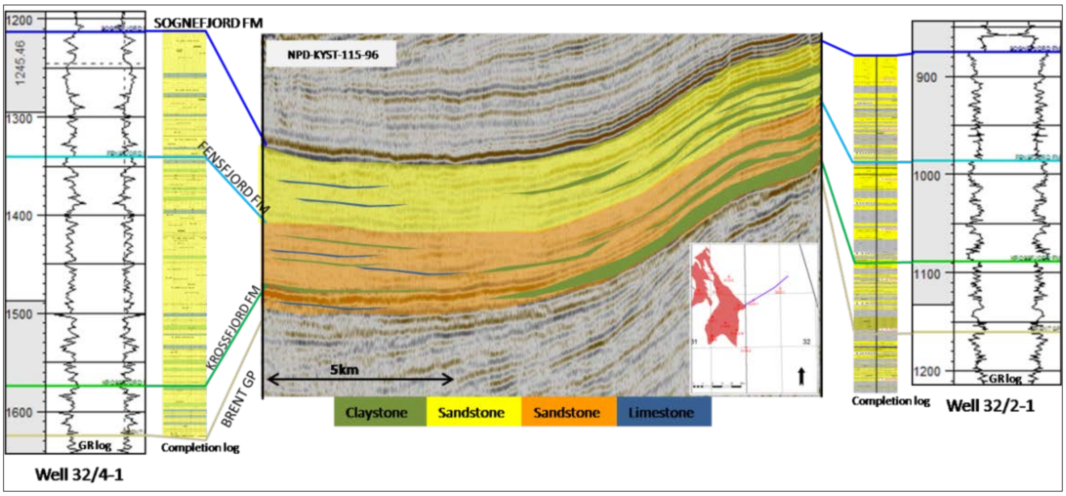

Figure 4-11 Composite figure showing Troll Kystnær storage formation from well 32/4-1 to well 32/2-1.

The storage formation is interpreted to be present throughout the Troll Kystnær fault block, based on observed seismic characters of the top and base of the storage formation (Figure 4-7 and Figure 4-8) and the uniform thickness of the deposits on the fault block (Figure 4-11). The total storage formation thicknesses reach up to 700m in the mapped area and between 310m to 450m in the modelled CO_2 plume area.

The storage formation sand system is assumed to pinch out southwards, where a pronounced change in the storage formation thickness is seen on seismic data (Figure 4-12) and displayed on the associated thickness map (Figure 4-13).

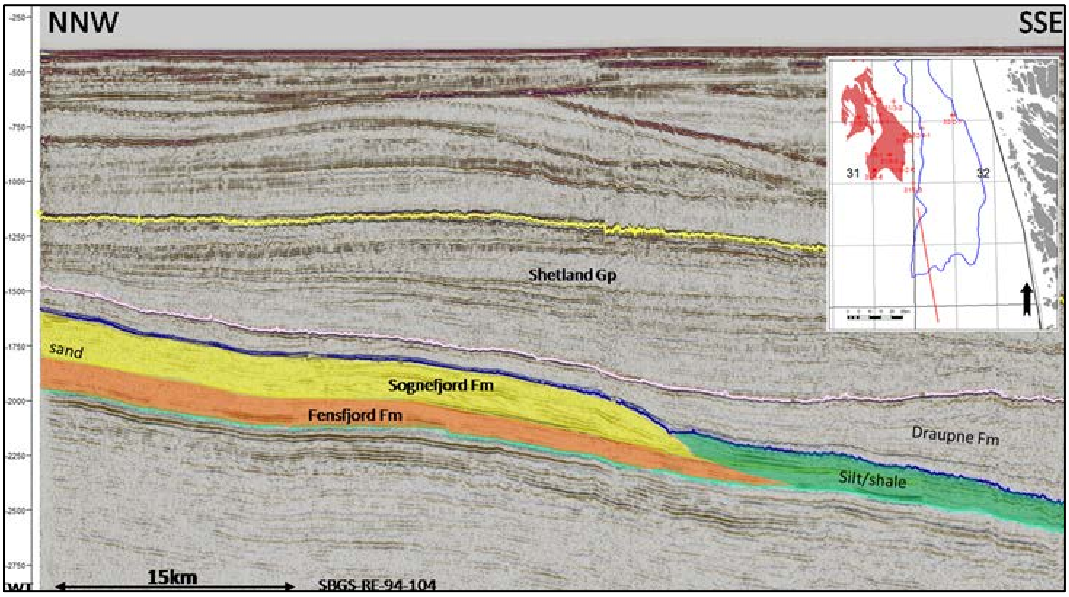

Figure 4-12 Seismic line showing the southward pinch out of the storage formation sand system.

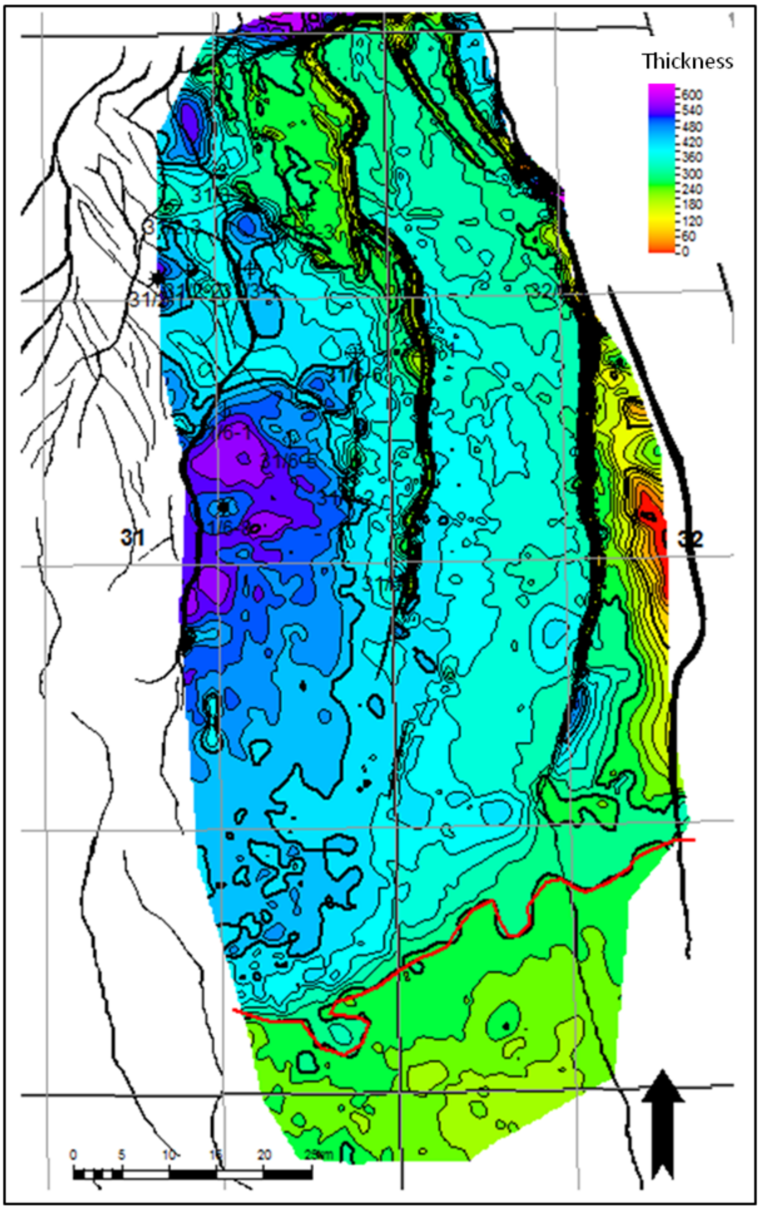

Figure 4-13 Storage formation thickness map (in metres) expresses the southward pinch out of the sand system.

The seismic mapping over the Troll Kystnær and Troll East area indicates extensive pore volume connectivity at storage formation level from the Troll Kystnær fault block southwards and up northwards to the Troll East fault block (Figure 4-14). This interpretation is further supported by well data and by analysis of the Troll field pressure depletion and its influence on adjacent regions. This is documented by Statoil (Wijngaarden, Tjøstheim, Torp, Førde) and suggests that the pressure is already depleted by 20-40 bars in the Troll Kystnær region (Sognefjord) due to Troll production, and that the pressure will continue to decline over the next few decades. Any such depletion is positive with respect to CO_2 storage potential. The risk of leakage through faults is reduced, as well as the risk of cap rock fracking due to excessive pressure build up.

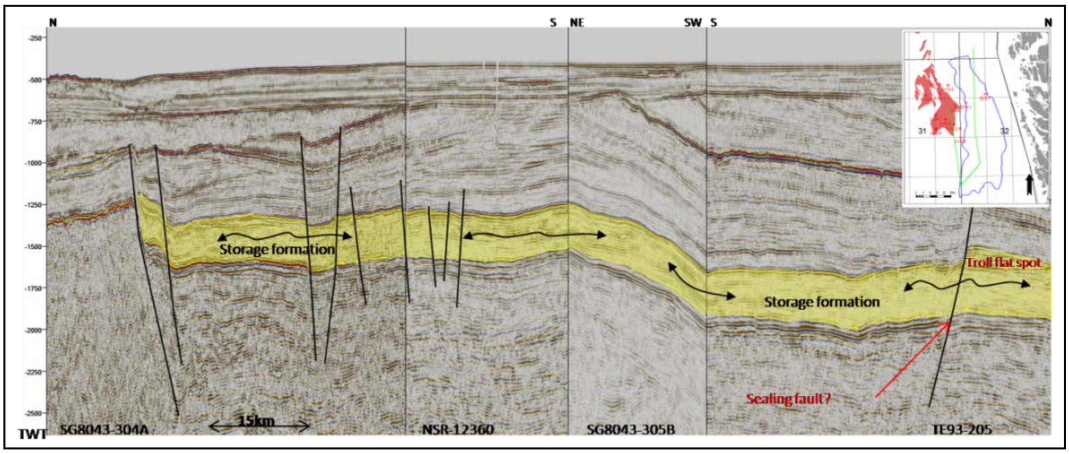

Figure 4-14 Seismic composite line from the Troll Kystnær storage site south-, southwest- and northwards to the Troll Field. The arrows indicate the possible connecting pore volumes.

4.3.2 Storage Formation Quality

Petrophysical data from key wells (Table 4-1) indicate good to excellent reservoir properties for the storage formation. Well information from Troll West Gas Province indicates Sognefjord Formation sand deposits in the range of 3-45m thick units with porosities between 28-32 % and permeabilities in the range of 1-20 D (ref. Dreyer et al., 2005). There are no core data or offset wells available to produce trustworthy porosity-permeability relationships for well 32/2-1. Porosity data from well 32/2-1 (Table 4-1) and observed thinning (Figure 4-15) towards the eastern margin of the Troll Kystnær block fault block, indicates slightly less developed reservoir properties eastward on the fault block.

New petrophysical evaluations (Chapther 3.3) give slightly lower average porosities when including VCl, with Sognefjord Formation porosities between 22-30 % and Fensfjord Formation porosities between 21-25 %. A new property model was not constructed to reflect these values due to time constraints and limited impact of the new values. The reservoir models (Chapter 4.8) were built in the 2009-2010 study and the average porosities are based on the key well properties presented in Table 4-1.

Table 4-1 Average storage formation (reservoir) properties from Troll Kystnær key wells

Well	Sognefjord Formation				Fensfjord Formation			
	Average porosity (%)	Average permeability (mD)	Thickness (m)	N/G	Average porosity (%)	Average permeability (mD)	Thickness (m)	N/G
32/2-1	25	-	110	0,58	25	-	103	0,61
32/4-1	32	200-1000	70	0,95	25	-	230	0,81
31/6-6	27	1000-2000	150	0,97	25	3000	228	0,95
31/3-3	25	>1000	150	0,91	20	-	150	0,97

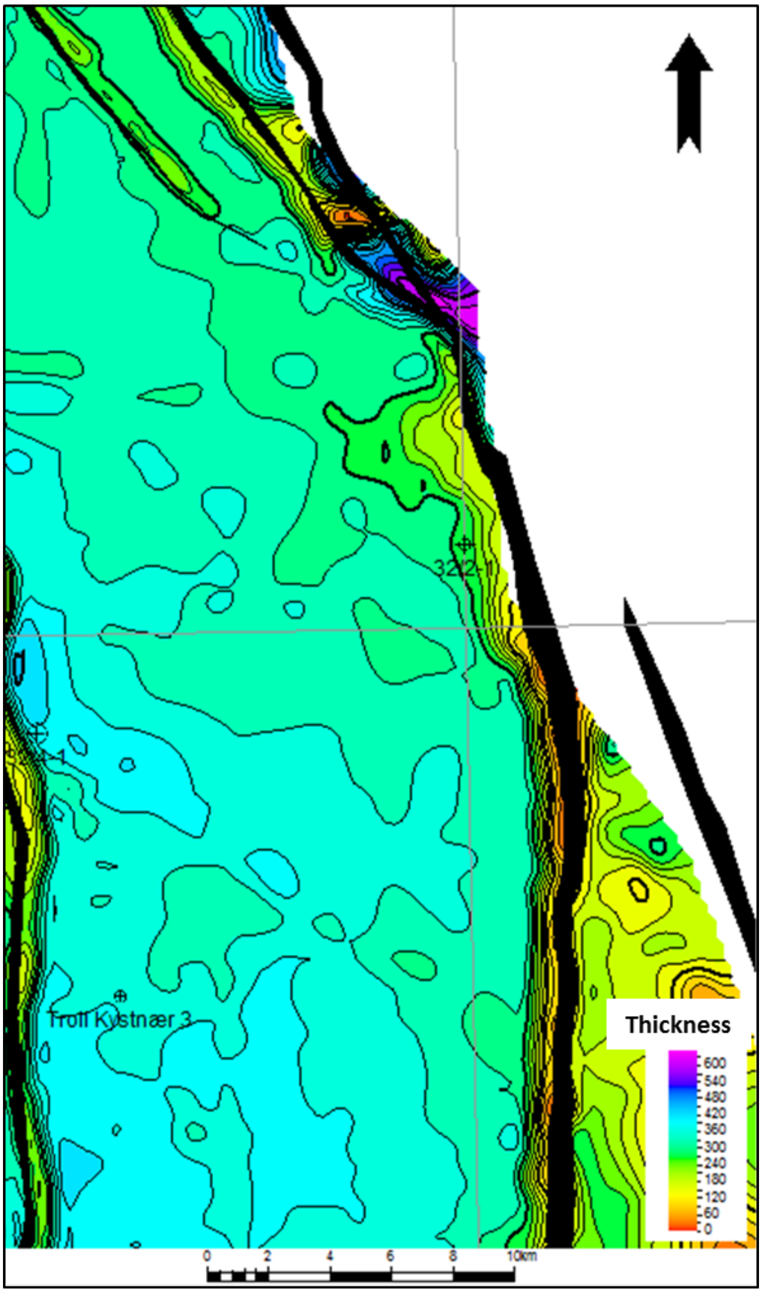

Figure 4-15 Storage formation thickness map showing thinning of the formation from West to East on Troll Kystnær fault block.

4.4 Structural Framework

The Troll Kystnær storage site is a fault block located on the north-eastern part of the Horda Platform (Figure 4-1), east of the Viking Graben. The fault block is bounded by major faults to the west, north and east (Figure 4-16). To the north and west the storage formation constitutes the foot wall of the Vette fault, while to the east the storage location is downthrown (hanging wall) from the Øygarden Fault Complex (ØFC). The sealing capacity of the ØFC has been of particular interest in the Q1 2012 evaluation.

The ØFC defines the border between the Norwegian mainland to the east and the Horda Platform to the west. The ØFC and Vetta Fault are two out of several major faults between the coast of Norway and the North Viking Graben. The faults are still registered with minor tectonic and seismological observations (ref. Smethurst, 2000).

Seismic observations indicate that the ØFC is composed by several minor faults growing together. From north to south the ØFC is widening, seen as a horst structure. The fault frequency connected to the ØFC seems to be lower in the south compared to the northern areas (See Figure 4-16), implying that the degree of deformation along the Fault Complex diminish southward.

Triassic inception of the Viking Graben rifting imposed a structural grain of easterly dipping fault blocks over the Troll Field area. Progressive northward dextral offset of the graben axis produced a series of NE-SW faults during the Middle to Upper Jurassic (ref. Gray, 1987). The development of these structural elements was completed in Paleocene time (Figure 4-17) with N-S to NNE-SSW fault orientations as the dominant trend. A set of faults oriented NW-SE can also be observed (see Figure 4-5).

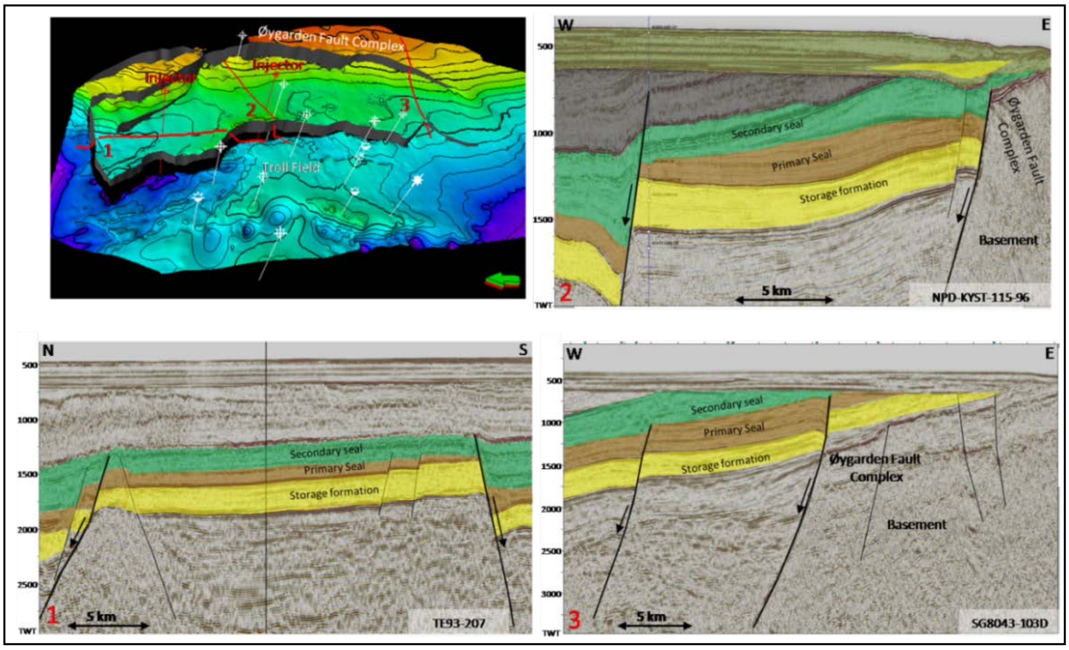

Figure 4-16 Structural setting of the Troll Kystnær storage site, where the location of each seismic profile is posted on the Top Sognefjord Fm depth map in the upper left corner.

4.4.1 Stratigraphic/structural reconstruction along the Øygarden Fault Complex (Q1 2012)

In order to examine the stratigraphic and structural development along the ØFC within the GN1101 3D cube, a reconstruction of sedimentation and movement along the fault was conducted using the interpreted seismic data sets and existing literature regarding basin development in the North Sea region (e.g. refs. Jones & Underhill, 2011, Goldsmith, 2000, Ravnås et al., 2000 and Badley et al., 1988).

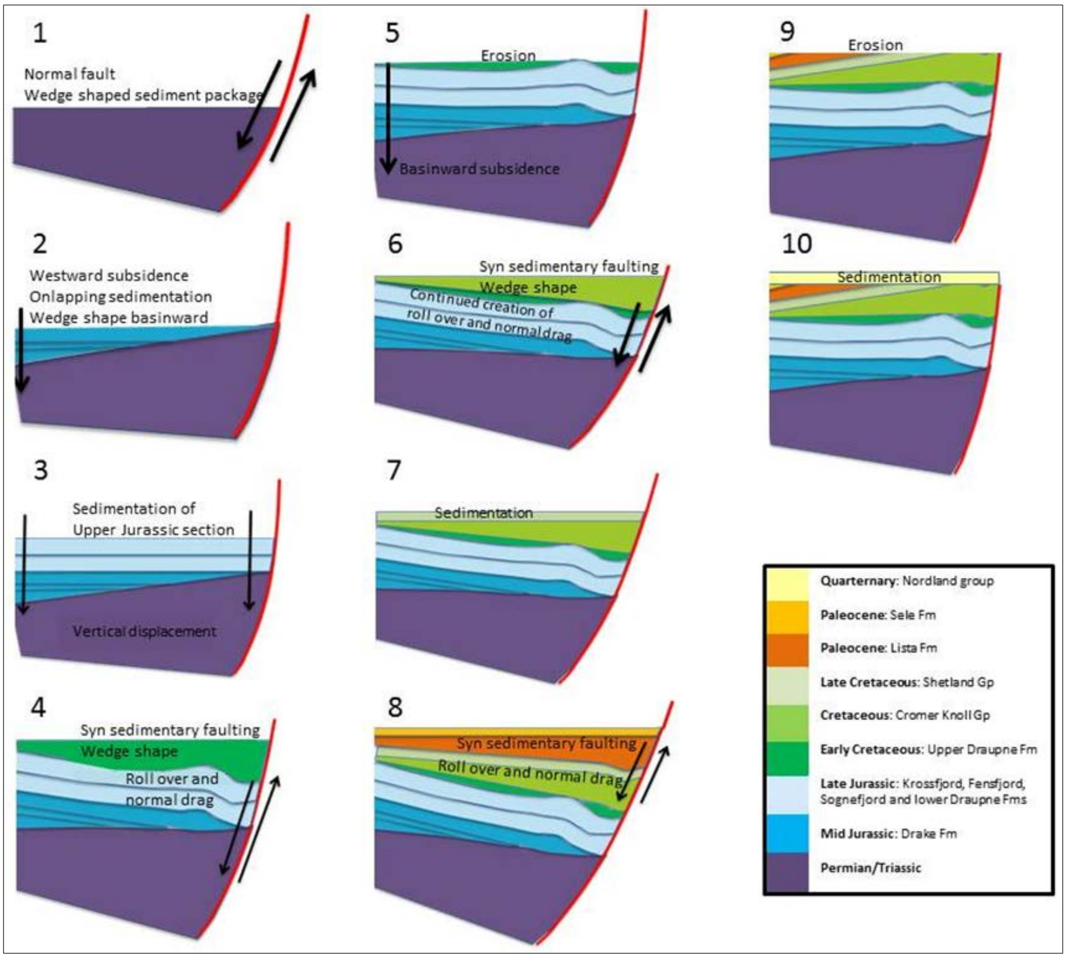

Figure 4-17 Stratigraphic/structural reconstruction Troll Kystnær. Arrows indicate relative movement along the fault or basinward.

The paloe-reconstrution was conducted by flattening one by one of the interpreted horizons, starting with the oldest and consecutively towards the youngest. The different steps are shown in Figure 4-17 and described below:

1) Flattened on Cook Formation:
Permian- Triassic-Early Jurassic: North Sea rifting episode due to crustal extension. Syn-rift sedimentation causing wedge shaped sediment package towards the ØFC.

2) Flattened on top Drake Formation:
Early - Mid Jurassic: Basinward subsidence. Onlapping sedimentation of the Drake Formation.

3) Flattened on Sognefjord Formation:
Mid Jurassic: Major faulting in West accommodated by major faulting along ØFC, generating accumulation space for Fensfjord and Krossfjord formations.

Late Jurassic: Complex faulting at edges of blocks, but low disturbance in eastern parts, vertical displacement of Hordaplatform creating accumulation space for Sognefjord and Lower Draupne formations.

4) Flattened on Upper Draupne Formation:
Early Cretaceous: Extension and normal faulting, Upper Draupne Formation deposited.

5) Flattened on Upper Draupne Formation:
Early Cretaceous: Relative basinward tilting. Erosion of Upper Draupne Formation.

6) Flattened on Cromer Knoll Group:
Cretaceous: Extension and normal faulting, Cromer Knoll Group deposited.

7) Flattened on Shetland Group:
Late Cretaceous: Subsidence, creation of accumulation space for sedimentation of Shetland Group.

8) Flattened on top Sele Formation:
Paleocene: North-sea forming, seafloor spreading. Normal faulting along Øygarden fault, Lista Formation and possibly syn-fault sedimentation of Sele Formation.

9) Flattened on erosional surface/base of Nordland Group:
Miocene – Pliocene: North-sea tilted basinward (uplift of Norway), erosion of tilted successions.

10) Flattened on sea bed:
Quaternary: Deposition of the Nordland Group.

The paleo-reconstruction of the deposition on Troll Kystnær and the faulting along ØFC reveal that there have been several episodes of syn-sedimentary faulting between Permian/Triassic and Paleocene. Corresponding normal faulting was also observed along the Vette fault to the west of the Troll Kystnær fault block. The reconstruction also indicates that there have been no episodes of reverse faulting and no significant activity along ØFC or Vette fault in the period post-dating Paloecene.

It also appears that during deposition of the storage formation (Upper Jurassic sequence), the Horda Platform has been tectonically stable. This is observed through the lack of thickening towards faults within the area (also confirmed by ref. Dreyer et al., 2005).

4.5 Geological Development of cap rock

The upper Jurassic/lower Cretaceous Draupne Formation is defined as the primary cap rock to the Troll Kystnær storage complex (Figure 4-18). The formation consists of marine, organic rich claystones. The sealing capacity of the Draupne Formation is verified by the Troll Field wells.

Cretaceous limestone and shales belonging to the Shetland and Cromer Knoll groups represent secondary seal units for the storage complex (Figure 4-18). Tertiary and Quaternary deposits are also assumed to have sealing capacity. The total seal present is approximately between 750m and 1200m over the modelled CO_2 plume areas (Figure 4-19).

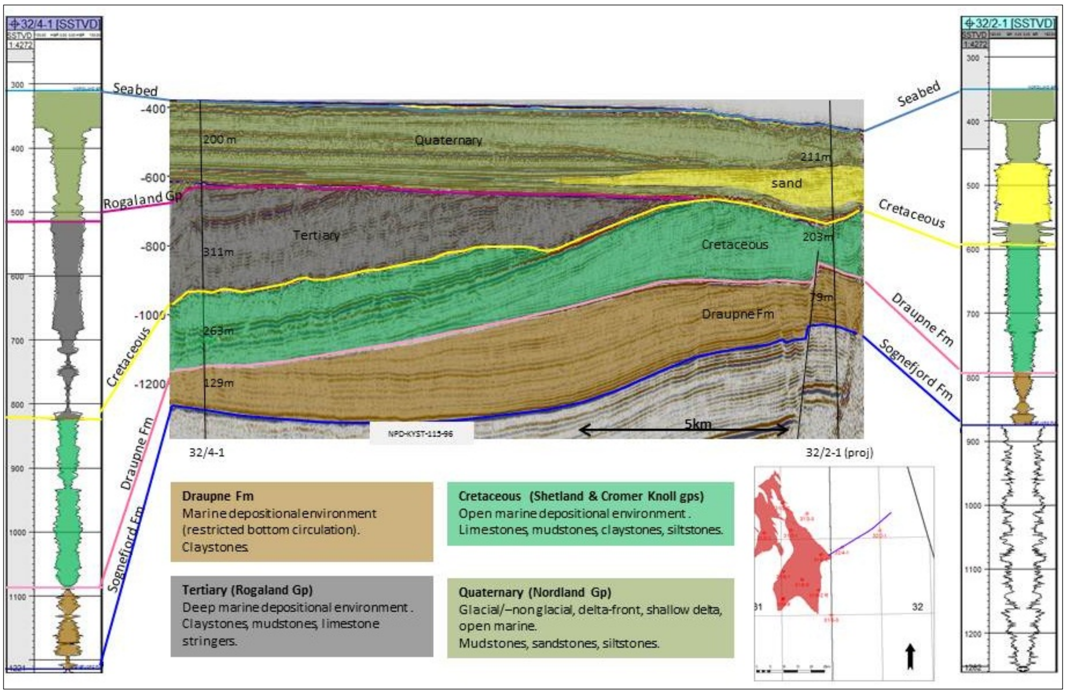

Figure 4-18 Storage complex main seal units identified by well correlation and seismic interpretation.

4.5.1 Primary Cap rock

The presence of the primary cap rock is confirmed by well 32/4-1 and 32/2-1 penetrating the Troll Kystnær fault block. In well 32/4-1 129m of Draupne Formation was encountered as an organic rich black claystone. Well 32/2-1 encountered 79m of the Draupne Formation in the form of grey claystone (Figure 4-18). This was interpreted not to be a typical hot shale, neither in gamma readings, nor claystone colour and organic content. This indicates a change in the depositional environment from east to west for the Draupne Formation on the Troll Kystnær fault block.

The Draupne Formation is assumed to be present over the entire fault block. This is supported by seismic interpretation where the seismic facies (transparent reflectivity) indicates massive shale deposits (Figure 4-20). Thinning of the primary seal is observed both eastward and westward (Figure 4-19 and Figure 4-20) on the fault block and the seal thickness varies from approximately 70m up to 300m in the modelled CO_2 plume area. The westward thinning is probably erosional (Figure 4-20). The thickness of the Draupne Formation increases toward the faults on the down thrown blocks signifying periods of faulting during the deposition of the Draupne Formation (section 4.4.1).

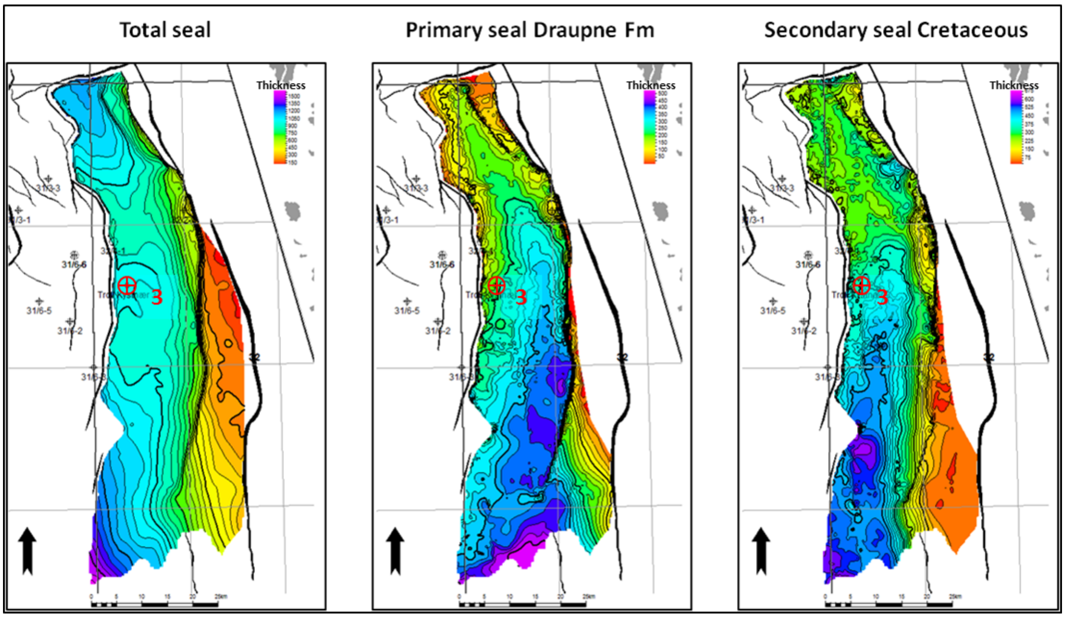

Figure 4-19 Main seal unit thickness (m) maps for the Troll Kystnær Storage Complex.

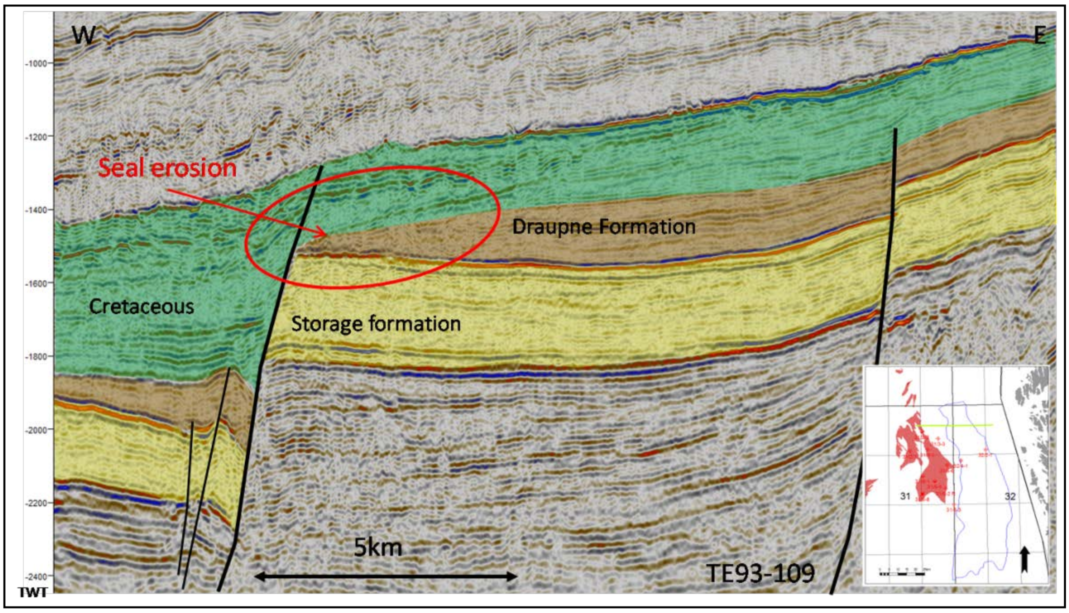

Figure 4-20 East-west trending seismic line showing erosion of the Draupne Formation claystones towards the Vette fault.

4.5.2 Secondary Seal – The Overburden

Well 32/4-1 and well 32/2-1 penetrated over 200m of Cretaceous mudstones and limestones representing the Shetland and Cromer Knoll groups (Figure 4-18). The thickness map (Figure 4-19) shows that the secondary seal unit varies between approximately 250m and 450m in the modelled CO_2 plume area.

4.5.3 Cap rock sealing potential

There are four main leakage mechanisms though a cap-rock. Each of these are described below in relation to Draupne in the storage Complex area.

Leakage through porous layers: sand bodies within the cap rock may function as conduits for fluid flow. Such sand bodies may exist as a singular or multiple point deposit. They may be deposited as submarine fans or channels transported in turbidites or other mass movement processes (Boggs Jr, 1995). In some cases they can be subjected to subaerial processes where the clay or shale deposit is followed by tectonic uplift with subsequent erosion and sand deposition from rivers or deltas. Sand intervals in shales are very common, and may be a significant risk in cap rocks (Daniel and Kaldi, 2008). Due to the possible sub-seismic nature of such deposits they may be very difficult to track on seismic data.
A well evaluation was performed by analysing reports and interpretations from the wells drilled in the Troll field, Breiflabb area and Troll Kystnær fault block. A petrophysical evaluation was performed with respect to cap rock properties and cap rock potential (Chapter 3.3.9). A general description of the Draupne Formation is given in Chapter 4.5.1. From the evaluation the Draupne Formation do not reveal any sand or porous layers of significance in relevance to leakage. This could be further studied using seismic attribute analysis. It should, however, be kept in mind that the sand bodies will have to be interconnected through Draupne in order to form a complete leakage path. The probability of this existing seems low keeping in mind the extensive thickness of the Draupne formation.

Juxtaposed porous layers: Normal faults can cause a juxtaposition situation (Yielding et al., 2011) where porous zones are aligned allowing cross-fault communication (Yielding et al., 2011) (Friedmann and Nummedal, 2003). Porous zones in faulted areas may be subject to effective leaking through a network of faults adding significant risk in CO_2 storage purposes. This can be further evaluated once porous layers have been mapped, and a more detailed fault study has been done. However, the low fault density and lack of evidence of porous layers as indicated above, gives a low probability of this being an issue.

Weak palaeo-leakage paths and leakage through dissolution of calcite cemented fractures or faults should also be investigated further using seismic attribute analysis.

Other mechanisms include leakage through capillary migration and diffusion. The permeability of deeply buried shale is a function of depth, temperature and pressure. Rocks with normal pressure are considered to be ductile due to the progressive burial (Hager and Handin, 1957). Migration though such shales therefore probably requires high over-pressures and hydro-fracturing to provide sufficient vertical fracture permeability (Bjørlykke et al., 1997).

In general the faults are described in Chapter 4.2.3. The majority of faults within Troll Kystnær Fault Block have throws of insignificant magnitude, only the major faults flanking the fault block have fault throws greater than the seal thickness. Since the small faults have throws less than the seal thickness they are not subject to cross-fault leakage scenarios. Small faults have been mapped where continuous and possible. Sub-seismic faults (~10m) are not considered a risk in terms of cross-fault leakage as the throws are of corresponding size. Fractures have not been mapped due to their non-continuous nature.

4.6 Injection location

Figure 4-21 shows the location of Troll Kystnær with the suggested injection location indicated in red. The areal extent of the Troll Reservoir is seen on the western part of Troll Kystnær Storage Complex. This location was selected based on a number of simulations done prior to selecting an area for 3D survey (see appendix A). A more northern location will come into conflict with PL577, and also give migration up to the Øygarden faults zone. Injection south of the chose location gives a higher possibility of migration past the Øygarden fault as the throw becomes smaller. The selected location seems to give a plume that does not migrate towards the Øygarden fault, but does expose the 32/4-1 well fairly early. A well integrity assessment has been done for the well and it does pose a leakage risk (see appendix B). As the formations are very flat in the area, the plume migration is very sensitive to uncertainties in dip. The location should be viewed as preliminary.

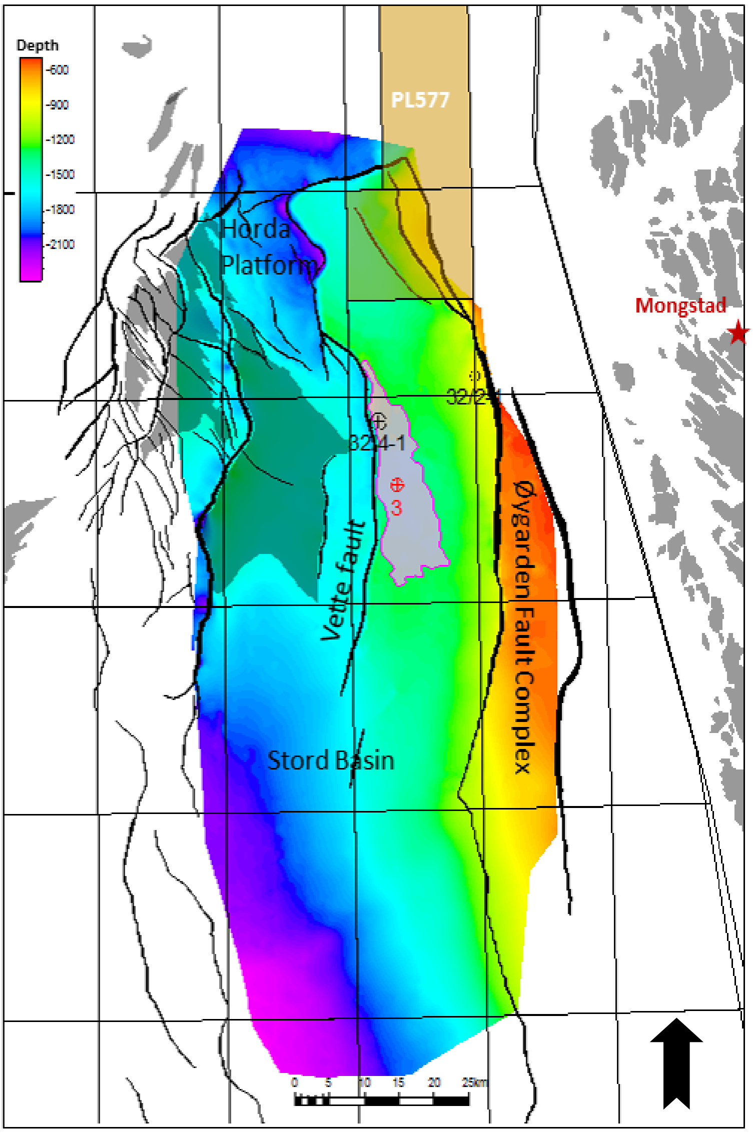

Figure 4-21 Depth map of Top Sognefjord with preliminary injection well in red. The figure shows the CO_2 plume extension after 500 years.

4.7 Safe Pressure Evaluation

A preliminary safe pressure evaluation was done as part of the initial study. This was purely based on depth of plume and overburden gradient, assuming a normally stressed environment. A more detailed study was done in 2012, based on LOT and an assessment of the stress regime in the area. This is outlined below.

4.7.1 Geomechanical Assessment of Minimum Stress and Fracture Initiation

Estimates were made to determine the allowable CO_2 pressure build-up before leakage occurs into the primary cap rock, Draupne Formation, owing to processes of pre-existing fracture propagation and/or the initiation of new tensile fractures in intact rock. Thermal stress modelling was not conducted as part of this evaluation. Conservative estimates, assuming propagation of pre-existing fractures, are based on minimum horizontal stress (Sh) models, assuming leakage will occur when the pressure build-up exceeds Sh. For intact Draupne Formation, models based on fracture initiation, incorporating both minimum stress and intrinsic tensile strength is a more realistic estimate of allowable injection pressure.

A range of minimum horizontal stress models were tested, including theoretical minimum and three models calibrated to a combination of mini-frac data and leak off tests for the 7 wells incorporated in this evaluation (Figure 3-3). Figure 4-22 summarizes the various leak-off test (LOT) data used to define the minimum horizontal stress models, together with the overburden, pore pressure and base, low and high case minimum Sh models for 32/2-1. Note that the LOT data are plotted versus TVD but have not been corrected for water depth and air gap effects. Water depth in the Troll Kystnær area is approximately 320m.

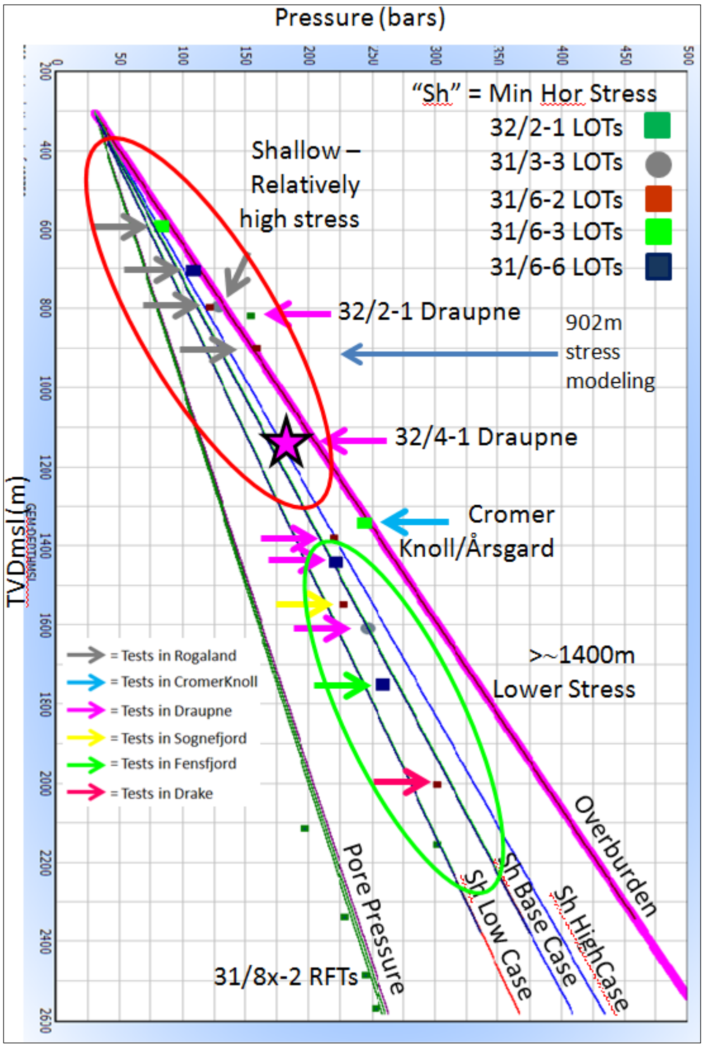

Figure 4-22 Overburden, high, base and low case minimum horizontal stress models, and pore pressure for 32/2-1, together with LOT data from the 7 wells included in this evaluation.

The base case minimum horizontal stress model honours the lower bound of the majority of LOTs and the low case minimum stress model honours a mini-frac Sh estimate from 31/6-A-21 (ref. Bretan et al, 2011). A minimum stress estimate from an injection test in the Sognefjord Formation in 31/6-2 suggests minimum stress is closer to the base case estimate (Figure 4-22, yellow arrow). The theoretical lower bound of minimum horizontal stress is not shown here, but has been used to estimate the worst case scenario for allowable pressure build up as shown in the first column of results in Table 4-2. Due to the relatively thin overburden in the shallowest parts of the storage complex, LOTs in this area may give unreliable results. It is recommended that a full suite of dedicated test is run as part of a formation evaluation programme for an appraisal well to better estimate safe pressure build-up.

Higher allowable pressure build-up was estimated using Fracture Initiation models, assuming that the formations are not fractured and have some inherent tensile strength, calibrated to Brazil test tensile strengths from Drake and Upper Amundsen formations. An average tensile strength of 4.22MPa was established for these formations.

The Base Case Minimum Stress is considered to be a reasonable estimate of allowable injection pressure (33bars) if Draupne Formation contains pre-existing fractures, which is considered to be a conservative case geologically. The case where Draupne Formation is intact allows an injection pressure of 65bars.

Table 4-2 Results of allowable CO_2 pressure build up before leakage of CO_2 into cap rock, for various minimum stress and fracture initiation models.

	Minimum allowable pressure build-up (bar) accounting for minimum horizontal stress and tensile strength					
	Minimum Horizontal Stress Models (Conservative)				**Fracture Initiation Models**	
Modeled location	Min Stress - Theoretical Minimum	Min Stress - Low	Min Stress – Base Case	Min Stress – High Case	Low Case	Base Case
32/2-1 at top Sognefjord Formation (902mTVDrkb)	**17.7**	**23.4**	**33.1**	**38.8**	**65**	**75**

4.7.2 Summary

Assuming no thermal stress effects due to the injection of cold CO_2, it is considered that the lowest likely pressures build-up before leakage into the Draupne Formation is represented by the ‘Min Stress – Base case’ (which is 33bars at a depth of 900mTVDmsl). Injection pressures of 65bars are also allowable at 900mTVDmsl if Draupne Formation is intact, before CO_2 leakage occurs.

Draupne Formation is considered to provide excellent sealing properties with respect to CO_2 injection, possessing ultra-low permeability, sufficient thickness, and consistent facies regionally, and apparently no or limited pre-existing fracturing. However, further analyses should be conducted to establish CO_2 leakage risk associated with proposed injection pressures, such as minifrac test and rock mechanics testing of Draupne cores.

4.8 Development of geological 3D model

The geo-model was constructed as part of the 2009-2010 work. There were no findings from the 2012 work requiring an update to the model. The geo-model (Figure 4-23) is the main input for the CO_2 storage formation simulation. The model was constructed from the structural model derived from the interpreted major faults and the Top Sognefjord Formation, Top Fensfjord Formation and Top Brent Group (base of the model), which defines the CO_2 storage formation.

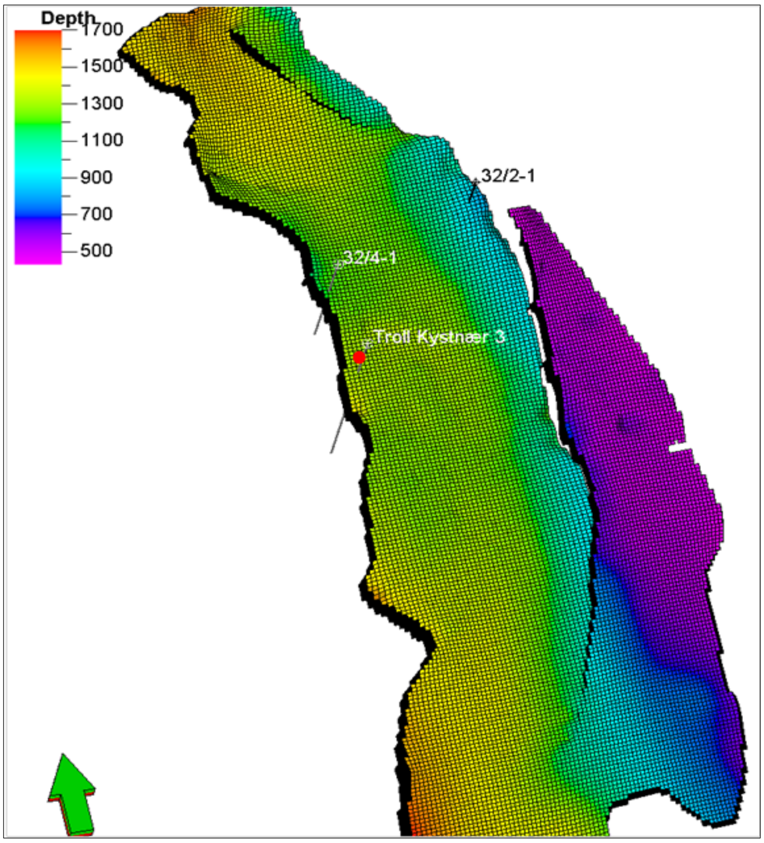

Figure 4-23 Troll Kystnær Base Case 400x400m geo-model.

The geo-model grid resolution is 400x400m grid with zigzag faults. The layering of the model is approximately 20m and the model comprises 27 layers. Porosity and permeability properties are based on the available well data given in Table 3-1.

4.8.1 Reservoir models

Four different geo-models (low-, base-, high 1- and high 2 case) were generated (Figure 4-24, Figure 4-25, Figure 4-26and Figure 4-27). The corresponding reservoir models are based on the reservoir parameters presented in Table 3-1. Reservoir simulations were performed on the low- and base case geo-models.

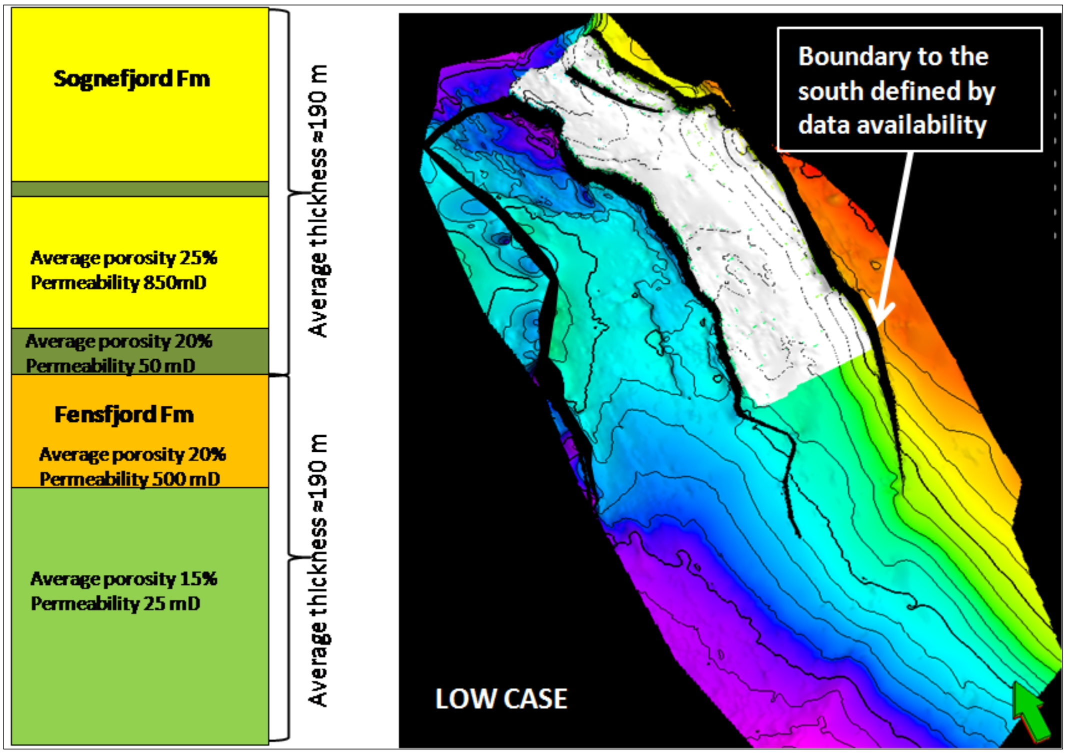

Figure 4-24 Troll Kystnær Low Case reservoir- and geo-model.

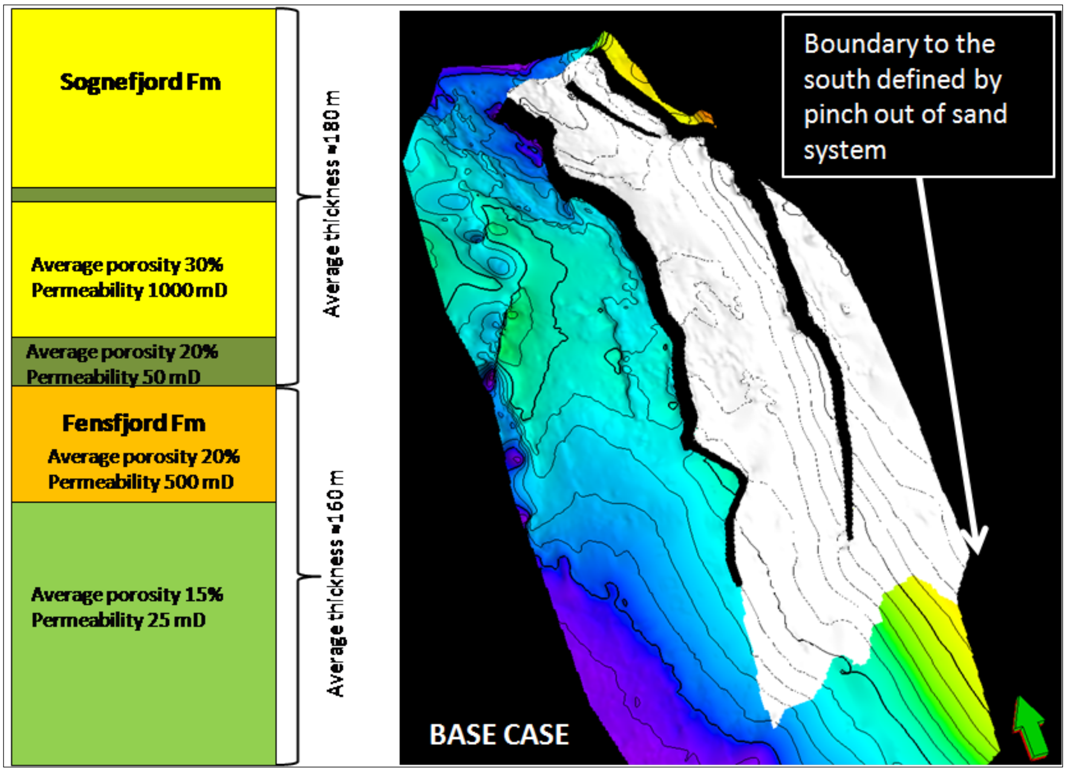

Figure 4-25 Troll Kystnær Base Case reservoir- and geo-model.

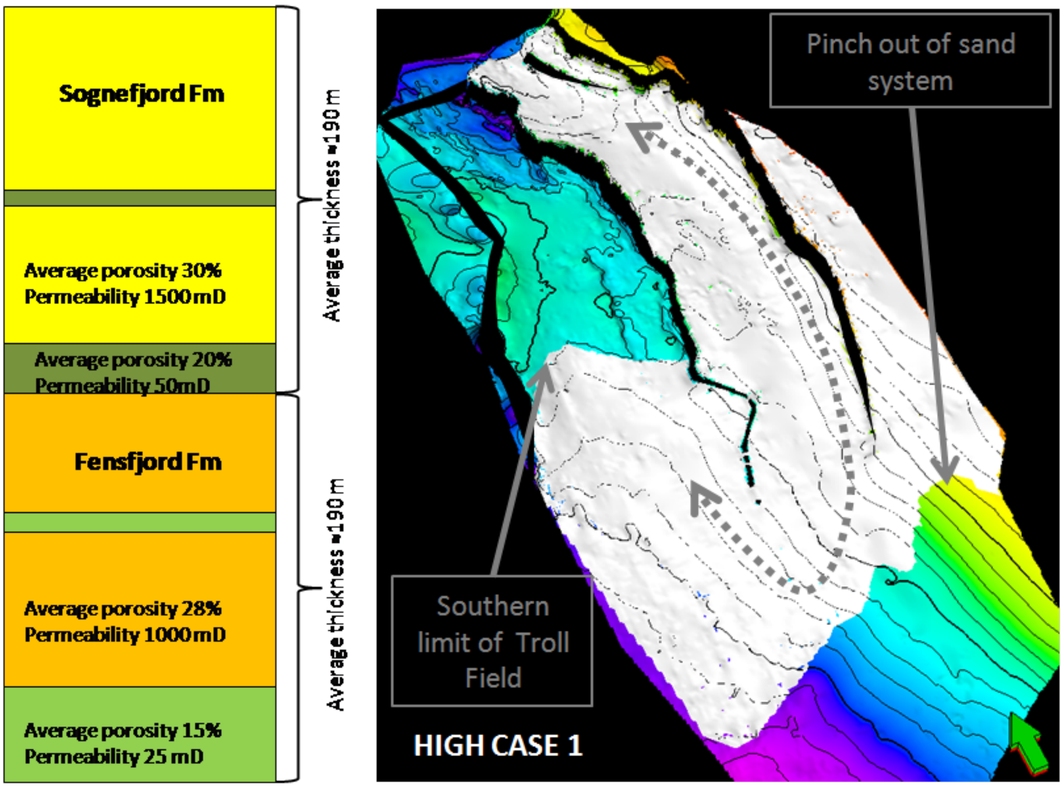

Figure 4-26 Troll Kystnær High 1 Case reservoir- and geo-model.

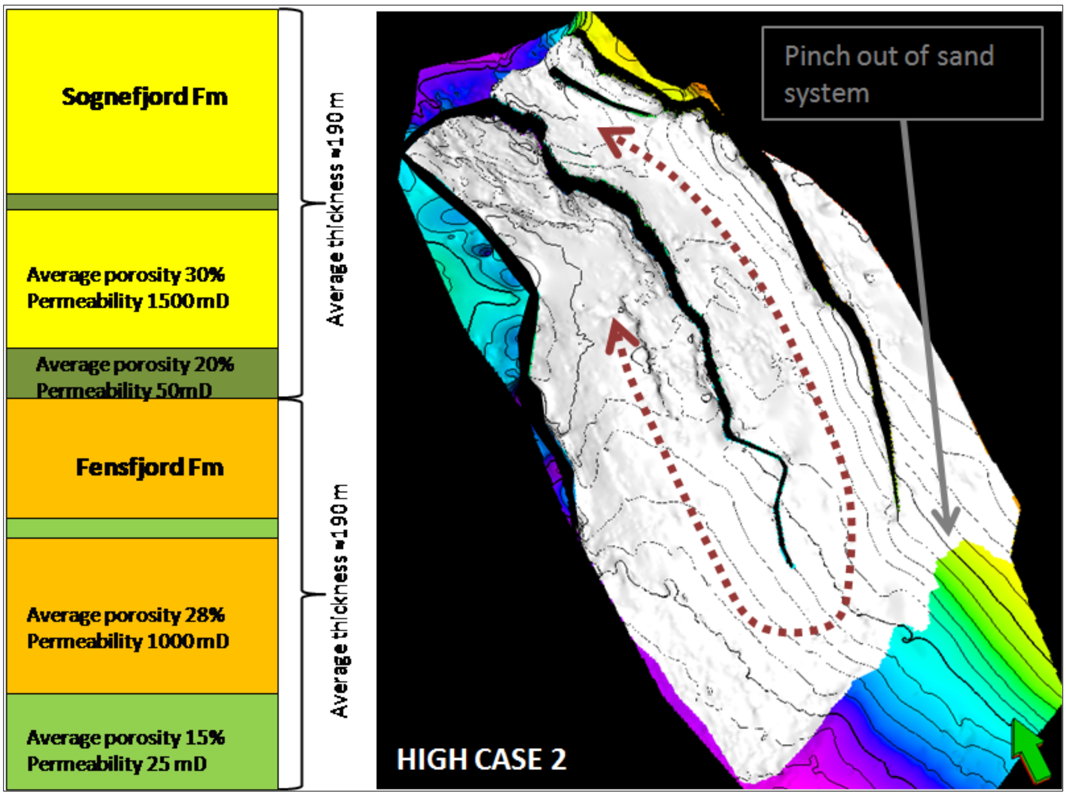

Figure 4-27 Troll Kystnær High 2 Case reservoir- and geo-model.

4.8.1.1 Volumes

Bulk rock and pore volume calculations were performed based on the different reservoir models presented above. The results are summarized in Table 4-3.

Table 4-3 Volumes Troll Kystnær Storage Complex.

	Bulk Rock x10^9 Sm^3	Pore volume x10^9 Sm^3	Areal km^2
Troll Kystnær Low	253	51	1042
Troll Kystnær Base	731	160	2215
Troll Kystnær High 1	1201	297	3103
Troll Kystnær High 2	1586	418	3998

5 DYNAMIC STORAGE BEHAVIOR AND PREDICTIONS

The main bulk of the objective of the reservoir engineering work was carried out in 2009-2010 with the objective to estimate the expected pressure increase based on a high case CO_2 injection volume of 3.3 Mt/yr. Plume spread based on two northern injection locations was also evaluated. An update to the work was performed early in 2011 to arrive at the now proposed injection location, and this result is presented in this summary. The work was performed in the following way:

- Build reservoir simulation model based on geological model
- Simulate with a CO_2 injection volume corresponding to a high case Mongstad (3.2 mill tonnes per year) with three different pore (rock) compressibility values.
- Simulate plume spread to find shallowest point of migration
- Based on simulations, assess acceptable injection volumes and number of years with injection before reaching the maximum acceptable pressure.
- Conclude and recommend

Other aspects like various rates of dissolution, rock-CO2 interaction, injection point optimisation, detailed injectivity assessment, PVT assessment etc., is not covered in this brief reservoir evaluation at this stage of the development. This will be covered in more detailed should Troll Kystnær be selected for further development.

5.1 Parameter description

The main simulation model characteristics and properties are as follows:

- Grid block size: 400m x 400m
- Number of grid blocks: 109 x 253 x 27 = 744579
- Average model thickness is 340 m
- Thickness in the well area is 400m.
- Average permeability is 690 mD, and the kv/kh-ratio equals 0.1. Porosity has an average of 0.26.
- The simulations are done with no solubility of CO2 in water (Eclipse keyword DRSDT=0), this will give results on the conservative side.
- CO2 and water PVT and relative permeability from SINTEF (refs. Bergmo & Lindeberg, 2007 and Bergmo et al, 2009).

Pore volume (rock) compressibility values (SINTEF), C_r:

$1.6x10^{-6}$ bar^{-1} (pessimistic case)

$4.0x10^{-5}$ bar^{-1} (reference case)

$1.6x10^{-4}$ bar^{-1} (optimistic case)

Due to lack of laboratory experiments on Troll Kystnær the value of the rock compressibility is uncertain. The compressibility values cover the range used by in the Johansen studies, the reference value of $4.0x10^{-5}$ bar^{-1} is also found to match Troll Kystnær according to Hall's correlation (ref. Bradley, 1987). The rock compressibility factor is important, and directly decides the ability of the reservoir to “absorb” injected CO_2, from the compressibility equation:

$\Delta P = V_{inj}/(V*C_t)$, (Equation 5.1)

where $C_t = C_r + C_w$ and C_t is total compressibility, C_r rock compressibility and C_w water compressibility.

5.2 Preparation of dynamic model

5.2.1 Assumptions

In the reservoir simulation model the reservoir pressure corresponds to hydrostatic water pressure. The top reservoir depth at the simulation injection locations are 1224 meters in south and 1477 meters in north. The reservoir temperature is approximately 45 deg. C.

5.2.2 Simulation model extent and volumes

The extent of the reservoir simulation model with permeability is shown in Figure 5-1.

This model is the Base geological model, and represents the Base simulation case with respect to volumes and properties. The base geological model assumes a closed system. Three alternative models with different volumes have also been defined by G&G to illustrate a more open system with pressure communication to surrounding segments. The alternative models have been scaled by using results from the base case simulation results.

The volume (Water In-Place, WIP) range is as follows:

- Base case: 160 GSm^3
- Low case: 51 G Sm^3
- High1 case: 297 G Sm^3
- High2 case: 418 G Sm^3

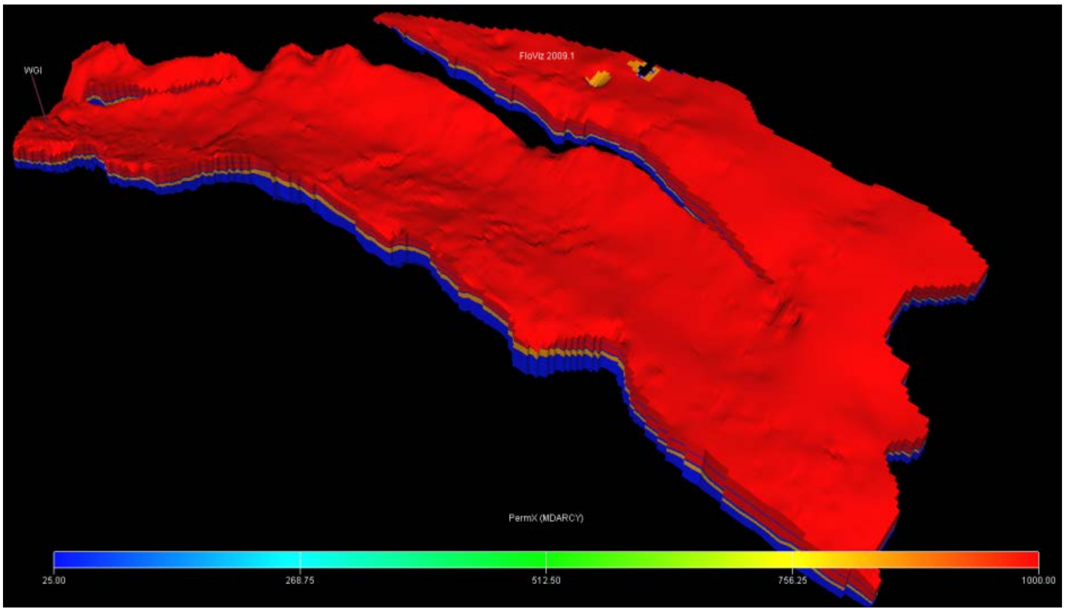

Figure 5-1 Troll Kystnær reservoir simulation model showing permeability.

5.3 Prediction of storage behaviour

5.3.1 CO_2 injection rate and injectivity

In the simulation work on Troll Kystnær an injection rate of 3.2 million tonnes per year has been used, this rate corresponds to the high case for Mongstad.

Based on work done for Utsira and Johansen the injectivity in Troll Kystnær is expected to be good. One well will have capacity to receive all the CO_2 although two wells will be used for redundancy. More detailed work regarding injectivity modelling and relative permeability effects will be an issue in further work, although there are no indications that Troll Kystnær formations should offer any negative surprises.

5.3.2 Base Case Simulation results

The simulated pressure build-up developments in the well area for the different rock compressibility values are shown in Figure 5-2. The boundary pressure can be considered the global pressure increase ΔP_g while the difference between the pressure increase in the well area and the boundary can be considered the "flow" increase, ΔP_f. The results are tabulated in Table 5-1.

Table 5-1 Pressure increases after 50 years, the results are with pessimistic, reference and optimistic rock compressibility values.

CO_2 inj. rate (M tonnes/year)	Rock compr (bar^{-1})	Pressure build up (bar)		Diff. pressure (bar)
		Well area	Plume boundary	
3,2	1,6E-06	39,4	36,2	3,2
3,2	4,0E-05	25,2	22,0	3,2
3,2	1,6E-04	14,5	11,4	3,2

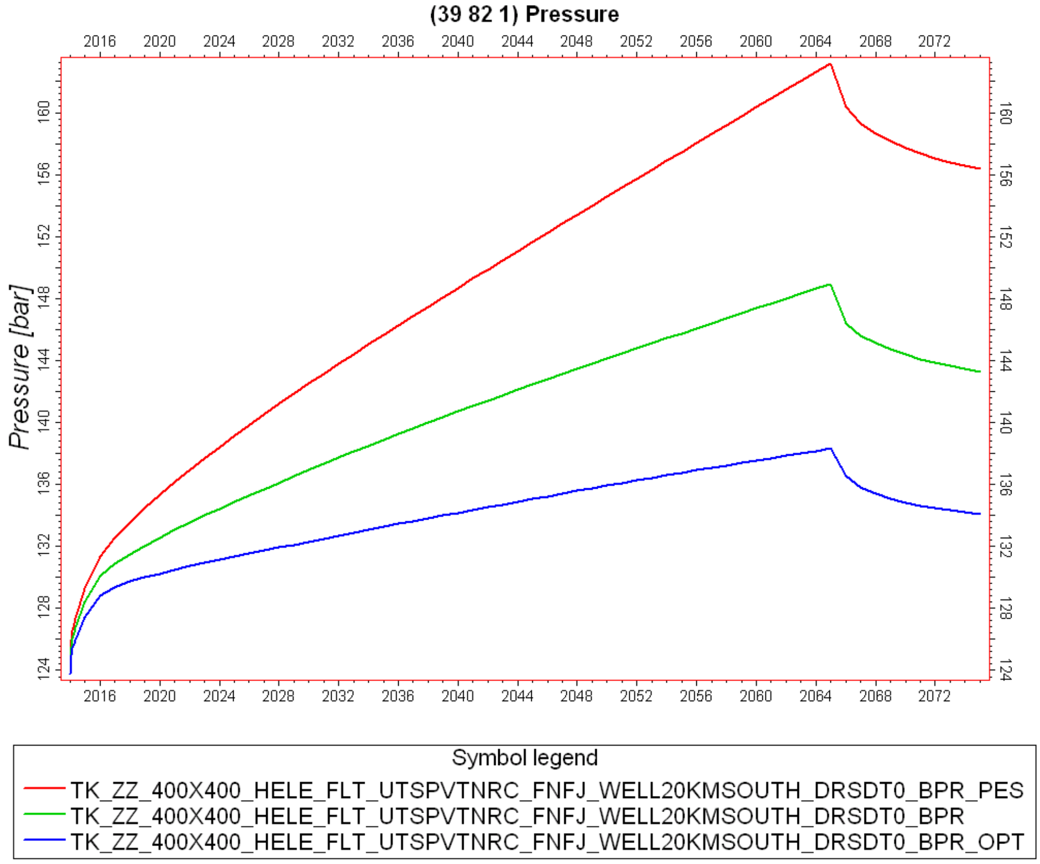

Figure 5-2 Pressure build-up in the well area with different rock compressibility values, injection rate is 3.2 mill tonnes per year.

The simulated CO_2 plume extensions 500 years after injection of 3.2 mill tonnes CO_2 per year in 50 years are shown in Figure 5-3 and Figure 5-4. Plume movement is rather slow due to a relatively flat overburden.

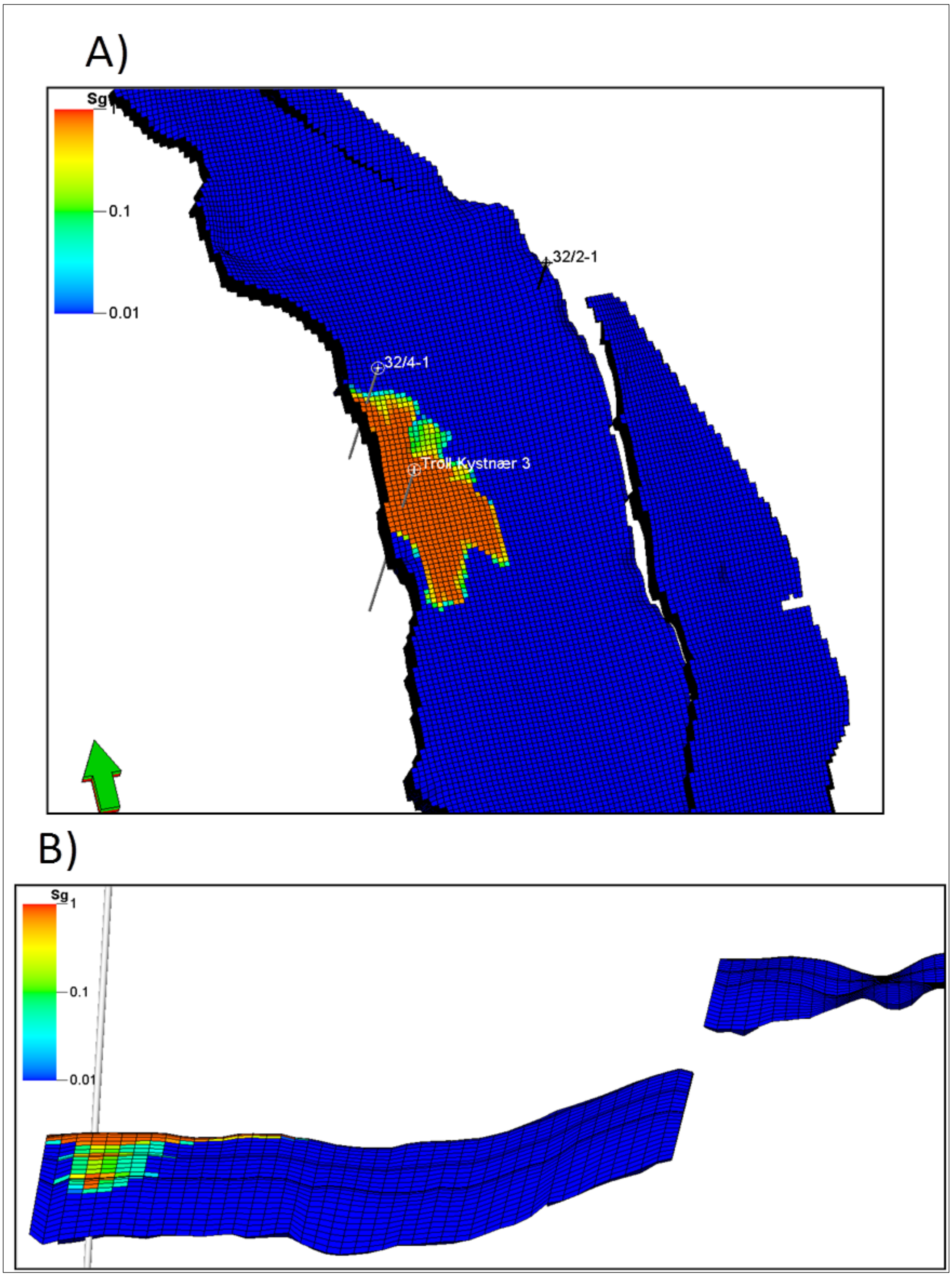

Figure 5-3 A) CO_2 plume extension after 50 years and B) cross section E-W through injection well.

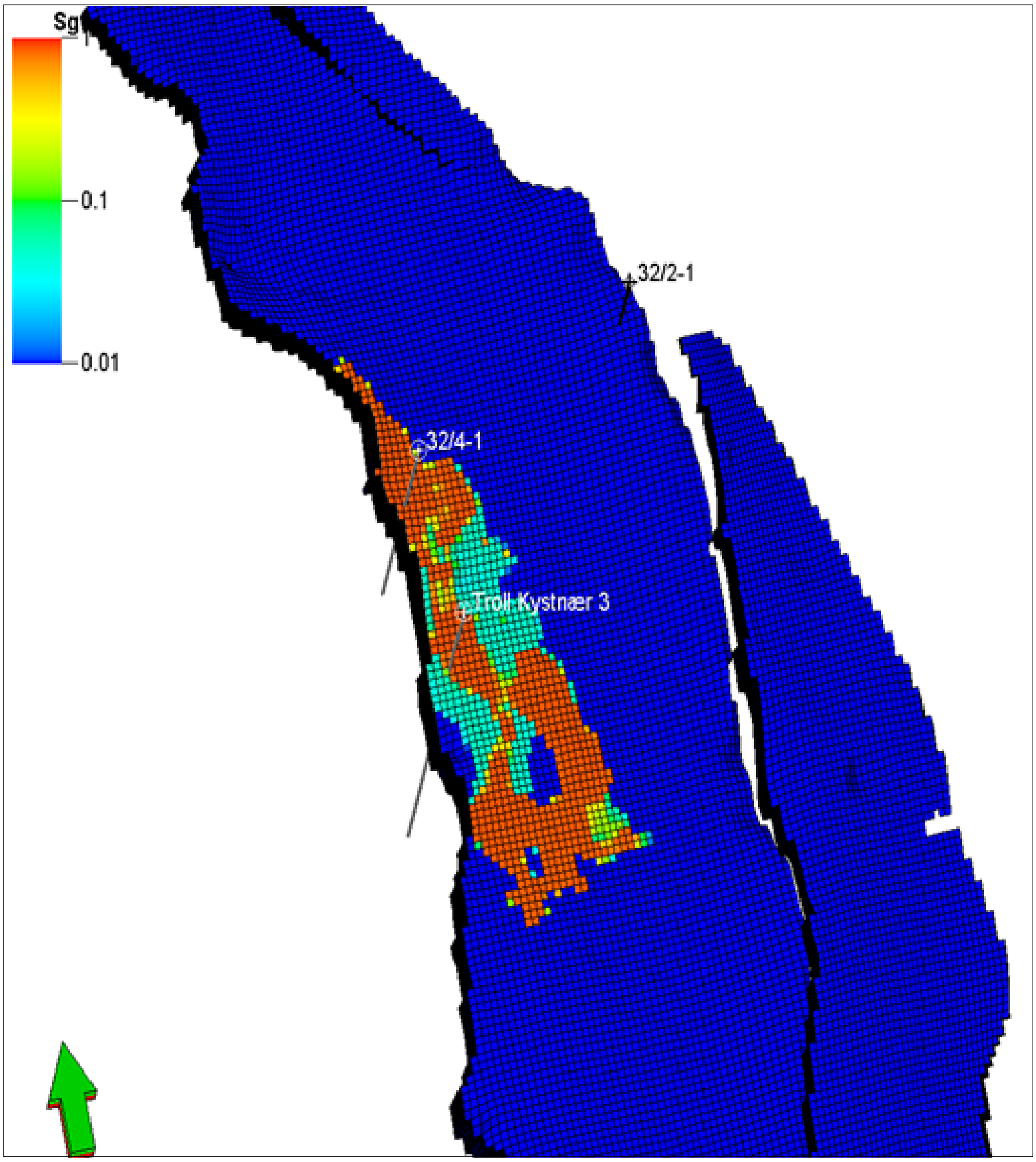

Figure 5-4 CO_2 plume extension after 500 years.

5.3.3 Simulation sensitivities

CO_2 dissolved in water is run as a simulation sensitivity. The result from the sensitivity shows that the pressure build up will be around one bar lower compared to not having CO_2 dissolved in water (Figure 5-5). This means that solubility of CO_2 in water has minor effect on the simulation result.

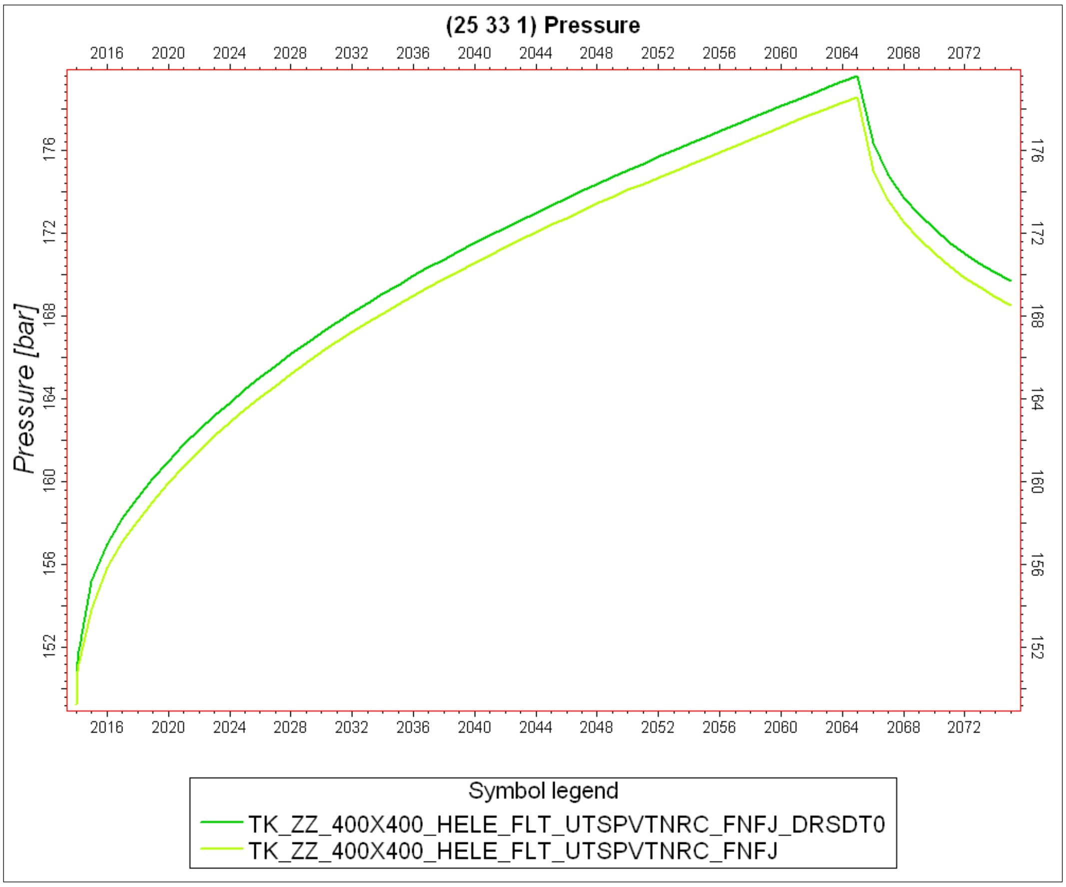

Figure 5-5 Simulation results from no solubility of CO_2 in water (dark green) compared to CO_2 solved in water (light green) in the well area, CO_2 injection rate of 3.2 mill tonnes per year in 50 years.

5.3.4 Results

The simulated Base case results have been scaled to the Low, High1 and High2 case volume scenarios. It is assumed that the global pressure increase (ΔP_g, pressure build-up at the boundary) is affected, and that this pressure increase is inversely proportional to the volume (Equation 5.1). It is also assumed that the "flow" pressure increase is not affected by the volume variations. This assumption holds if the volume variations are away from the well, but would not hold if the volume variations were due to thinner sands, lower net/gross etc. near the well. Anyway, the dominant pressure term is the ΔP_g, so the mistake is small if the volume variation assumption is wrong.

The scaled pressure increases are tabulated in Table 5-2 for the different rock compressibility cases with an injection rate of 3.2 million tonnes per year. The table have also been transposed to corresponding no. of years of acceptable injection. Based on an estimation of fracture initiation pressure of 20bars (2009 evaluation), the OK case is colour labelled yellow, the cases that are acceptable after 50 years are labelled green and the non-acceptable cases are labelled red. The maximum pressure build-up in the Base case (base volume and base rock compressibility) is 25 bars. This is an acceptable pressure build up. Updated estimation of fracture initiation pressure described in chapter 4.7 has not been included in this evaluation.

A different injection point giving a deeper ultimate plume migration will increase the safe pressure. Figure 5-2 shows that the pressure increase is gradual and only to a small extent immediate. This means any higher and more rapid pressure increase than expected will be detected through monitoring, and there will be sufficient time to evaluate and implement alternatives like other locations, pressure relief wells, lower injection rates etc.

Table 5-2 Pressure build up in well area after 50 years injection of 3.2 mill tonnes per year.

Injection rate: 3.2 mill tonnes per year				
	Pressure build up (bar)			
Rock compr. (bar-1)	**Low** (51 GSm^3)	**Base** (160 GSm^3)	**High 1** (297 GSm^3)	**High 2** (418 GSm^3)
1,6E-06	117	39	23	17
4,0E-05	72	25	15	12
1,6E-04	39	15	9	8

If pressure depletion is detected with an exploration well in Troll Kystnær, the storage capacity will increase. This will indicate a regional pressure communication, ie. High case 1&2 of the geological models will become more likely scenarios (Connecting pore volume 300-400 GSm3). It will also affect the pressure build-up.

5.3.5 Summary and discussions

- Troll Kystnær is expected to take injection of 3.2 mill. tonnes CO_2 per year for 50 years without any significant risk of leakage.
- Observed pressure depletion in Troll Kystnær due to pressure communication with oil and gas production from Troll field increases the storage capacity.
- Most uncertain factors are the connecting reservoir volume, and the compressibility of the bulk reservoir. The compressibility can be determined through rock mechanics testing on core samples from 32/4-1. Connecting reservoir volume may also be narrowed in on through more detailed interpretation of additional seismic. These are tasks that naturally form part of the maturing process.
- If these factors should prove to be more pessimistic than expected, there can still be many years of safe injection, and time to evaluate and implement alternative storage solutions (lower rates, alternative storage locations, pressure relief wells etc.)
  More sensitivities regarding injection point is needed in order to find optimum deep plume spread and also plume spread over 500 years.
- Long term storage behaviour regarding dissolution and reactive transport modelling (chemical dissolution and precipitation), as well as capillary trapping are issues that will be dealt with during the next phase.
  More detailed and accurate estimation of safe pressure through rock mechanics testing will ensure site integrity.
- Proper monitoring is important and required. The shallower depth of the storage formations offers good opportunity for 4D monitoring of plume spread. Monitoring will be further looked into should Troll Kystnær become the preferred option.

6 STORAGE SITE UNCERTAINTY AND INTEGRITY

The Troll Kystnær Storage Complex (Figure 6-1) is identified as a fault block bounded by major faults to the North, East and West. The depth range in the suggested injection area is between 900–1300m. The seismic mapping together with well observations suggests good reservoir properties and extensive pore volume connectivity for the storage formation (Figure 4-14).

The eastern boundary for the storage complex is the ØFC and it is assumed that this Fault Complex has good sealing capacities (Section 6.3). 3-way fault bounded and 4-way dip closures are observed along both the eastern and western fault boundaries and south on the block (Figure 6-1).

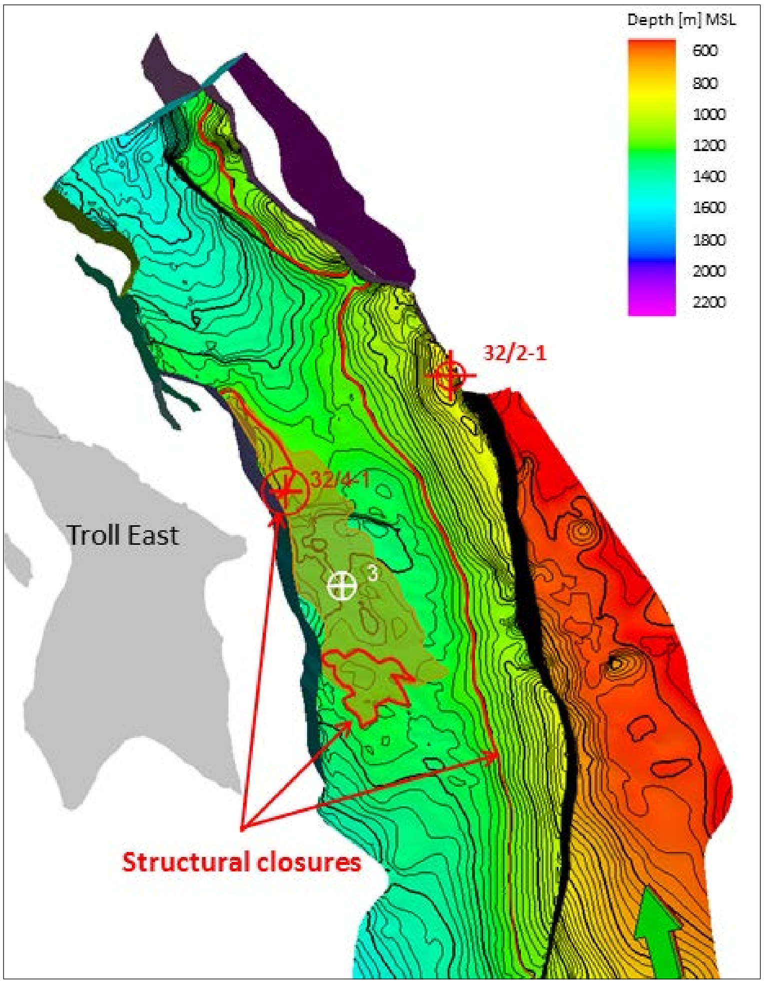

Figure 6-1 The Troll Kystnær storage complex. Top Sognefjord Formation depth map with the proposed injection point (Well location 3) and corresponding CO_2 plume (beige area; 500 years after injection start).

In order to assure long term and safe subsurface storage of CO_2 in the Troll Kystnær storage complex, main uncertainties and risk factors have been assessed:

- Storage formation - presence and quality
- Cap rock - type and thickness
- Faults - number and permeability

6.1 Storage Formation Integrity

The presence of the storage formation on the Troll Kystnær fault block is confirmed by the key wells and the reservoir properties are known by the Troll Field wells. Seismic interpretation supports the assumption of well-developed storage formation in the proposed injection area. Thinning of the storage formation is observed towards the eastern margin (Figure 4-20) and well data (well 32/2-1) indicate a less developed storage formation in this direction.

The storage formation integrity risk is considered be low to moderate. The main uncertainty is the southward presence and quality of the sand system primarily due to limited data coverage.

6.2 Seal Integrity

The cap rock, Draupne Formation, is proven by all key wells and the seal efficiency is tested by several of the Troll Field wells. The sealing capacity of Draupne Formation in the wells (32/4-1 and 32/2-1) penetrating the Troll Kystnær fault block is regarded as good, as no significant permeable layers are observed within the formation. The Draupne Formation sealing potential is dependent upon the lateral extent of the seal unit. Seismic facies (transparent reflectivity) indicates the presence of shale deposits covering the Troll Kystnær fault block (Figure 4-3).

The thickness of the Draupne Formation varies from 70 m to 300m (See Figure 4-18 and Figure 4-19) in the plume area, indicating acceptable seal capacity, however it is thinning towards west and east of the Troll Kystnær fault block. In addition, thick impermeable Cretaceous deposits with good sealing capacity are assumed to be present over the entire injection area (Figure 4-18). Only minor deformation of the seal units is observed (Figure 4-5, Figure 4-7 and Figure 4-8). Some faults cut through the cap rock and parts of the secondary seal up to base Quaternary. The displacement of these are insignificant and there are no signs of leakage observed on the seismic associated with these faults.

The seal integrity risk is considered to be moderate. Between 750m and 1200m of seal units are present over the possible injection area. However, the available data on cap rock properties does not provide adequate confidence on the cap rock sealing efficiency, therefore further assessment is recommended.

6.3 Fault Integrity

The ØFC is registered with minor tectonic activity (ref. Smethurst, 2000) and NORSAR study. Fault activity along the major fault is observed from the Permian/Triassic up to the Cretaceous (possibly Paleocene, see Figure 4-17). Across the ØFC a deformation zone is observed and this deformation is decreasing southwards. The storage formation overburden (seal units) is decreasing towards the ØFC (Figure 4-18); however, it is assumed to have sufficient thickness to secure the ØFC from leakage. No seismic anomalies indicate the presence of a leaking fault.

The Vette Fault dividing the Troll Kystnær fault block from the down-faulted Troll Fault Block (Figure 4-16) could represent possible sand-sand contact; this fault complex dies out southwards from the Troll area into the Stord Basin. In the northern part of the storage complex, the fault throw on both the northern and western bounding fault complexes are up to 500m. The fault and horizon interpretations indicate no sand-sand juxtaposition across the fault complex in the injection area (Figure 6-2).

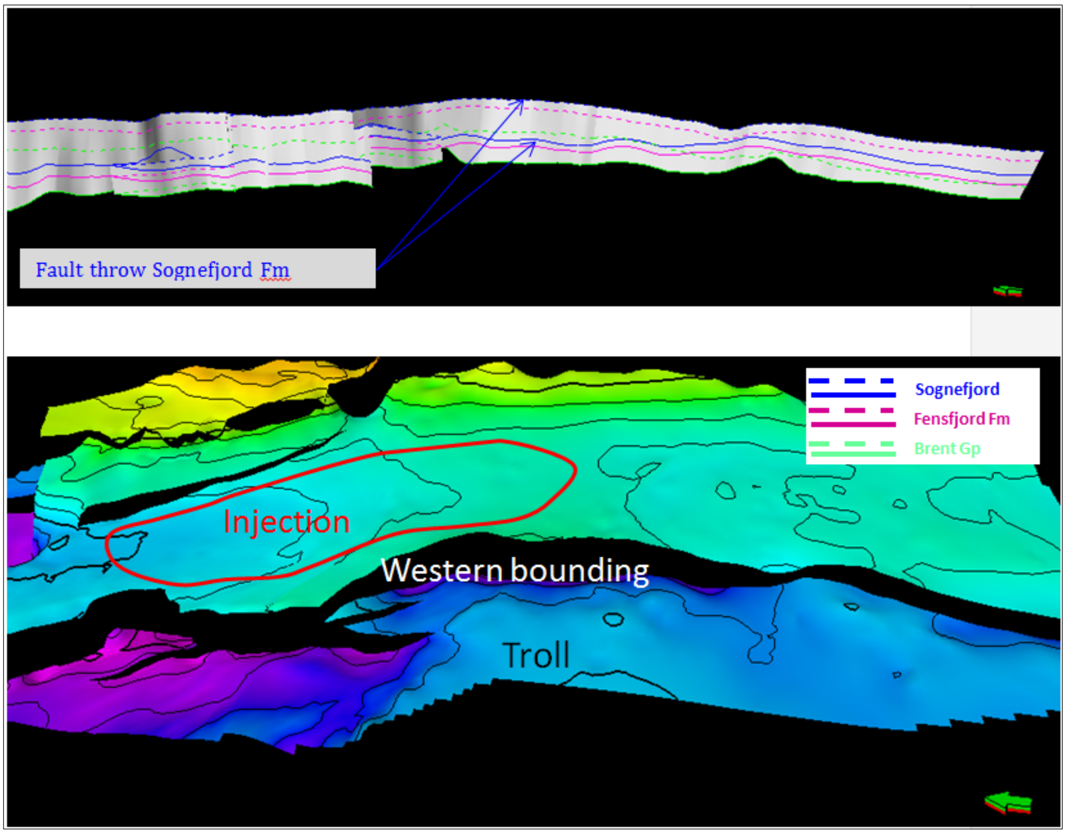

Figure 6-2 Overview of the Vette fault. No observed sand-sand juxtaposition over the northern part of the Fault Complex.

Towards the East observations suggest the ØFC to be sufficiently stable to not compromise the storage integrity:

- Interpretations of the 3D seismic cube GN1101 display no pockmarks above the ØFC, indicating that there is no active leakage from the fault.
- Well data from the Troll area, including Breiflabb and Troll Kystnær indicates that there is depletion in the Troll Kystnær area. This pressure depletion is positive with respect to CO_2 storage potential.

According to Fjelskaar et al. (2000) deep WNW-ESE compression is observed north of the Horda Platform and shallow WNW-ESE compression is observed east of the platform (Figure 6-3). These observations indicate a compressional regime also present on the Horda Platform. A compressional stress regime will keep the ØFC tight and hence contribute to the integrity of the fault complex. The well data from the Troll Kystnær wells indicate a normal/relaxed stress state. This implies that the regional compressional stress is not in the magnitude where one would expect a reverse activation of the normal faults of the ØFC.

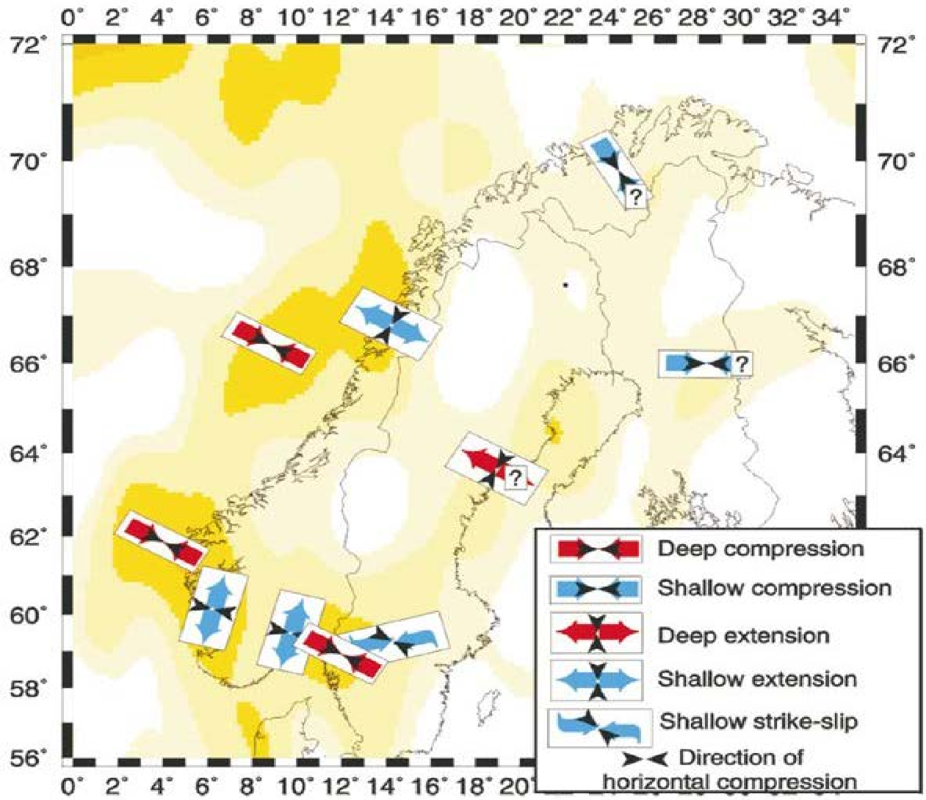

Figure 6-3 Regional stress. The figure shows compressional stress north of the Horda Platform (Fjeldskaar et al. 2000).

6.4 Legacy wells

There are two legacy wells within the Troll Kystnær area 32/4-1 and 32/2-1. Both are abandoned exploration wells with target in Upper Jurassic Sognefjord sand. Only 32/4-1 has been investigated regarding barrier status as this comes in direct contact with the CO2 plume with the selected injection point and due to the fact it was drilled in 1996. The well was abandoned according to the prevailing rules and regulations at the time. The integrity evaluation was done according to the method outlined in the DnVs JIP "CO_2 wells".

The conclusion is the well is not plugged in a satisfactory way regarding CO2 migration:

- There is no cement in open hole
- Only a mechanical plug in 9 5/8 casing
- Only one shallow cement plug in 13 3/8 casing

This gives the following risk picture related to nearby CO2 injection:

- All formations from Heather to basement are exposed with possibility for x-flow
- At best, there is only one barrier in the well that might be qualified.

The recommended action is to contact ConocoPhillips to get more information on well (detailed drilling reports, FWR from BJ and mudlogging company, LOT records etc. further assess barrier in well. Further it should be investigated whether it is possible to re-enter the well with the aim to re-abandon. This could be done either prior to injection or if a leak is detected from the well. Alternative injection points could also be investigated, especially since the license situation in the area is likely to change (valid until 2018) before injection starts.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The identified Troll Kystnær storage formation has adequate thickness and porosity to sustain acceptable storage capacity needed for the Mongstad volumes. It is located at sufficient injection depth for efficient CO_2 phase conditions. Uncertainties in volume (capacity) estimations are expected due to the limited data availability, however all estimations are cautious and the capacity may probably be larger. If pressure depletion is detected with an exploration well in Troll Kystnær, the storage capacity will increase further. This will indicate a regional pressure communication, i.e. High case 1&2 of the geological models are more likely scenarios (Connecting pore volume 300-400 GSm3). It will also lower the maximum simulated pressure build-up with the according pressure depletion. The full impact on storage potential with large pore connecting pore volume and depleted reservoir has not been fully assessed and should be investigated further.

The Troll Kystnær storage formation is capped by several extensive shale and mudstone units. Based on presence, quality, thickness and extent of the cap rock the risk of CO_2 escaping to the surface through overlying units is considered to be moderate to low. The observed faults and sub-seismic faults (~10m) within the fault block are not considered a risk in terms of cross-fault leakage as the throws are of corresponding size (Chapter 4.5.3). Fractures have not been mapped due to their non-continuous nature. However, to reveal the origin and properties of the possible fracture patterns, assessment of fractures within the shale is an option.

The ØFC is considered to be stable and sealing. However, due to limited data availability the fault integrity risk is considered moderate to low. Further assessment of this risk is necessary to assure the storage integrity.

7.2 Recommendations

To fully mature and characterise the Troll Kystnær storage complex as a safe CO_2 storage complex, a verification well is necessary. However, it has not been possible to explore all data available in the area and to use this to the full extent in the characterisation due to time constraints. This should be the primary task should the area be brought forward as a candidate and the will also make it easier to assess the necessity of a verification well before an investment decision. The following work should be performed to further mature the area. The list does not have any priority, but it is recommended to construct and uncertainty model for the Storage Complex in order to investigate the like impact on reduced uncertainty for the different tasks:

- Update to the regional depletion study performed in 2007 for NPD, based on recent welldata in area.
- Gather high resolution 3D or 2D data (NSR) (stacking velocities) to prove and confirm the southern extension of the Upper Jurassic depositional system
- Seismic analysis
    - Rock physics (e.g. fluid substitution, seismic inversion)
- Seismic attribute study
    - E.g. inversion studies for property modelling of storage formation

    - Inversion/SviPro studies for cap rock property modelling/ leakage path investigation.
- Fault seal study
    - Fault Analysis
    - Stress analysis through Permo-Triassic, and post-Triassic times
    - Current stress state on ØFC
    - Study on changes in stress from current stress state and to injection induced stress state
- Key well studies - storage formation mineralogy and geochemistry
- Cap rock fracture pressure – rock mechanical testing on any available Draupne cores.
- Depth conversion
    - Test of three depth conversion models, structural dip have strong effects on the CO_2 migration and hence the storage risk
    - Further refinement of existing depth conversion model
    - Linear velocity model
    - Stacking velocity model
- Construction of overburden model for leak simulation as a basis for monitoring plan
- Optimisation of injection point
- Drill an exploration well to enhance storage complex knowledge and optimize injection well placement. Formation evaluation programme should as a minimum include
    - Minifrac testing of cap rock
    - Leak-off tests
    - Cap rock core samples
    - Storage formation core samples
    - Storage formation pressure measurements
    - Storage formation fluid sampling
    - Fluid sampling above/below cap rock
    - Extent of well/ injection test to be considered

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9 APPENDICES

- Recommendation regarding 3 D area
- 31/2 -4 Well integrity evaluation
- Time, depth and thickness maps of key horizons:
  - Seabed time map
  - Seabed depth map
  - Top Shetland Group time map
  - Top Shetland Group depth map
  - Cretaceous thickness (m) map
  - Top Draupne Formation time map
  - Top Draupne Formation depth map
  - Draupne Formation thickness (m) map
  - Top Sognefjord Formation time map
  - Top Sognefjord Formation depth map
  - Top Fensfjord Formation time map
  - Top Fensfjord Formation depth map
  - Sognefjord/Fensfjord formations thickness (m) map
  - Top Brent Group time map
  - Top Brent Group depth map
  - Top Johansen Formation time map
  - Top Johansen Formation depth map
  - Top Statfjord Formation time map
  - Top Statfjord Formation depth map

A: Recommendation regarding 3 D area

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Anbefaling 3D innsamlingsområde

TROLL KYSTNÆR

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Bakgrunn

- Lisens-situasjonen rundt Troll kystnær har total endret seg de siste 4 månedene
- Tidligere injeksjonspunkt styrt av åpne områder
  - PL369 blokkerte i sør
  - PL464 til dels i konflikt i nord
  - Begge disse er nå tilbakelevert
- Ny evaluering av injeksjonspunkt gjort uten å ta hensyn lisenser i området
  - Ny lisens PL 577 kommet i nordlig del av struktur.

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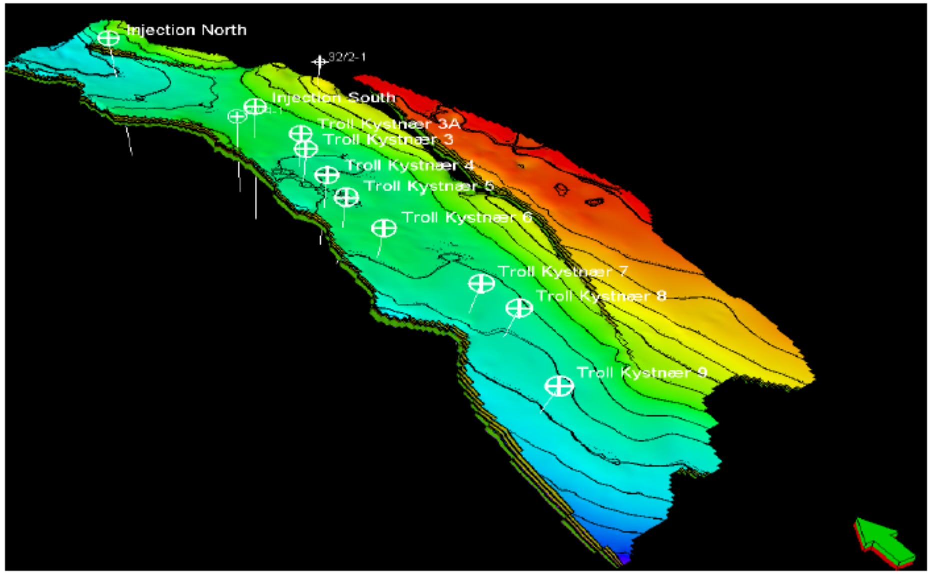
Screening av injeksjonsområder

- 9 forskjellige lokasjoner undersøkt
- Redusert til 2 hovedlokasjoner basert på
  - Migrasjon mot Øygarden og forseglingspotensial av Øygarden
  - Avstand til utforskningsbrønner



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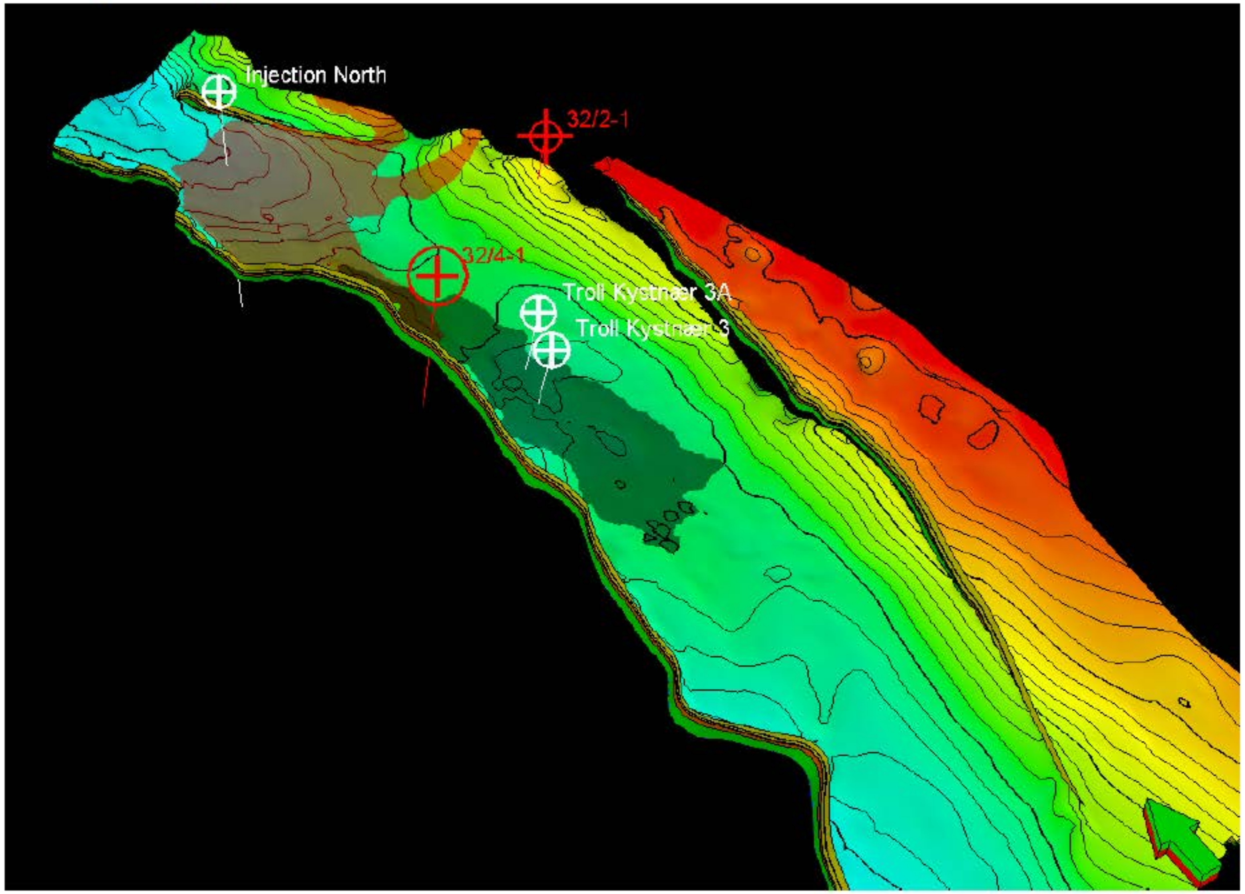
Injeksjonspunkter evaluert



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Faktorer brukt i evalueringen

- Geologiske faktorer
  - Dyp – tykkelse lagerbergart
  - Egenskaper på lagerbergart
  - Tykkelse/utstrekning primærforsegling (lekkasje)
  - Forkastninger/lekkasjepotensial
- Dynamiske faktorer
  - Migrasjonsretning/utstrekning/hastighet
  - Trykkoppbygging
  - Migrasjon inn i kritiske områder – forkastningssoner/ gamle brønner
- Monitoreringpotensial
- Lisens- situasjon

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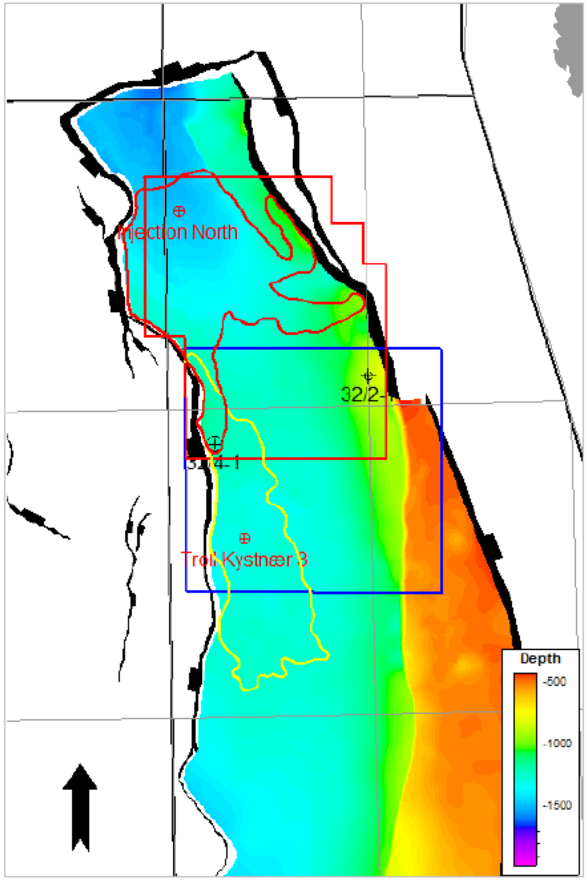
Dyp til lagerbergart (Topp Sognefjord)



- Injeksjonsbrønn Nord
  - fra 950 til 1500 m.
- Injeksjonsbrønn 3
  - fra 1150 til 1350 m.
- Over 1000m neogen heving og erosjon i lagerkomplekset .

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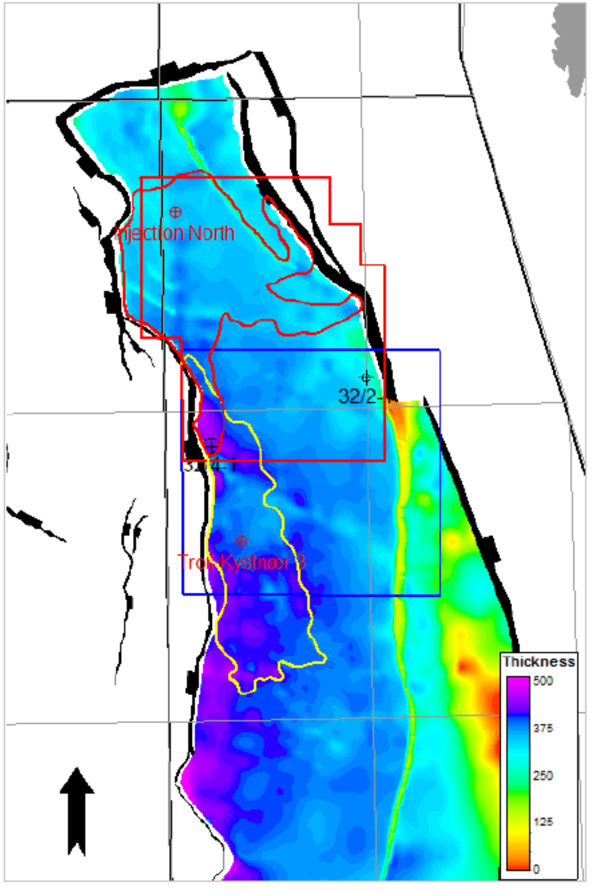
Tykkelse lagerbergart



- Økning av Sognefjord formasjonen sørover i lagringskomplekset.
- Injeksjonsbrønn N
  - 150 til 470 m i området
- injeksjonsbrønn 3
  - 340 til 470 m i området

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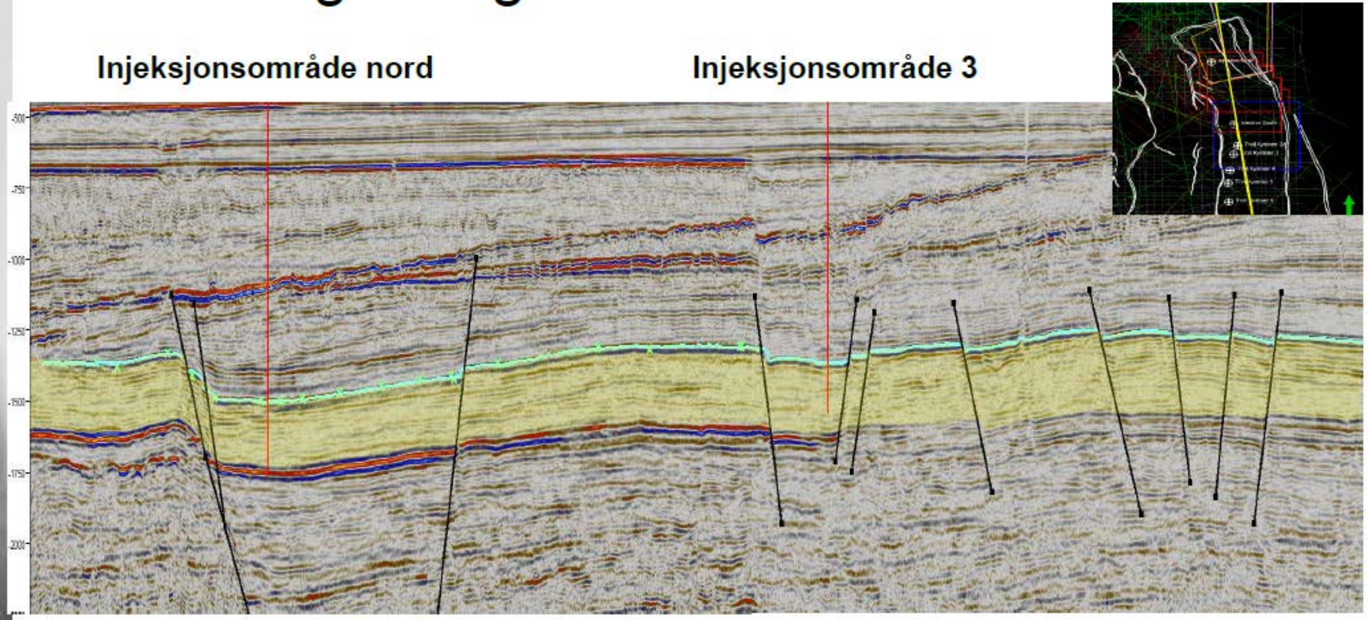
Kvalitet lagerbergart



- Det antas noe bedre utviklet lagerbergart i det sørlige injeksjonsområdet grunnet økt tykkelse av Sognefjord/Fensfjord.

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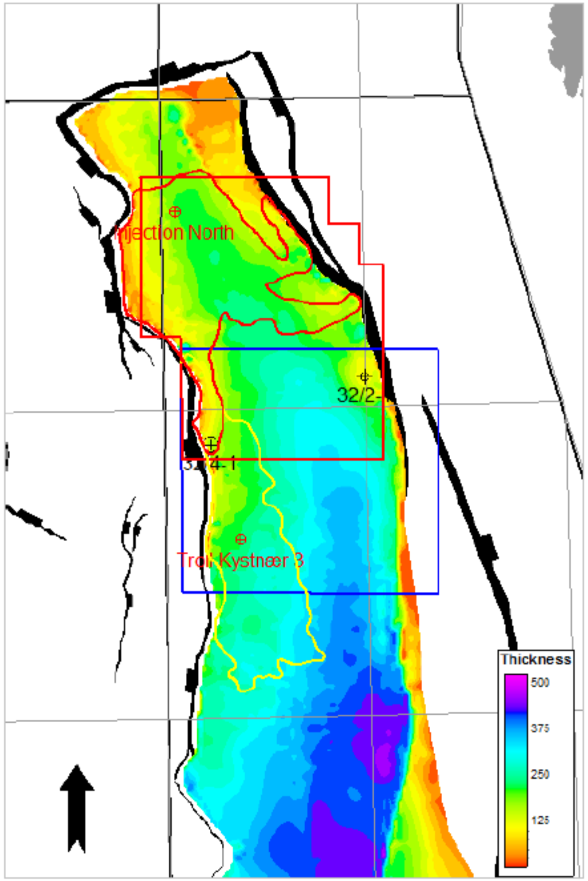
Primærforsegling (Draupne)



- Høyere grad av erosjon i den nordlige delen av lagringskomplekset.
- Markert tynning av Draupneformasjonen fra sør mot nord.
- Ned mot 15m tykkelse over den nordlige CO_2 plumen.
- Begge lokasjoner egnet, men tykkere Draupne over sydlig lokasjon gir større grad av sikkerhet.

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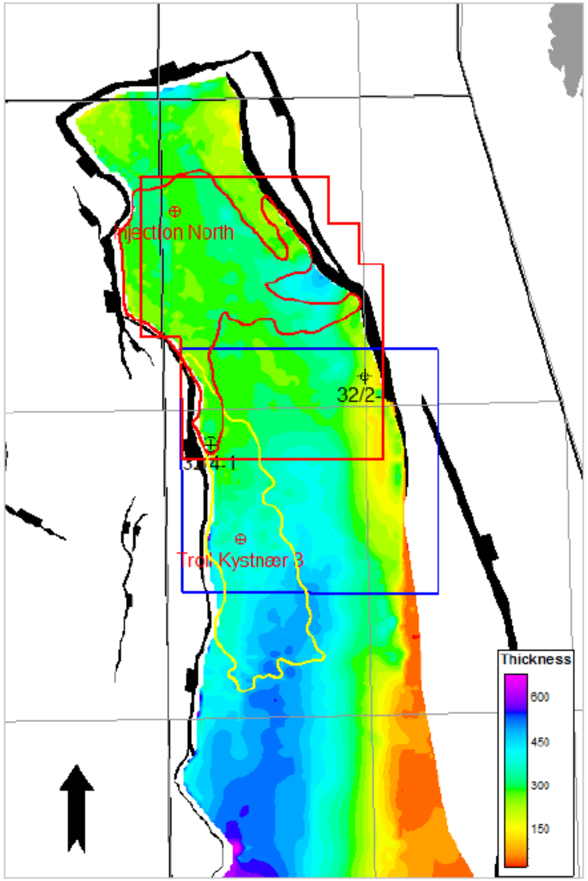
Sekundærforsegling (Kritt)



- Tynning av sekundær forsegling fra sør mot nord.
- Begge tilstrekkelig
- Injeksjonsbrønn Nord
  - Tykkelse sekundær 180 – 420m over plume
- Injeksjonsbrønn 3
  - Tykkelse sekundær 210 – 620m over plume

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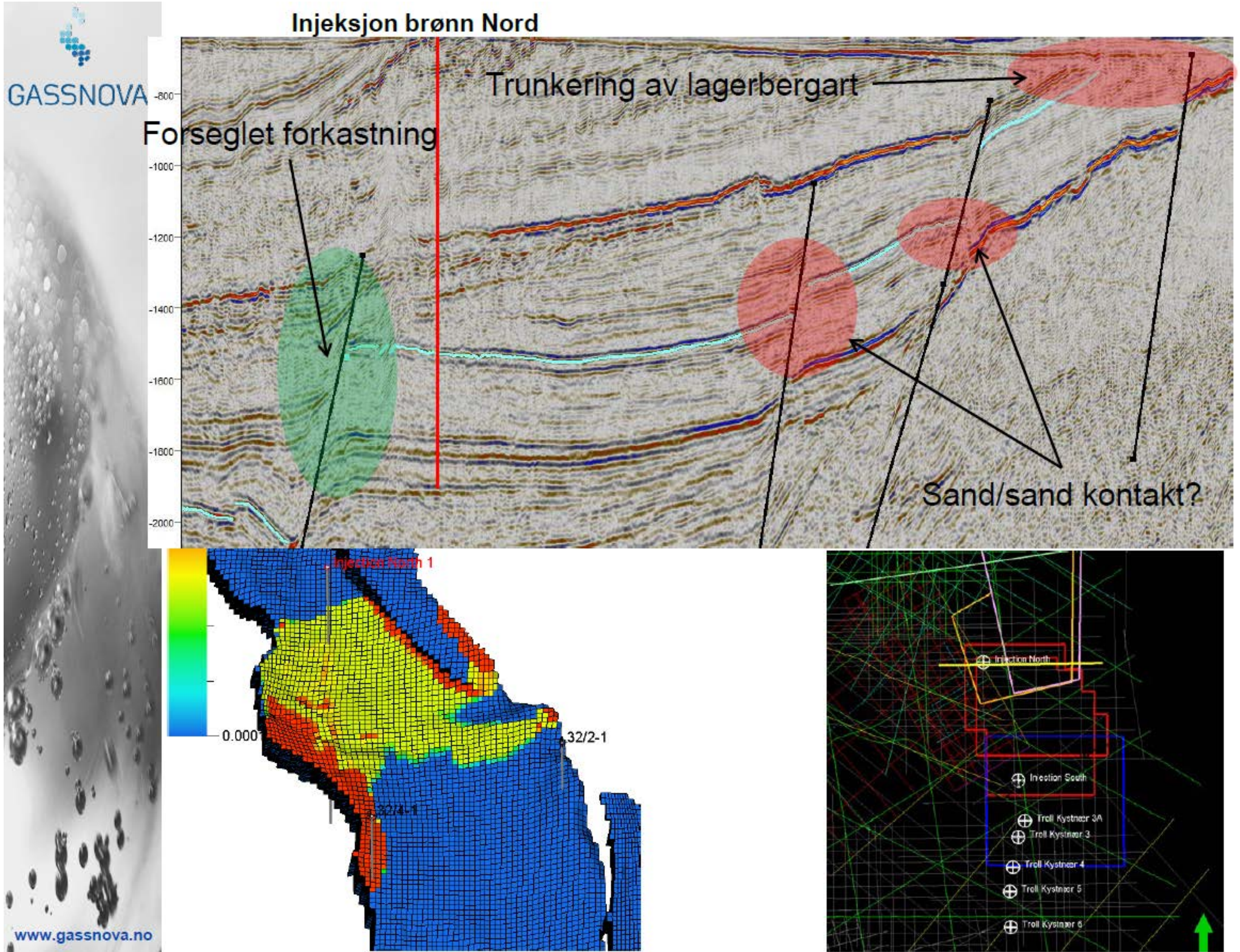
Lekkasje forkastninger

- Hovedforkastningene i den nordlige delen av lagringskomplekset synes å være avhengig av leirsmøring i forkastningssonen for å kunne ansees som forseglende.


Injeksjon brønn Nord
GASSNOVA
Trunkering av lagerbergart
Forseglet forkastning
-800
-1000
-1200
-1400
-1600
-1800
-2000
Sand/sand kontakt?
Injection North 1
0.0001
32/2-1
32/4-1
Injection North
Injection South
Troll Kystnær 3A
Troll Kystnær 3
Troll Kystnær 4
Troll Kystnær 5
Troll Kystnær 6
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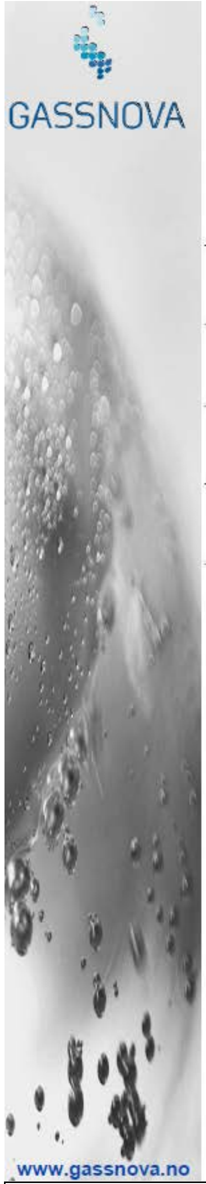
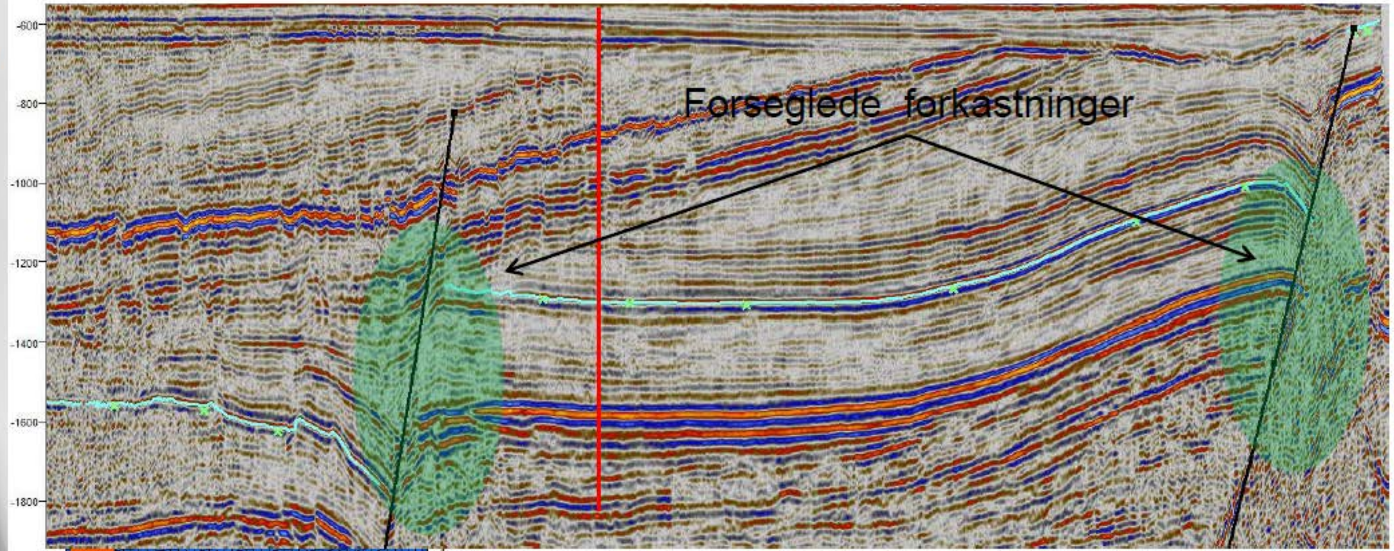
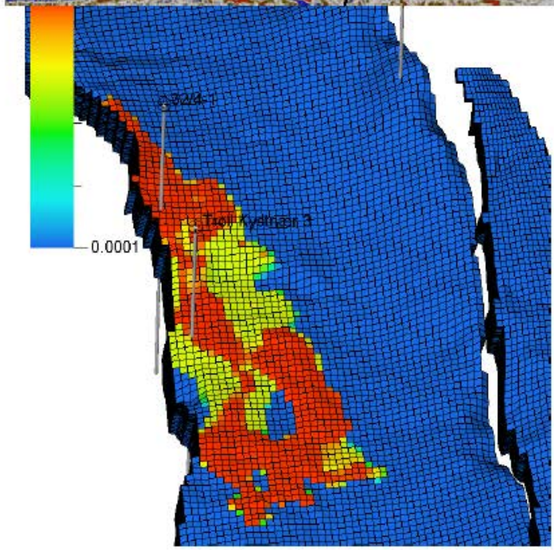
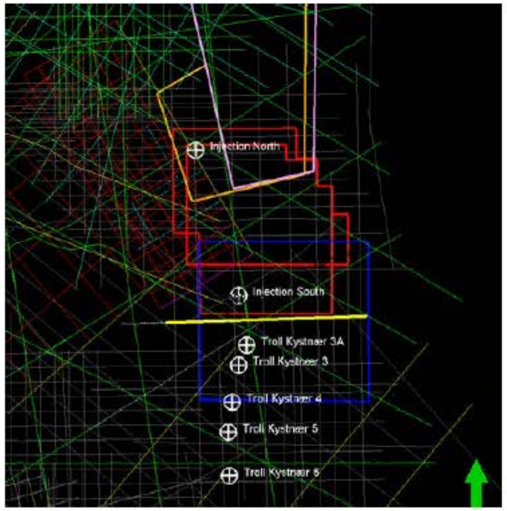


Injeksjon brønn 3A (proj)







Dynamiske vurderinger

- CO_2 migrasjon
  - Areal av plume
    - Nord ca. 200 km^2
    - Sør ca. 152 km^2
  - Utstrekning - hastighet:
    - Nordlig plume vil sannsynligvis nå Øygarden raskere dersom "intra-plume" forkastning ikke er forseglende
    - Sydlig plume ikke i kontakt med Øygarden, men dette kan endre seg ved ny modell/dybdekonvertering
    - Begge migrerer bort til forlatt brønn 32/4-1 – men sydlig plume antagelig på et tidligere tidspunkt.
  - Trykkoppbygging
    - Samme for begge lokasjoner

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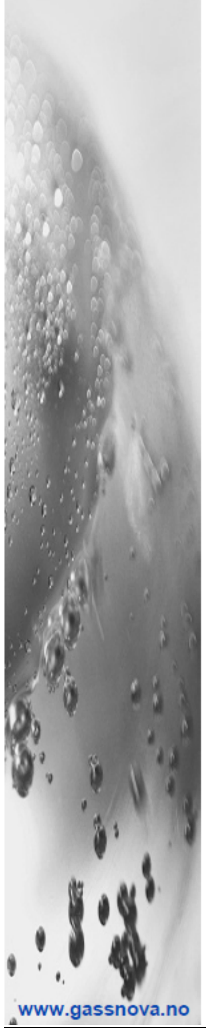

Monitorering

- Begge lokasjoner gir en tynn ansamling (<5m) med dagens modell. Det er ikke forventet at det vil være forskjell i egnetheten for monitorering for lokasjonene.

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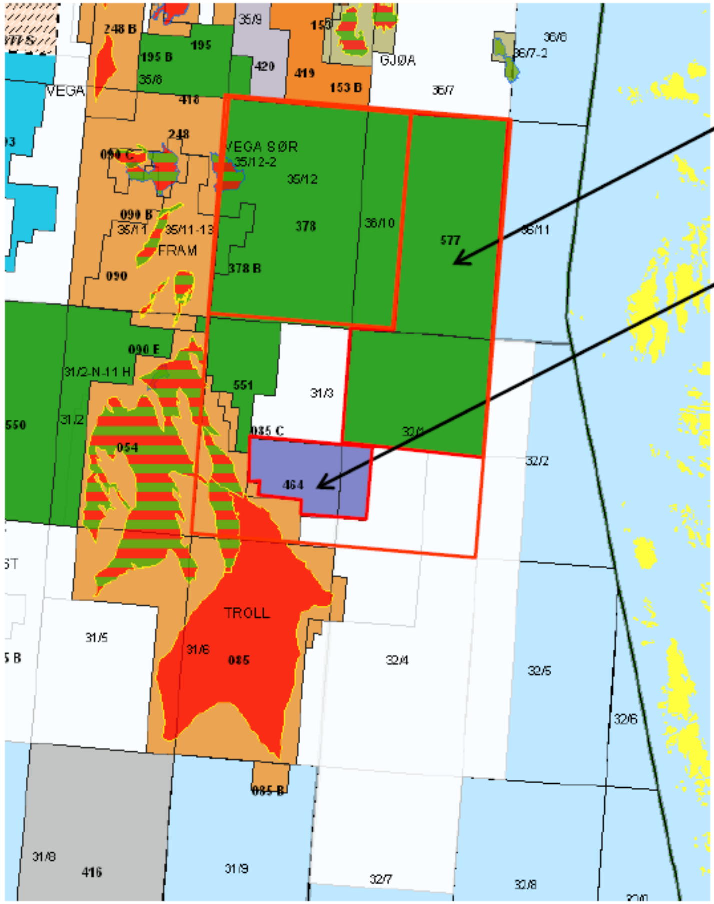
Troll kystnær – lisens status



NPD Faktakart

Ny lisens TFO2010 **PL577**
Wintershall operatør

TILBAKELEVERT

- Prospektivitet for PL577 i Kritt
- Forventet mindre fremtidig aktivitet sydover i området ?

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Anbefaling

- Sydlig lokasjon anbefales
- Anbefales at seismikk samles inn med de 2 utforskningsbrønner som tie-in punkter
- For bedre dekning syd for injeksjonspunkt 3 anbefales økning av areal til 500 km^2 og tilpasning av polygon
  - Sekundært nytt polygon for 340 km^2
- Nordlig lokasjon også egnet som injeksjonspunkt

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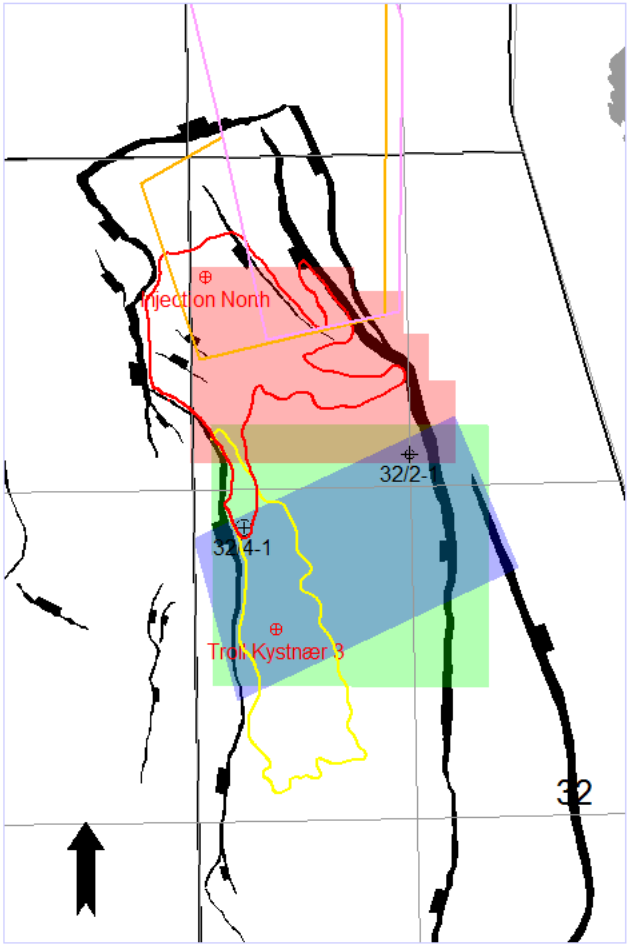
Troll kystnær – foreslåtte 3D områder



Wintershall

Wintershall

GN1101 323 km²

GN1101 500 km²

GN1101 347 km²

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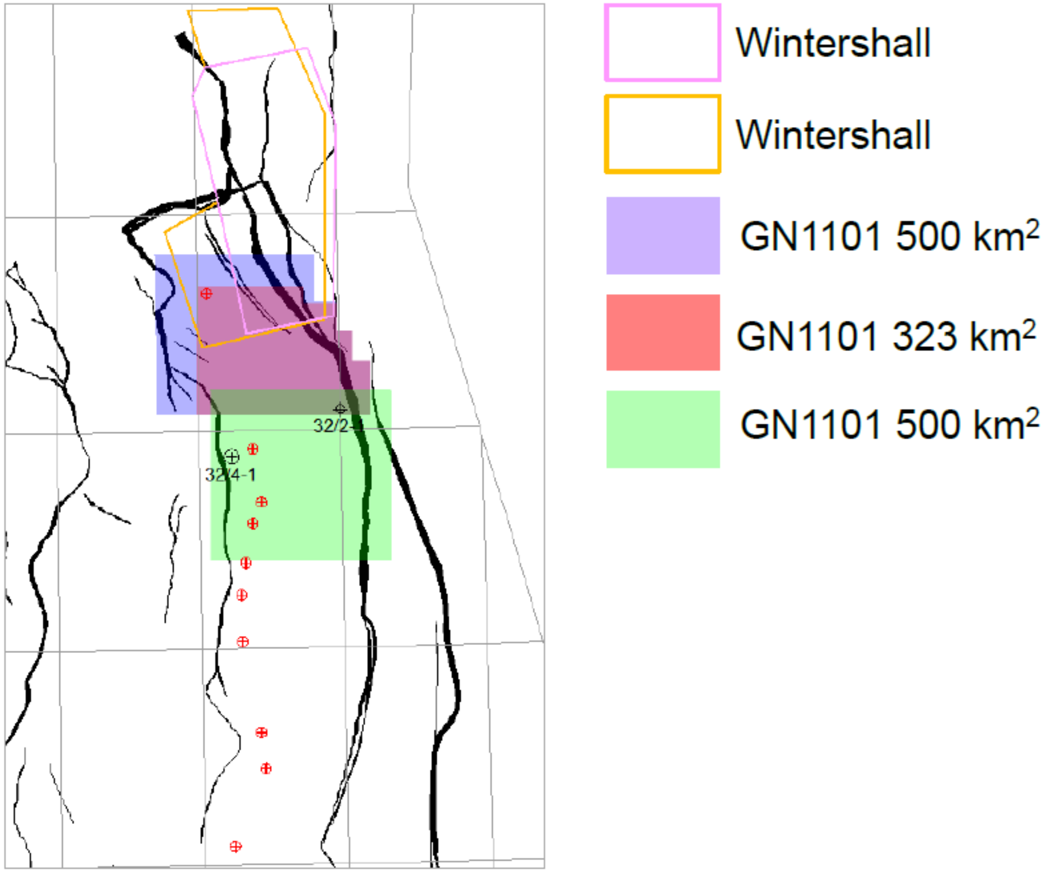
Troll kystnær – foreslåtte 3D områder



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31/2 -4 Well integrity evaluation

Summary Well barrier evaluation

Well:	32/4-1 T2
Air Gap:	23,5 m
Water Depth:	312 m
Operator:	Phillips

Well Drawing

RISK assessment

Barrier description

HISTORY:

Exploration well 32/4-1 was the first well drilled in Production License 205 which is located on the Horda Platform, Northern North Sea. The primary objective of the well was to prove commercial reserves within the Upper Jurassic Sognefjord Formation sand reservoirs. The well is positioned about five kilometres east of the East Troll Gas Field.

Well 32/4-1 was spudded 21 October 1996. using the semisubmersible drilling rig TransoceanNo.8. The Upper Jurassic reservoir interval was encountered 6 m shallower than prognosed andcontained 65.5 m of water-wet Sognefjord sandstones. No traces of hydrocarbons were detected in the well.

CONCLUSION:

Well 32/4-1 was not plugged in a satisfactory way:
- No cement in open hole.
- Mechanical plug in 9 5/8" casing.
- Only one cement plug in 13 3/8" casing - shallow. Ref attached drawing.

This abandonment design results in the following risk picture related to nearby CO2 injection:
1. All formations from Heather to basement are exposed. X-flow possible.
2. At best there is only one barrier in the well that might be qualified.

RECOMMENDED ACTIONS:

- It is recommended to attempt to move the injection point in Troll Kystnær to avoid this well.
- Alternatively one could attemt to re-enter the well to establish new barriers. This is not straightforward and a possible project killer (Part of long term qualification plan)
- Contact Phillips and get more information on the well (Detailed Drilling reports, FWR from BJ and Mudlogging company, LOT records etc.

Well Information

[Summary page](#)
[LINK to FWR](#)

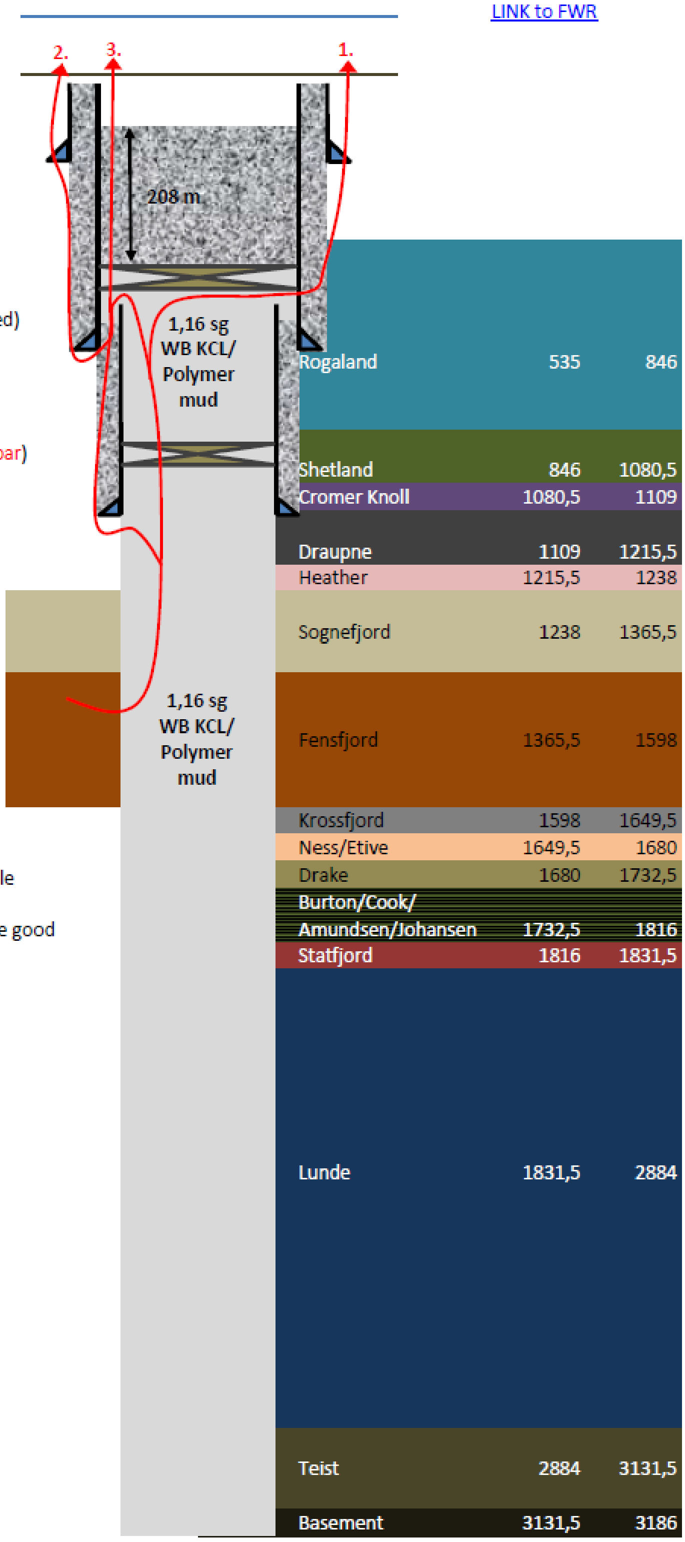
Well: 32/4-1 T2
Air Gap: 23,5 m
Water Depth: 312 m

Mudline: 335,5 m RKB
30" casing top /20" casing top: Cut @ 338 m RKB
Top cement plug: 375 m RKB
30" casing shoe: 394 m RKB

13 3/8" Plug/bottom cement plug: 583 m RKB
9 5/8" casing cut: 622 m RKB
Top cement in 9 5/8" x 13 3/8" annulus: 706 m RKB (Log confirmed)
13 3/8" casing shoe: 709 m RKB
LOT @ 720 m RKB - 1,61 sg EMW

9 5/8" plug: 1069 m RKB (pressure tested to 130 bar)

9 5/8" casing shoe: 1137,5 m RKB
LOT @ 1156 m RKB - 1,61 sg EMW



Barrier evaluation:
The most critical leak path is number 1.
9 5/8" plug - corrodes (Carbon steel and elastomer)
13 3/8" casing (583 - 706m) - corrodes
This leaves the cement and formation as the only real barrier to surface.

Barrier assumptions:
- Formation (@ 583m) must be strong enough to handle maximum pressure build up during the injection.
- The cement job on the outside of the 13 3/8" must be good (no log)
- Corrosion of the cement will not be severe (ordinary G-cement used)

CO2 leakage Risk Identification

Well: 32/4-1 T2

Key Words:

Well Drawing

Summary page

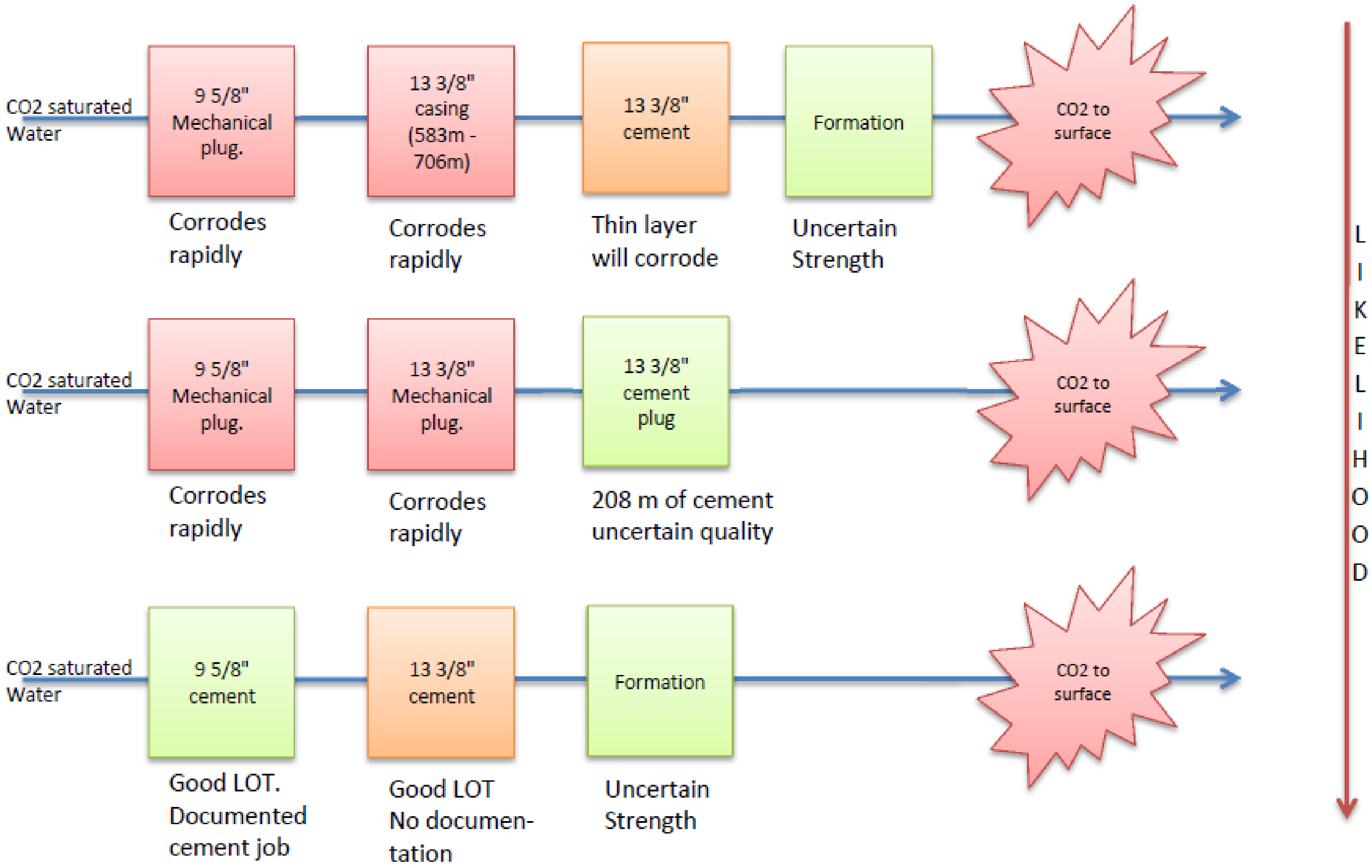
Well element	Risk source	Well Info	Indicators of sufficient well integrity under exposure to CO2	Indicators of insufficient well integrity under exposure to CO2	Probability (likelihood classes) *CIP – CO2 Injection Period	Impact on Well integrity	Comments
9 5/8" "Pengo" Cement retainer mechanical plug	Corrosion of plug.	Unable to find detailed information about plug. Normally these are made of carbeon steel with movable parts inside to enable a stinger to penetrate plug for cementing operations. This flapper function might have been plugged prior to running it. Pressure tested to 130 bar.		Carbon steel and CO2 will lead to corrosion over time. No cement above or below.	P5 Fail is ex. to occur dur. CIP* x 0,5	I3	
9 5/8" casing cement	Cement bond with formations above shoe.	The hole was circulated for 20 min., pumping 1700 l/min, before the cementing. I5 m3 of spacer was pumped followed by 14m3 with 1.9 sg cement. The cement volume calculations were based on top of cement 300 m above the shoe and with 30% excess over open hole volume. The cement was displaccd with mud and the plug bumped after 30308 liters, as calculated. No losses were observed during the cementing operation and calculated cop of cement, based on pressure increase during the cementing operation, was around 700 m. Top cement confimed by log to be 706m.	Generally G class cement is compatible with all formations encountered. One centralizer pr joint bottom 300m.		P2 Fail is ex. to occur dur. CIP* x 3	I2	
9 5/8" casing	Casing (casing body) condition under exposure to CO2	Carbon steel, N80		In the event that the casing is exposed to a corrosive CO2 environment the carbon steel is expected to corrode rapidly.	P5 Fail is ex. to occur dur. CIP* x 0,5	I3	

	Casing (casing connections) condition under exposure to CO_2	Carbon steel, N80 Buttress connections		In the event that the casing is exposed to a corrosive CO_2 environment the carbon steel is expected to corrode rapidly.	P5 Fail is ex. to occur dur. CIP* x 0,5	I3	
13 3/8" Cement retainer mechanical plug	Corrosion of plug.	Unable to find detailed information about plug. Normally these are made of carbeon steel with movable parts inside to enable a stinger to penetrate plug for cementing operations. This flapper function might have been plugged prior to running it. No pressure test.	Plug only set as a foundation for the cement plug above	Carbon steel and CO_2 will lead to corrosion over time. No cement above or below.	P5 Fail is ex. to occur dur. CIP* x 0,5	I1	
13 3/8" casing	Casing (casing body) condition under exposure to CO_2	Carbon steel, D95HC		In the event that the casing is exposed to a corrosive CO_2 environment the carbon steel is expected to corrode rapidly.	P5 Fail is ex. to occur dur. CIP* x 0,5	I3	
	Casing (casing connections) condition under exposure to CO_2	Carbon steel, D95 HC Antares connections		In the event that the casing is exposed to a corrosive CO_2 environment the carbon steel is expected to corrode rapidly.	P5 Fail is ex. to occur dur. CIP* x 0,5	I3	
13 3/8" casing cement	Cement bond with formations above shoe.	The 13 3/8" x 20" casing was run and landed with the shoe at 709 m. A total of 30 joints of 13 3/8" casing were run. The casing volume (37 m3) was circulated at a rate of 1000 l/min before the casing was cemented. A total of 64.8 m of 1.9 g/cc cement was pumped (100% excess over open hole volume). The cement was displaced with seawater and the plug bumped at calculated volume. No log run.	Generally G class cement is compatible with all formations encountered. One centralizer pr joint bottom 300m.		P2 Fail is ex. to occur dur. CIP* x 3	I2	

	Channeling	Mud and cement weights were greater than pore pressures at all times.	Channelling unlikely because influx from formations was inhibited by pressure gradient during cementing operation. Good LOT below 13 3/8" shoe indicates good cement job. Probably competent shale sections above shoe.		P2 Fail is ex. to occur dur. CIP* x 3	I2	
The top cement plug	Verification of surface plug	208m of cement placed on top of mechanical plug. No report of tagging the plug after displacement.	Mechanical plug used as a base. Reported that excess cement was circulated out. Job went according to plan.	No verification of plug.	P2 Fail is ex. to occur dur. CIP* x 3	I3	
Formation outside 13 3/8" casing	Reservoir pressure transferred to shallow formation	The mechanical plug is positioned at 583m. At this depth it is uncertain what the formation strength is on the outside of the 13 3/8" casing. It is only 248m to seabed and 48m to top Rogaland. It is reported that the 13 3/8" shoe LOT was 1,61 sg. This is high at this shallow depth. No details available for the LOT operation.	High LOT at shoe.	Shallow formation. If leakage through 13 3/8" and cement the formation will be exposed to the reservoir pressure minus the fluid gradient in the well. It is difficult to say what this gradient will be.	P3 Fail is ex. to occur dur. CIP* x 2	I4	Need to calculate worst case fluid gradient in well with maximum reservoir pressure.

Well Barrier Description

Well: 32/4-1 T2 Summary page



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		HSE & Reputation	Health, Safety, Environment & Reputation - subcategories					Increasing probability				
			People's health and safety	Environment (volume of pollution – not clean brine or CO2)	Environment (time to restoration for damage caused by clean brine / CO2)	Net GHG emissions benefit	Economic – disruption to CGS operations	Failure is not expected to occur during CIP* x 3	Failure is expected to occur during CIP* x 3	Failure is expected to occur during CIP* x 2	Failure is expected to occur during CIP* x 1	Failure is expected to occur during CIP* x 0,5
								P1	P2	P3	P4	P5
Increasing impact	I5	Catastrophic	Potential for several fatalities	> 100 ton	> 10 years	No benefit remains	Outage > 1 year					
	I4	Serious	Potential for fatalities.	> 10 ton	> 1 year	Net benefit reduced by > 50%	Outage > 1 month					
	I3	Significant	Potential for serious injury	> 1 ton	> 1 month	Net benefit reduced by > 10%	Outage > 1 week					
	I2	Low	Potential for minor injury	< 1 ton	< 1 month	Net benefit reduced by < 10%	Outage < 1 week					
	I1	Insignificant	No injury	No pollution	No damage	No affect	No effect within a defined period					

Time, depth and thickness maps of key horizons:

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- Seabed depth map
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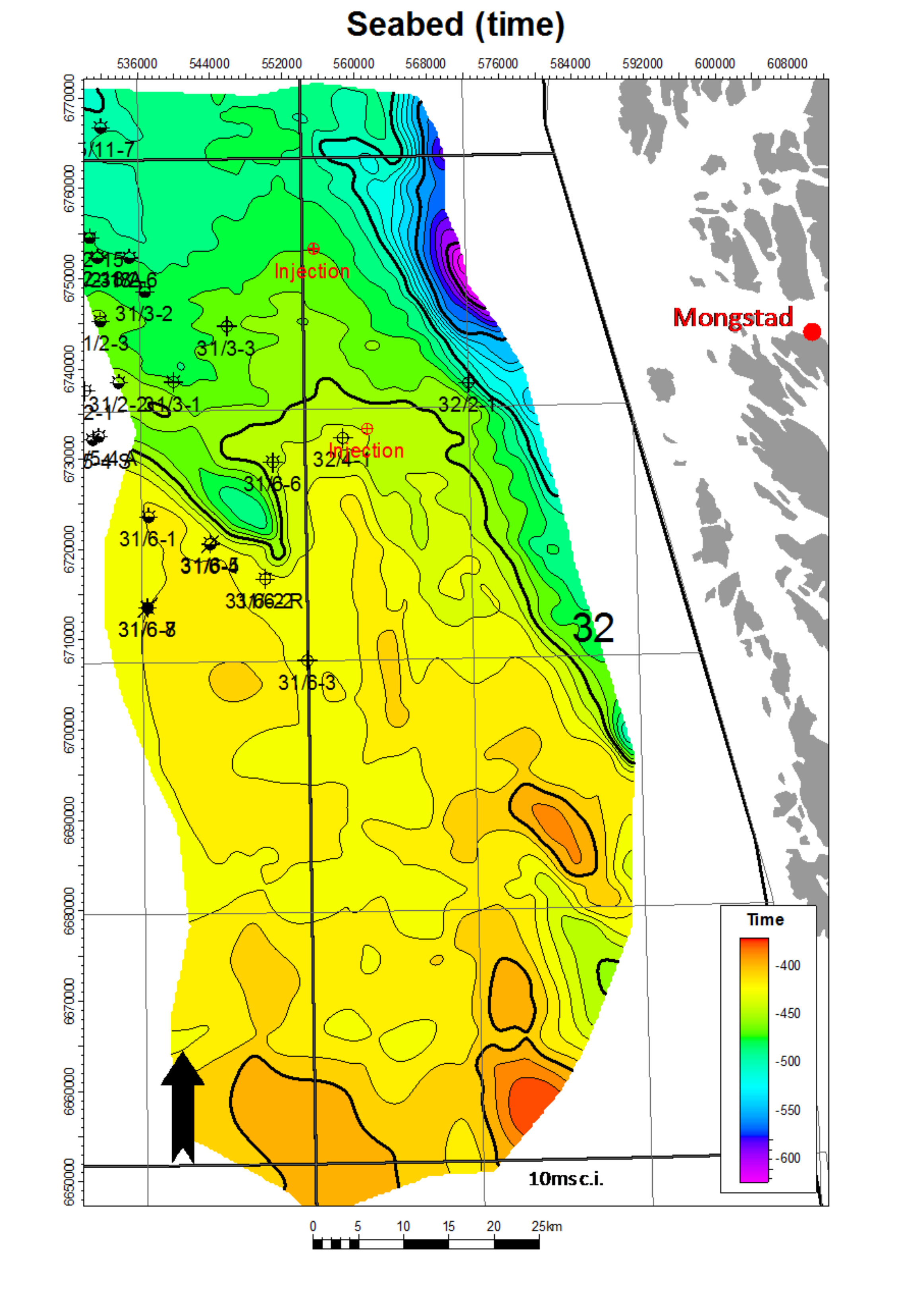
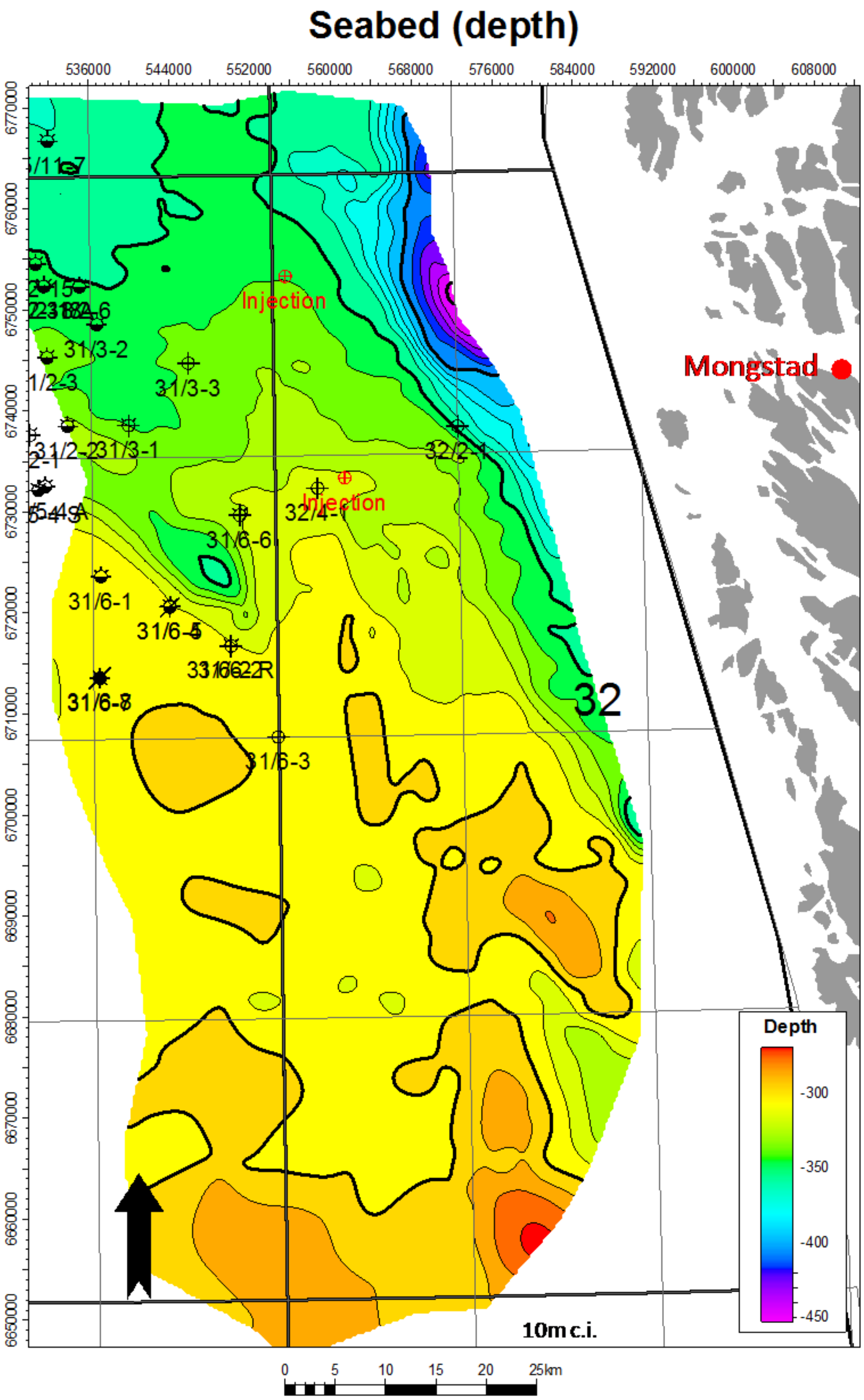
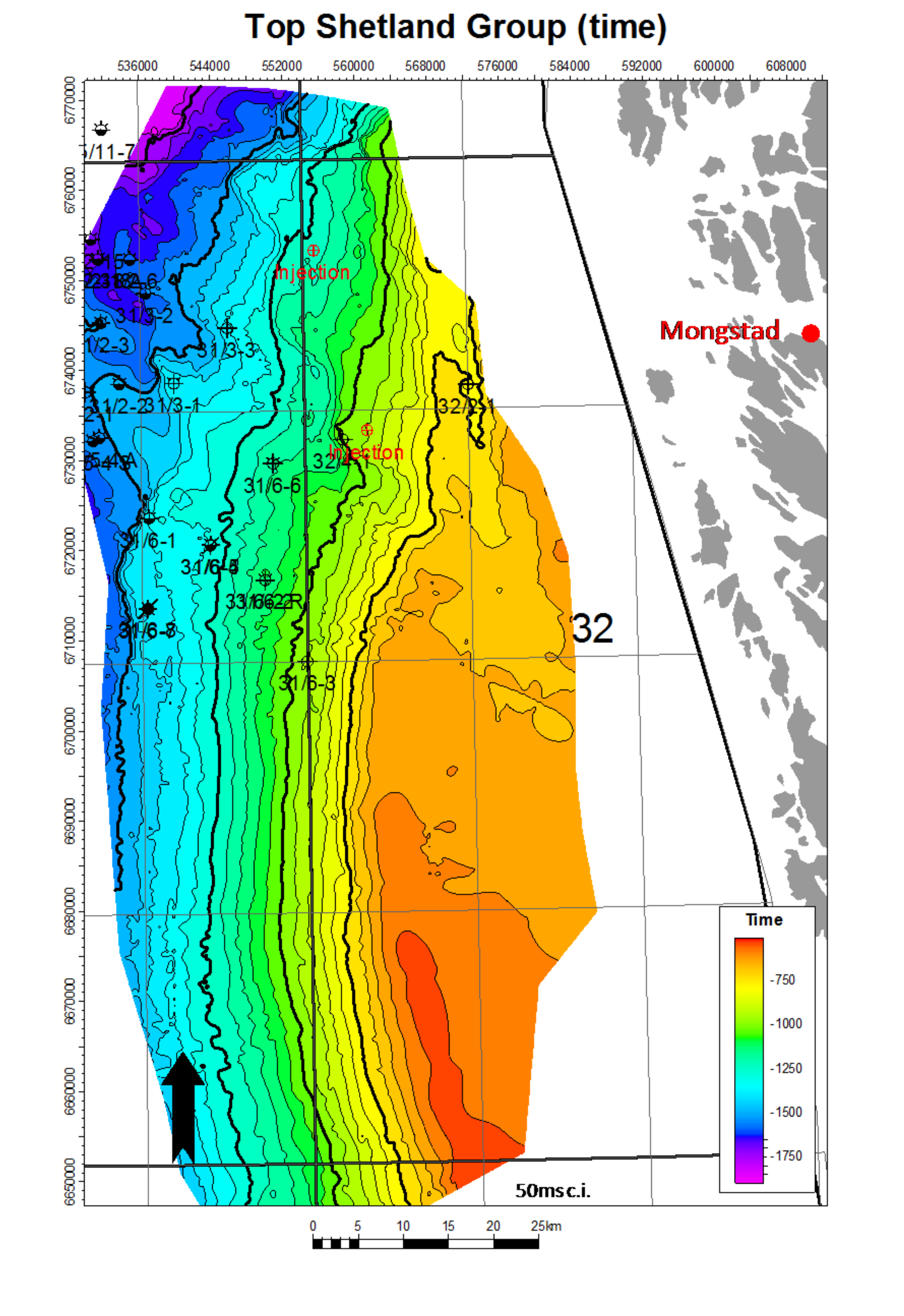
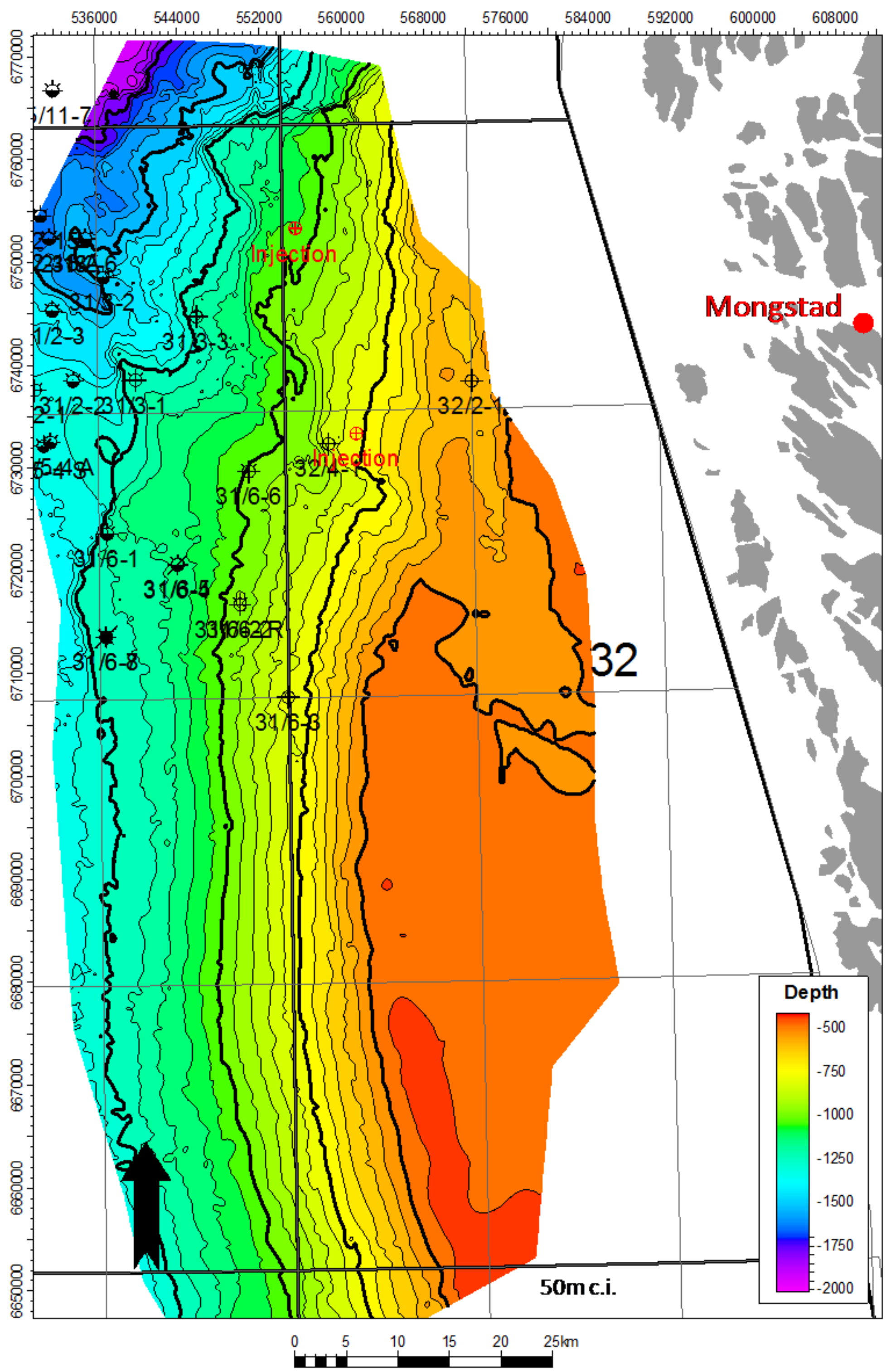
- Top Draupne Formation time map
- Top Draupne Formation depth map
- Draupne Formation thickness (m) map
- Top Sognefjord Formation time map
- Top Sognefjord Formation depth map
- Top Fensfjord Formation time map
- Top Fensfjord Formation depth map
- Sognefjord/Fensfjord formations thickness (m) map
- Top Brent Group time map
- Top Brent Group depth map
- Top Johansen Formation time map
- Top Johansen Formation depth map
- Top Statfjord Formation time map
- Top Statfjord Formation depth map

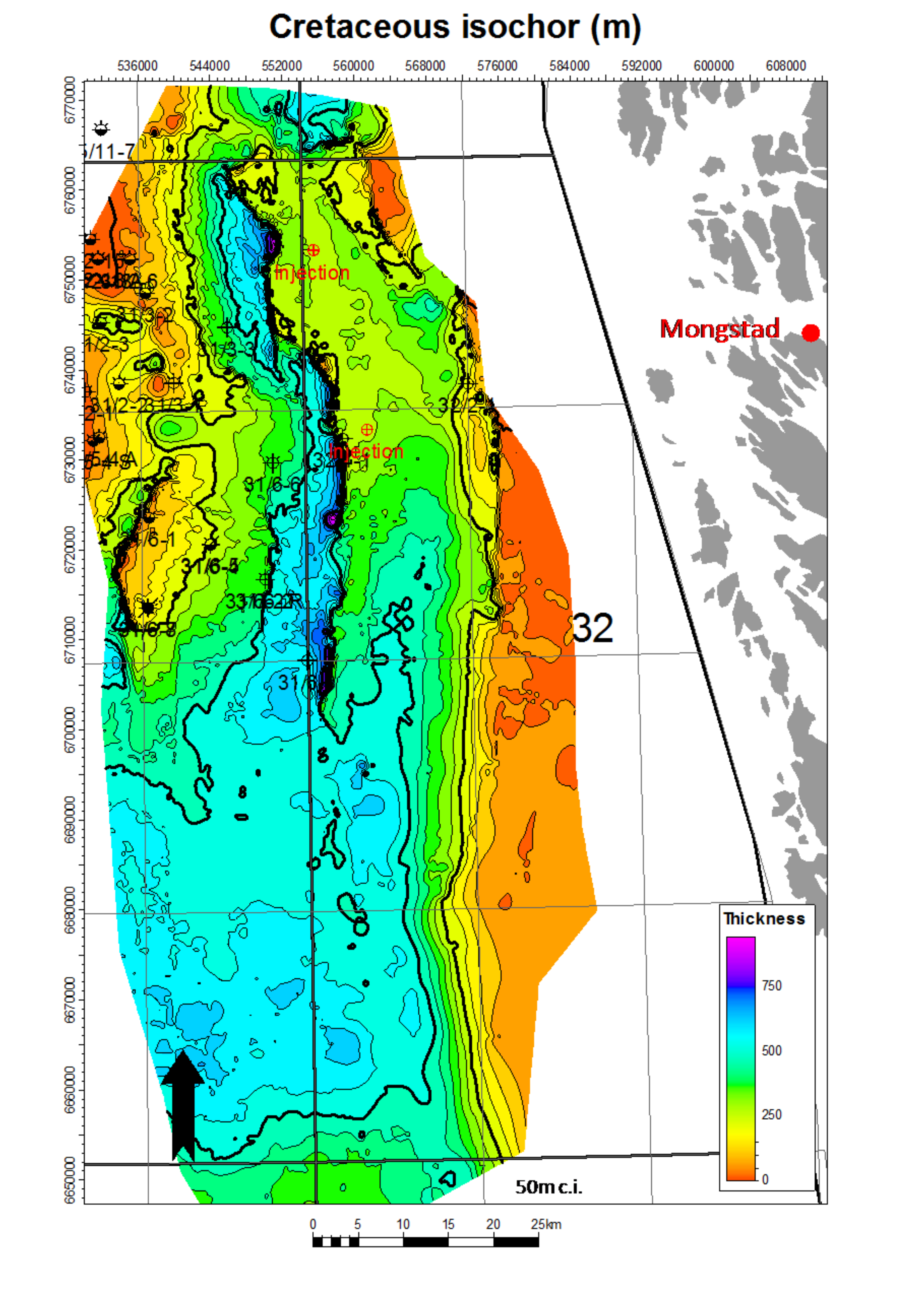

Seabed (time)
536000
544000
552000
560000
568000
576000
584000
592000
600000
608000
6770000
6760000
6750000
6740000
6730000
6720000
6710000
6700000
6690000
6680000
6670000
6660000
6650000
Injection
Injection
Mongstad
31/3-2
31/3-3
32/2-1
31/6-6
31/6-1
31/6-3
32
Time
-400
-450
-500
-550
-600
10ms c.i.
0
5
10
15
20
25km

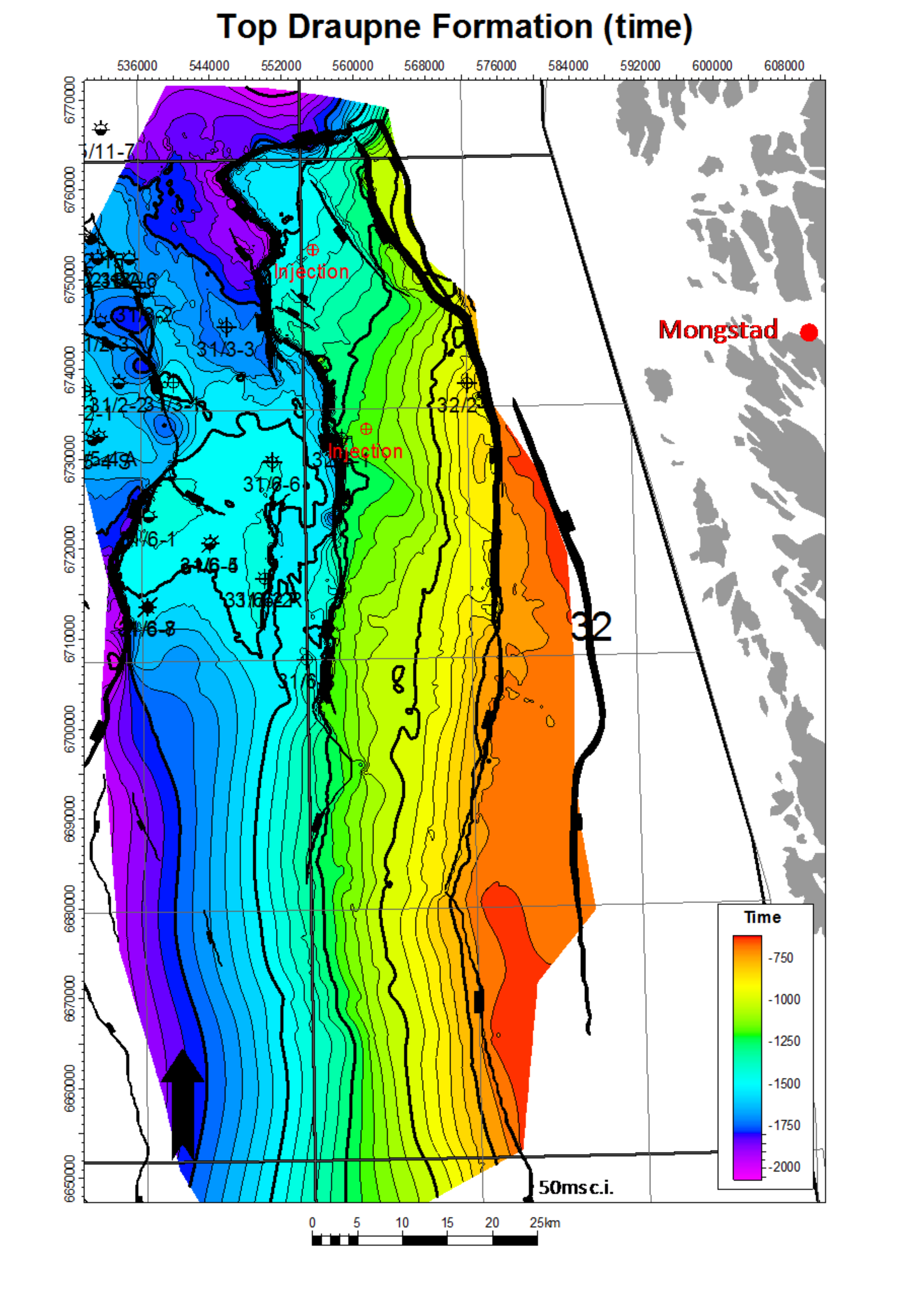

Seabed (depth)
536000
544000
552000
560000
568000
576000
584000
592000
600000
608000
6770000
6760000
6750000
6740000
6730000
6720000
6710000
6700000
6690000
6680000
6670000
6660000
6650000
Injection
Injection
Mongstad
31/3-2
31/3-3
31/3-1
32/2-1
32/4-1
31/6-6
31/6-1
31/6-5
31/6-3
32
10m c.i.
0
5
10
15
20
25km
Depth
-300
-350
-400
-450

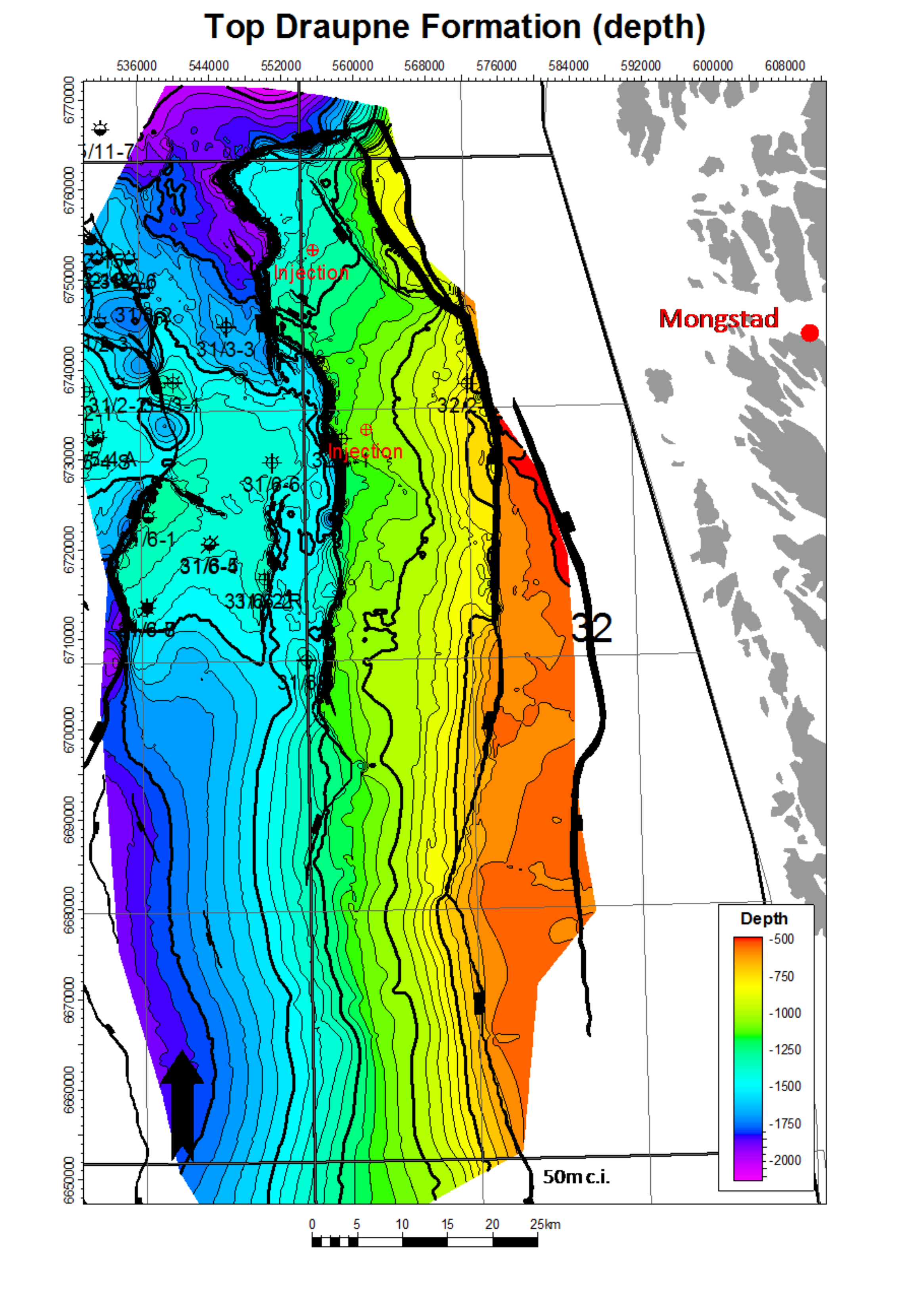

Top Shetland Group (time)
Injection
Injection
Mongstad
32
Time
-750
-1000
-1250
-1500
-1750
50msc.i.
0 5 10 15 20 25km

Top Shetland Group (depth)

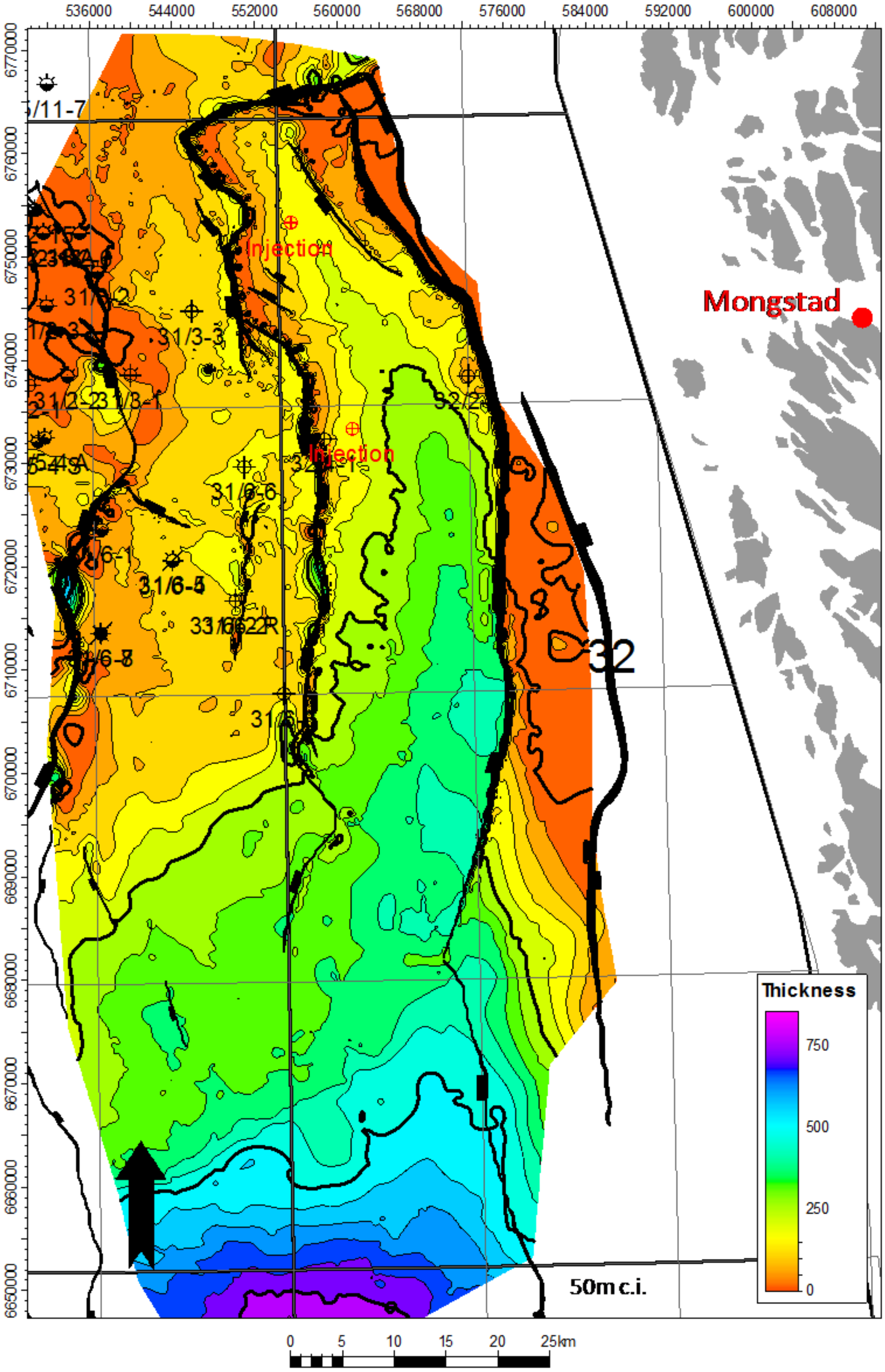


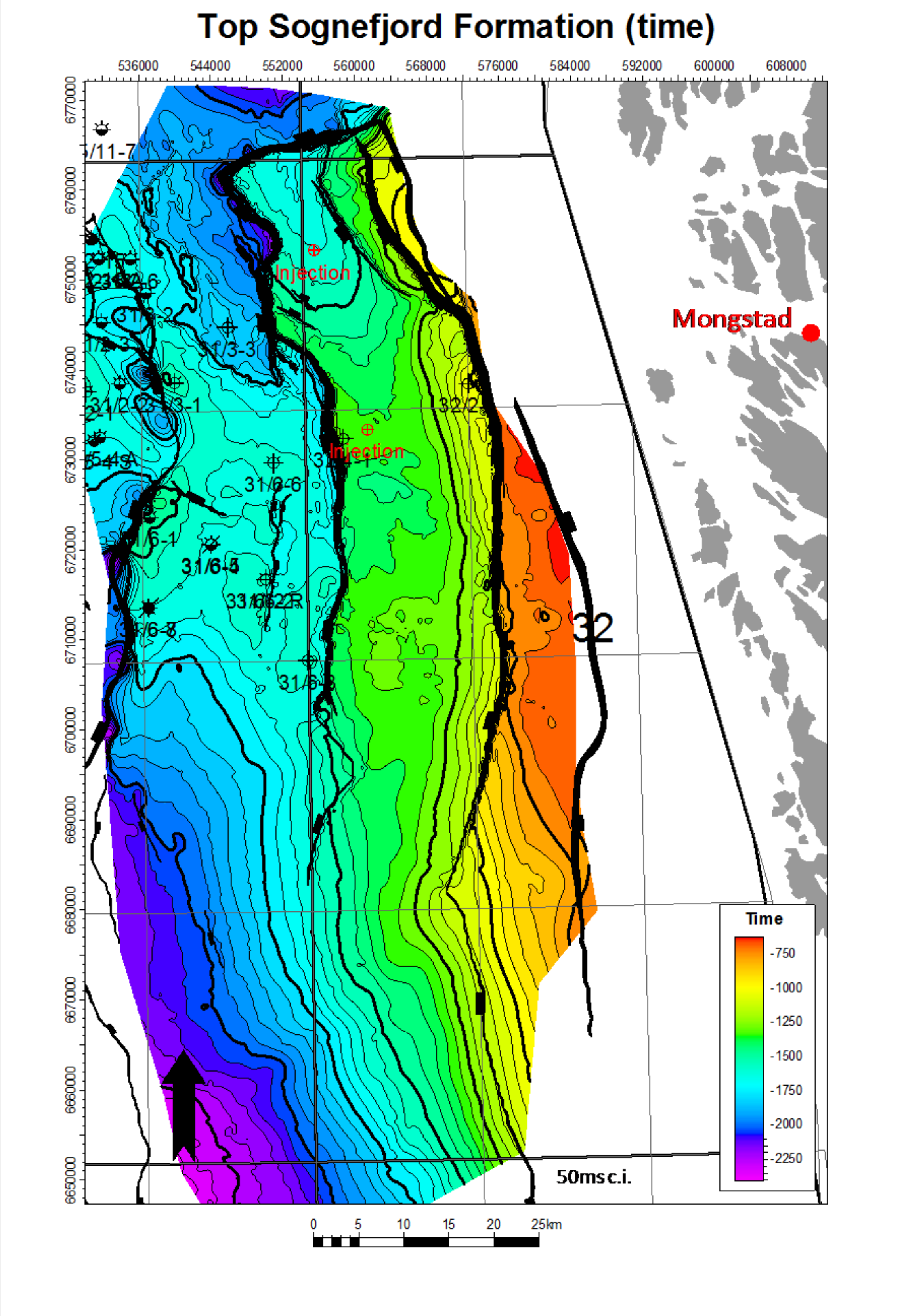

Cretaceous isochor (m)
536000
544000
552000
560000
568000
576000
584000
592000
600000
608000
6770000
6760000
6750000
6740000
6730000
6720000
6710000
6700000
6690000
6680000
6670000
6660000
6650000
Injection
Injection
Mongstad
32
Thickness
750
500
250
0
50m c.i.
0
5
10
15
20
25km

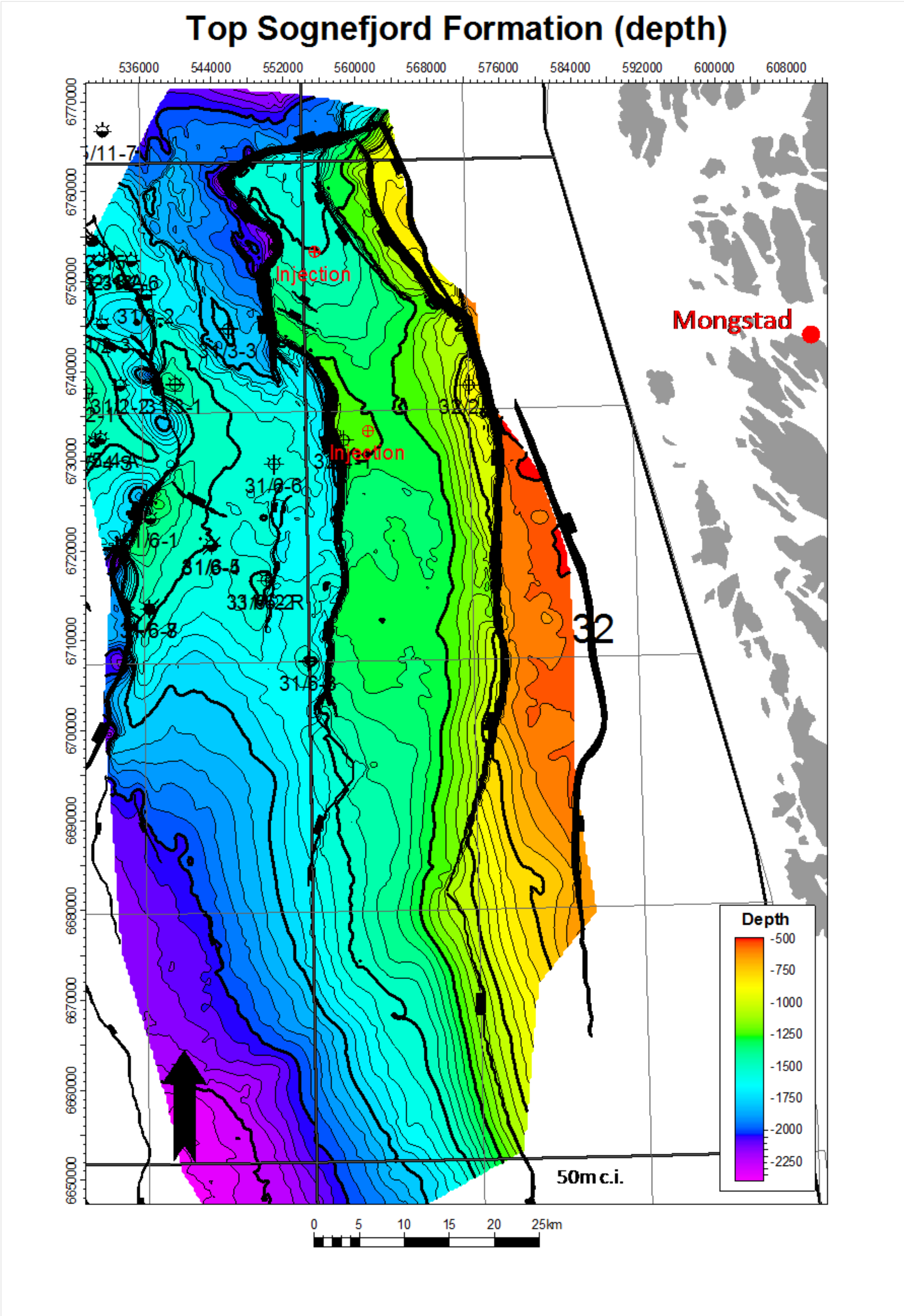

Top Draupne Formation (time)
536000
544000
552000
560000
568000
576000
584000
592000
600000
608000
6770000
6760000
6750000
6740000
6730000
6720000
6710000
6700000
6690000
6680000
6670000
6660000
6650000
Injection
Injection
Mongstad
31/3-3
31/6-6
32/2
32
Time
-750
-1000
-1250
-1500
-1750
-2000
50ms c.i.
0
5
10
15
20
25km

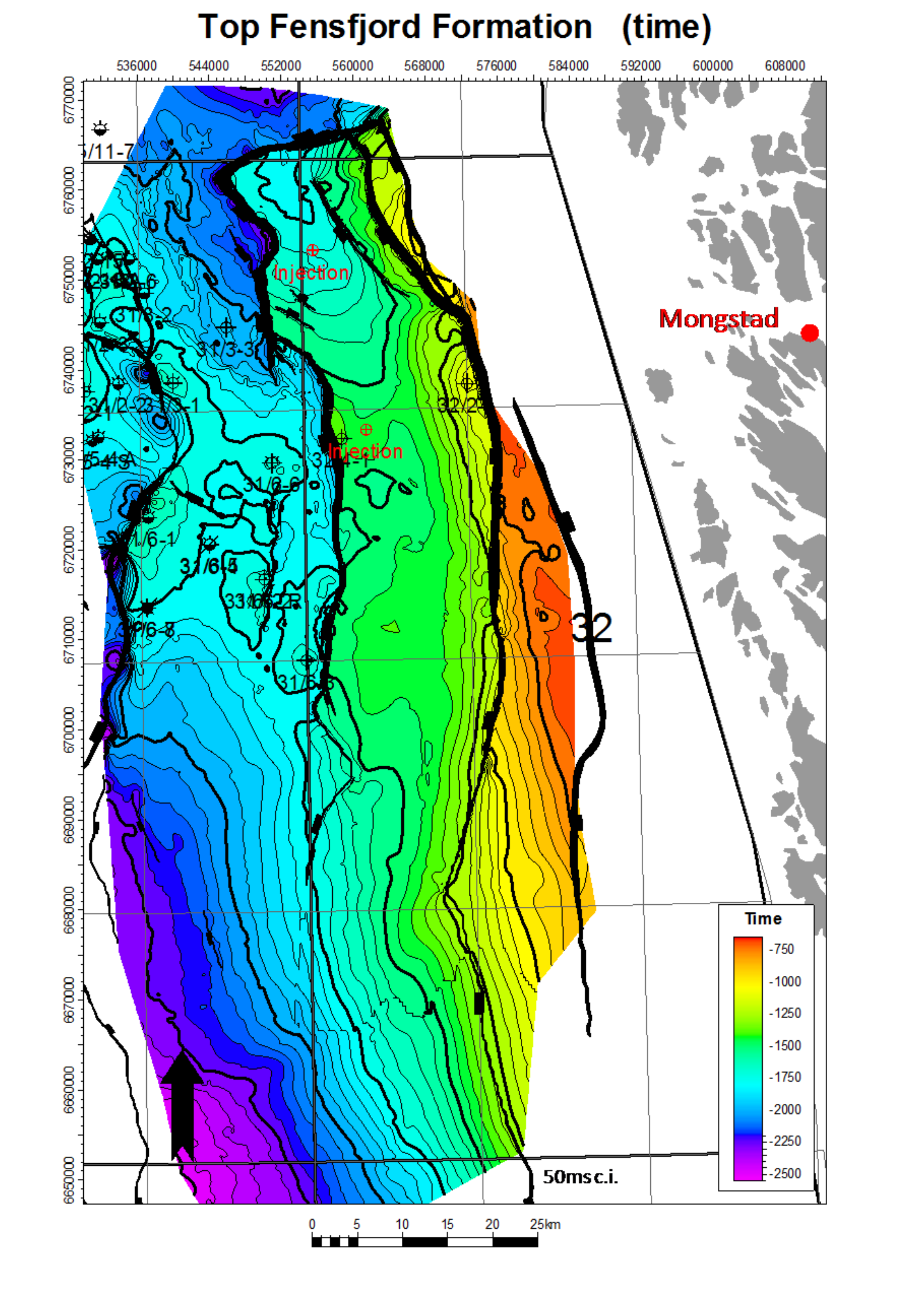

Top Draupne Formation (depth)
536000
544000
552000
560000
568000
576000
584000
592000
600000
608000
6770000
6760000
6750000
6740000
6730000
6720000
6710000
6700000
6690000
6680000
6670000
6660000
6650000
Injection
Injection
Mongstad
31/3-3
31/6-6
31/6-5
32
Depth
-500
-750
-1000
-1250
-1500
-1750
-2000
50m c.i.
0
5
10
15
20
25km

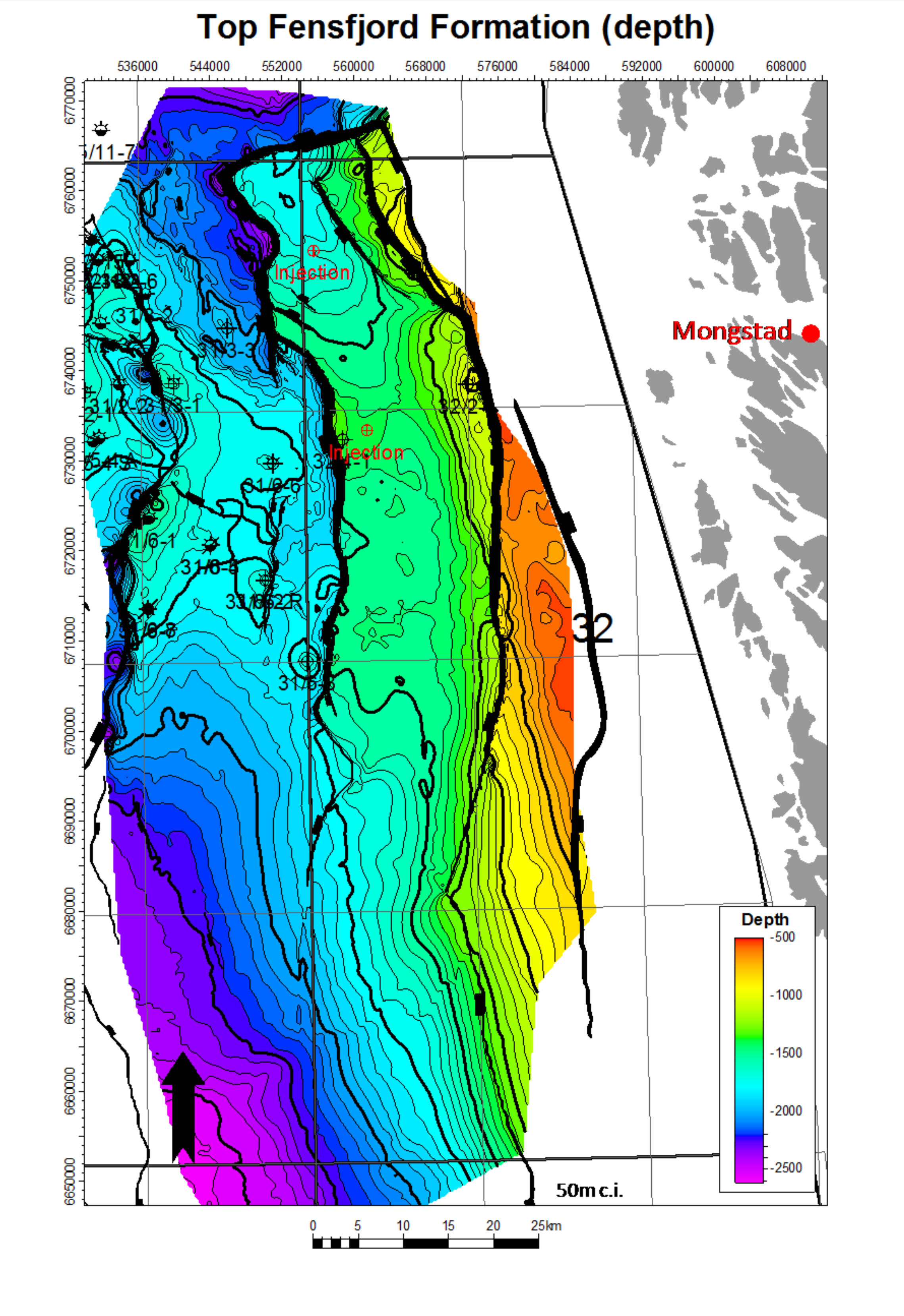
Draupne Formation isochor (m)

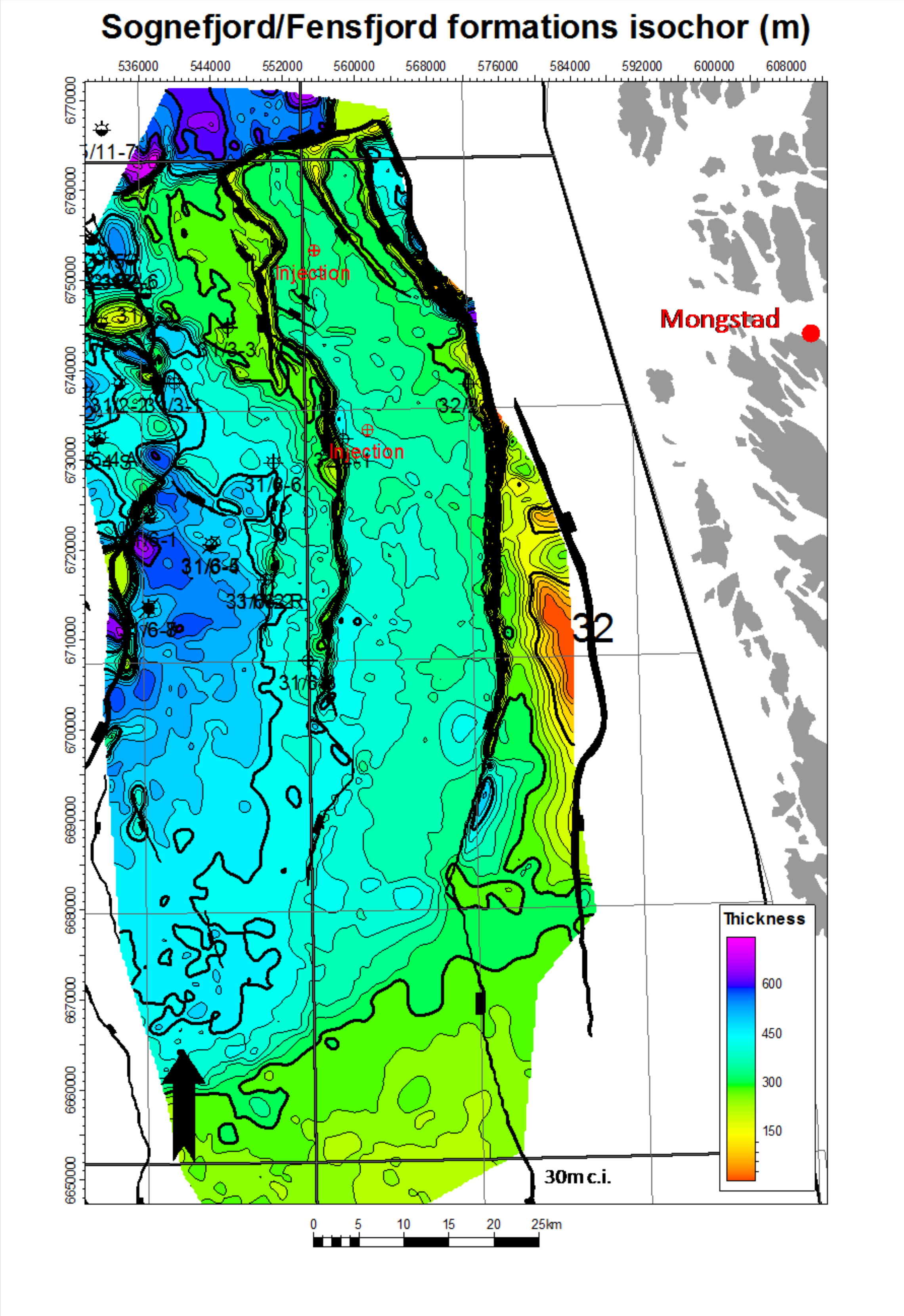


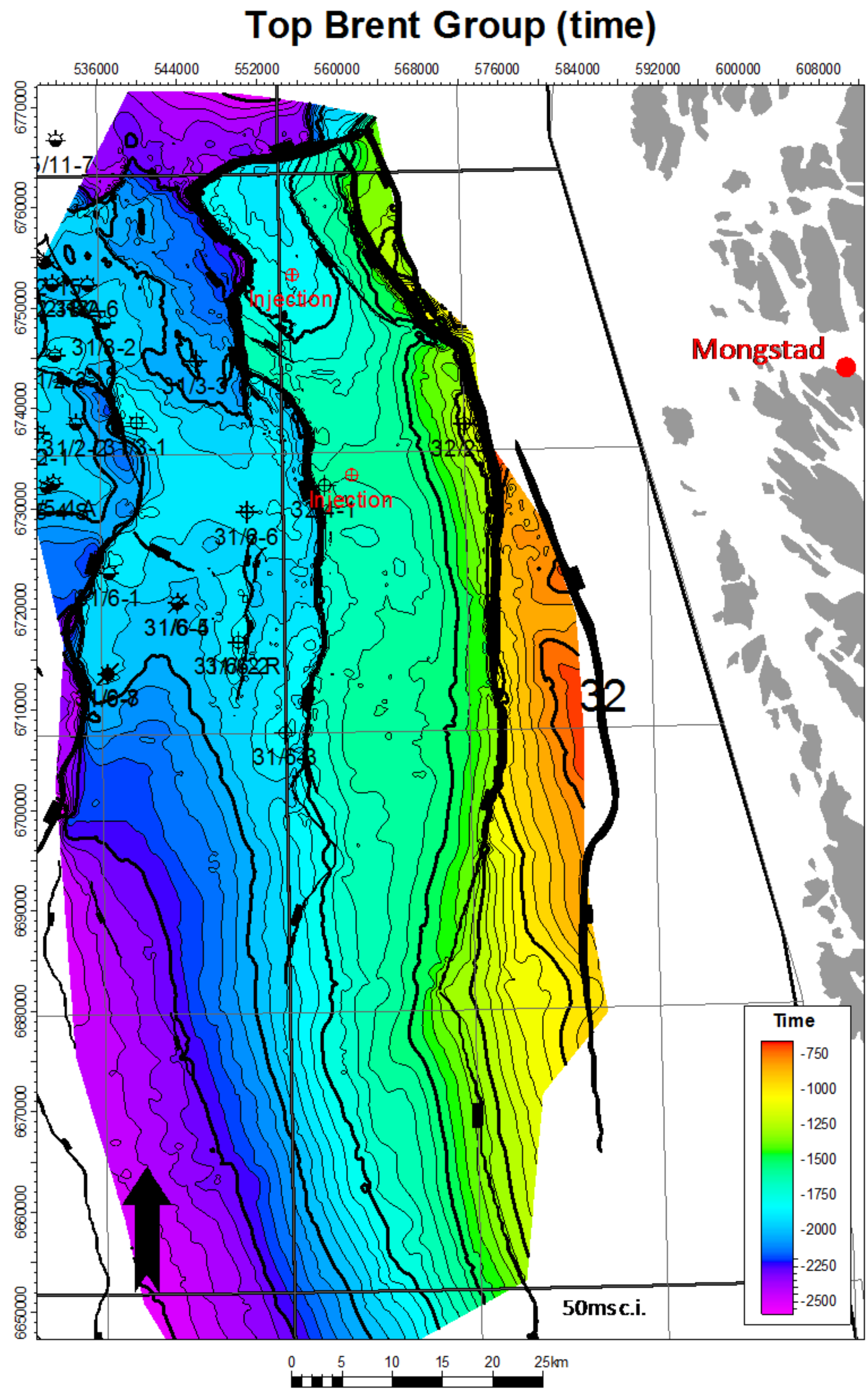

Top Sognefjord Formation (time)
536000
544000
552000
560000
568000
576000
584000
592000
600000
608000
Injection
Injection
Mongstad
32
Time
-750
-1000
-1250
-1500
-1750
-2000
-2250
50ms c.i.
0
5
10
15
20
25km

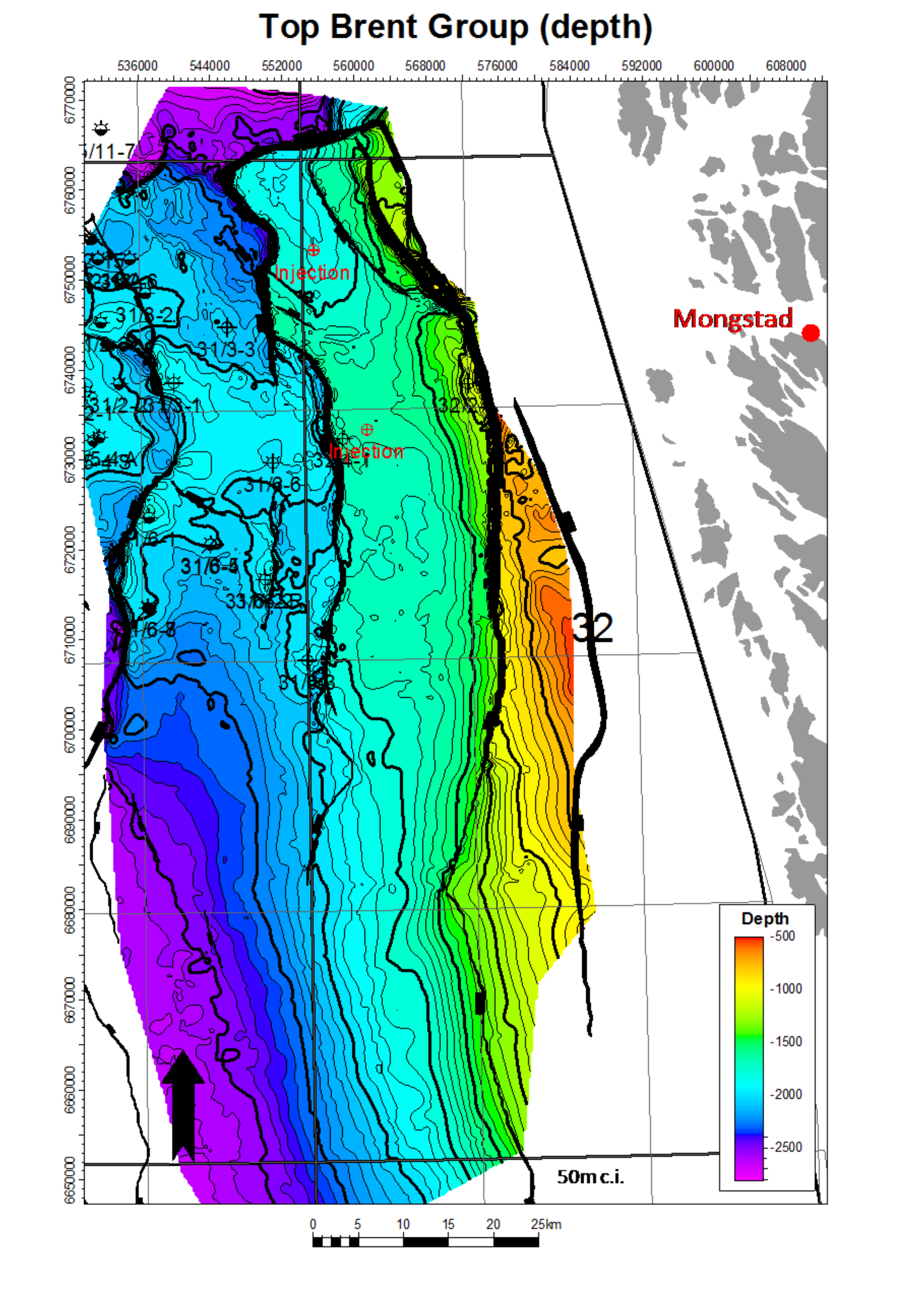

Top Sognefjord Formation (depth)
536000
544000
552000
560000
568000
576000
584000
592000
600000
608000
6770000
6760000
6750000
6740000
6730000
6720000
6710000
6700000
6690000
6680000
6670000
6660000
6650000
Injection
Injection
Mongstad
31/6-6
31/6-5
32
31/6-3
50m c.i.
Depth
-500
-750
-1000
-1250
-1500
-1750
-2000
-2250
0
5
10
15
20
25km

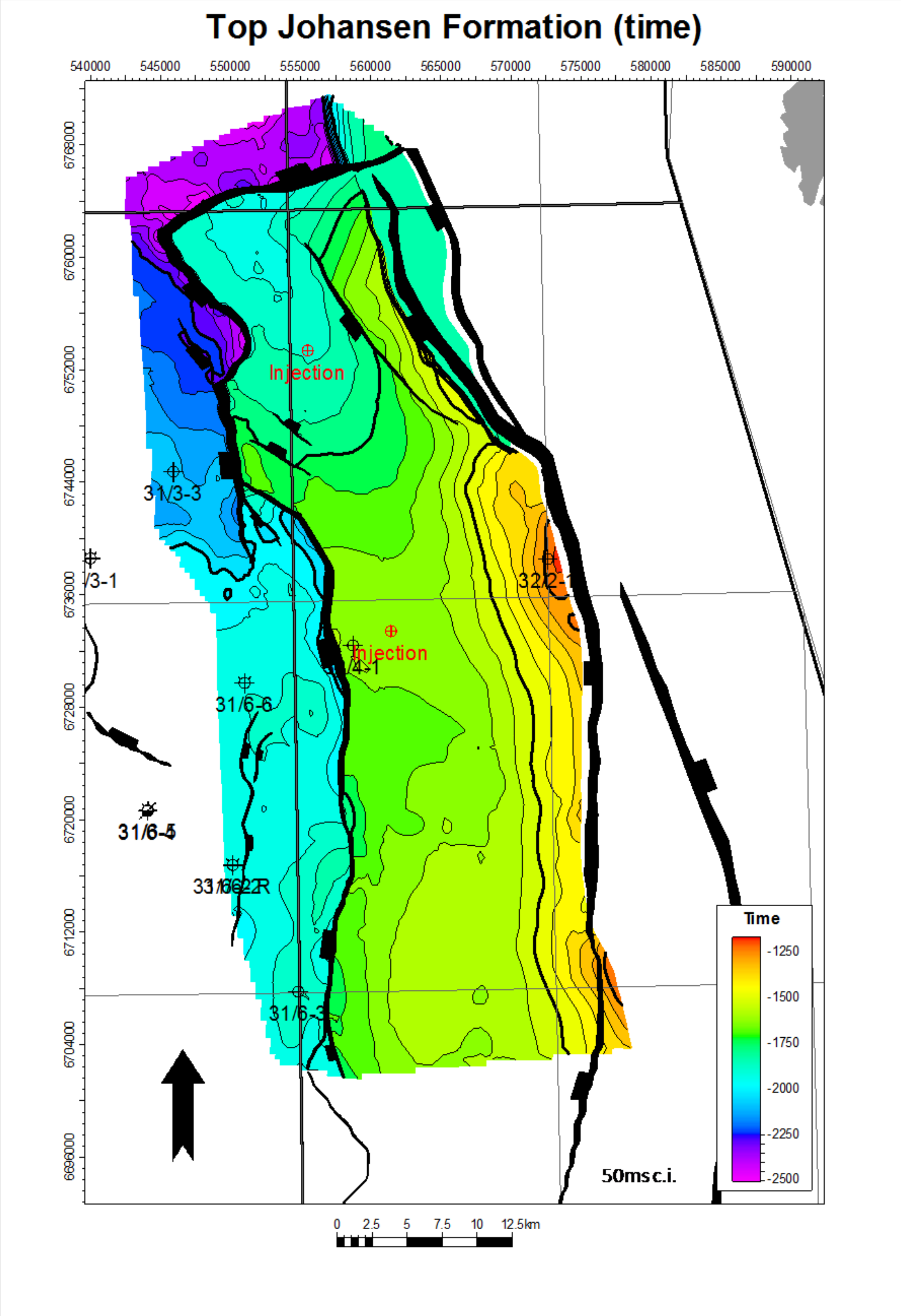

Top Fensfjord Formation (time)
536000
544000
552000
560000
568000
576000
584000
592000
600000
608000
6770000
6760000
6750000
6740000
6730000
6720000
6710000
6700000
6690000
6680000
6670000
6660000
6650000
Injection
Injection
Mongstad
31/3-3
31/6-6
31/6-1
31/6-5
32/2-1
32
Time
-750
-1000
-1250
-1500
-1750
-2000
-2250
-2500
50ms c.i.
0
5
10
15
20
25km

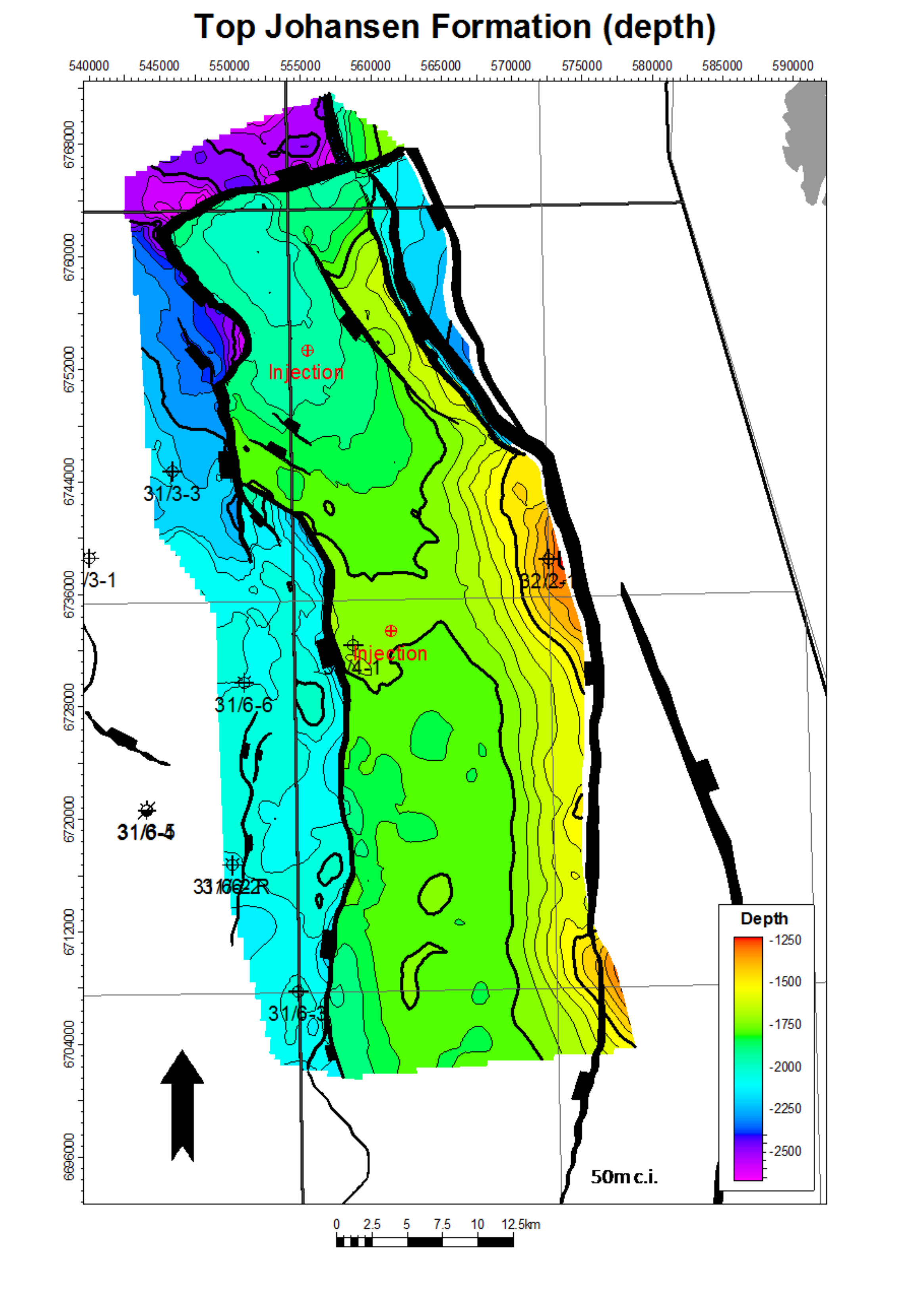

Top Fensfjord Formation (depth)
536000
544000
552000
560000
568000
576000
584000
592000
600000
608000
6770000
6760000
6750000
6740000
6730000
6720000
6710000
6700000
6690000
6680000
6670000
6660000
6650000
Injection
Injection
Mongstad
32
Depth
-500
-1000
-1500
-2000
-2500
50m c.i.
0
5
10
15
20
25km


Sognefjord/Fensfjord formations isochor (m)
536000
544000
552000
560000
568000
576000
584000
592000
600000
608000
6770000
6760000
6750000
6740000
6730000
6720000
6710000
6700000
6690000
6680000
6670000
6660000
6650000
Injection
Injection
Mongstad
32
Thickness
600
450
300
150
30m c.i.
0
5
10
15
20
25km

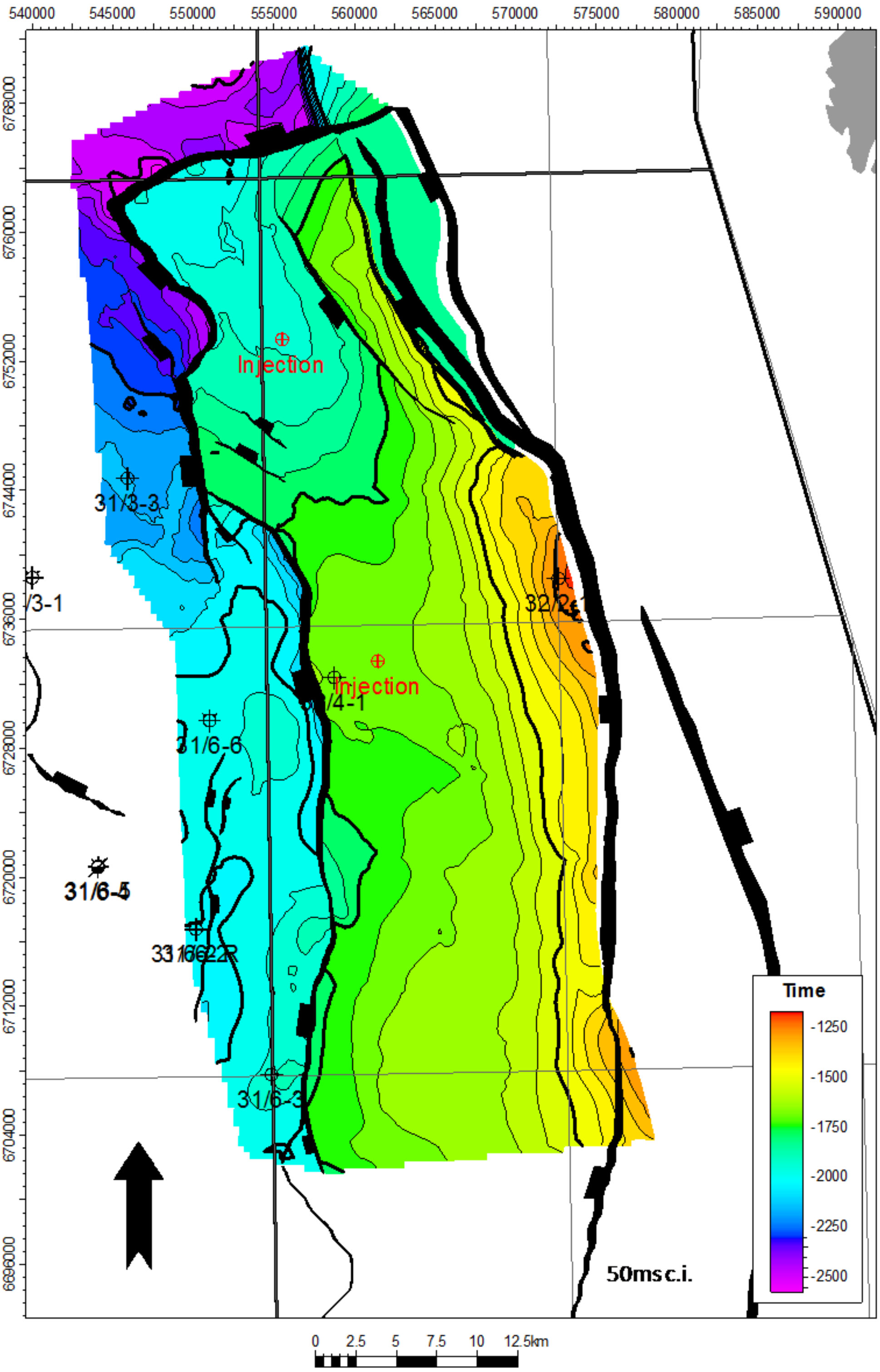

Top Brent Group (time)
536000
544000
552000
560000
568000
576000
584000
592000
600000
608000
6770000
6760000
6750000
6740000
6730000
6720000
6710000
6700000
6690000
6680000
6670000
6660000
6650000
Injection
Injection
Mongstad
31/3-2
31/3-3
31/6-6
31/6-5
31/6-2R
31/6-8
31/6-1
32
Time
-750
-1000
-1250
-1500
-1750
-2000
-2250
-2500
50ms c.i.
0
5
10
15
20
25km


Top Brent Group (depth)
536000
544000
552000
560000
568000
576000
584000
592000
600000
608000
6770000
6760000
6750000
6740000
6730000
6720000
6710000
6700000
6690000
6680000
6670000
6660000
6650000
Injection
Injection
Mongstad
31/3-3
31/6-6
31/6-5
32
Depth
-500
-1000
-1500
-2000
-2500
50m c.i.
0
5
10
15
20
25km


Top Johansen Formation (time)
540000
545000
550000
555000
560000
565000
570000
575000
580000
585000
590000
6768000
6760000
6752000
6744000
6736000
6728000
6720000
6712000
6704000
6696000
Injection
Injection
31/3-3
32/2-1
31/6-6
31/6-5
31/6-3
Time
-1250
-1500
-1750
-2000
-2250
-2500
50ms c.i.
0
2.5
5
7.5
10
12.5km


Top Johansen Formation (depth)
540000
545000
550000
555000
560000
565000
570000
575000
580000
585000
590000
6768000
6760000
6752000
6744000
6736000
6728000
6720000
6712000
6704000
6696000
Injection
Injection
31/3-3
/3-1
31/6-6
31/6-5
31/6-3
32/2-1
Depth
-1250
-1500
-1750
-2000
-2250
-2500
50m c.i.
0
2.5
5
7.5
10
12.5km

Top Statfjord Formation (time)



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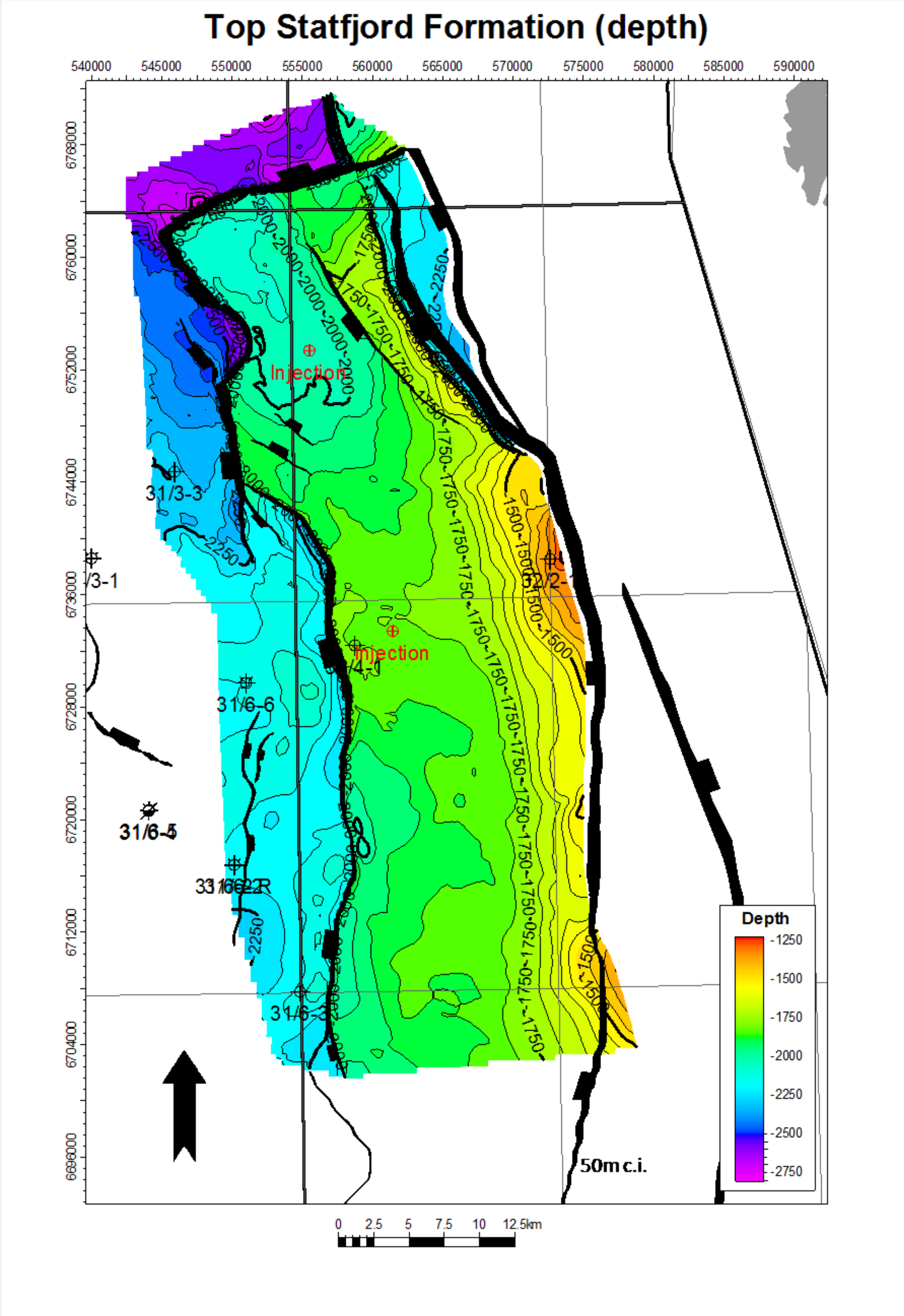
TL02-ROS-Z-RA-00005	03	04.05.2012	HH


Top Statfjord Formation (depth)
540000
545000
550000
555000
560000
565000
570000
575000
580000
585000
590000
6768000
6760000
6752000
6744000
6736000
6728000
6720000
6712000
6704000
6696000
Injection
Injection
31/3-3
31/6-6
31/6-5
31/6-2R
31/6-3
Depth
-1250
-1500
-1750
-2000
-2250
-2500
-2750
50m c.i.
0 2.5 5 7.5 10 12.5km