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Report on environmental risks associated to CO_2 storage at Sleipner

Deliverable number 5.1

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1. Main Executive Summary

As part of the ECO2 project, DNV GL has developed a Best Practice approach to Environmental Risk Assessment for offshore carbon dioxide (CO_2) storage sites. The methodology developed as part of the Best Practice is applied here to the Sleipner CO_2 storage site, in order to assess the environmental consequences of a potential leakage scenario. This document also illustrates the stages involved in the approach and the type of input data required. The assessment of consequence presented in this report is intended as input to environmental risk assessment (consequence x propensity to leak).

The first key step in the overall approach is the **Assessment of Ecologically or Biologically Significant Marine Areas for the Sleipner area.**

A transparent methodology is applied, which is based on mapping the valuable biological resources in a potential risk area. Parts of this methodology are applicable to many different impact scenarios which are at risk of causing effects to marine biota, not only to CO_2 leakage. The system that is described and applied here has its roots in a concept first initiated by the Convention on Biological Diversity (CBD COP9 Decision IX/20). A set of six so called EBSA (Ecologically or Biologically Significant Marine Areas) have been used to identify ecologically or biologically important components relevant for the Sleipner area:

- Uniqueness or rarity
- Special importance for life history stages of species
- Importance for threatened, endangered or declining species and/or habitats
- Vulnerability, fragility, sensitivity, or slow recovery
- Biological productivity
- Biological diversity

The data sources used to assess these criteria include OSPAR, Norwegian Red list for Species, Havmiljø.no, Mareano program (Mareano.no) and MOD database (Environmental Monitoring database).

The wealth of data on the benthos in the Sleipner area, gathered as part of the Norwegian compulsory monitoring program which has been carried out since 1997, enabled a comprehensive analysis of the benthic community in the area.

A total of four EBSA (Ecologically or Biologically Significant Marine Area) criteria were identified in the wider geographical area, bringing to light eight components/ species deserving special attention. These include:

- The benthic species *Apherusa bispinosa*, *Eteone suecica*, *Tellimya tenella*, *Thyasira dunbari*, all listed in the Norwegian Red List for Species under Data Deficiency (DD). *Arctica islandica* is defined by OSPAR being a species under threat and/or in decline within the Greater North Sea (OSPAR 2009).
- Sand eel areas (spawning and foraging area)
- Spawning ground for North Sea cod
- Mackerel spawning area
- North Sea herring larvae and juvenile area

The next step in the overall approach was to identify the presence of potential leak features that can connect the CO2 stored in the target formation with the seabed as well as understanding the behaviour of the carbon dioxide plume at the seabed (in leakage scenarios) in terms of pH change. This work was conducted by a number of other ECO2 work packages but the output of their work was integrated into the Environmental Risk Assessment. A total of 16 leak features/chimneys of interest were identified at Sleipner (Karstens, 2014 and Nicoll, 2011).

Each leak feature/chimney was overlaid with a generic modelled 'worst case scenario' plume of carbon dioxide, expressed as a plume of pH change. The leak features are assumed to leak perpetually. A worst case scenario is also assessed, in that the consequence of all leak features leaking at the same time is presented. This allows an understanding of the scale of the consequence, in the context of the wider geographic area.

Valuable resources within the area of potential risk

Overlay analysis between the plumes and the identified valuable resources at Sleipner revealed that 2 of the valuable species are found within the potential leak area, and could be affected by the pH change; the bivalves *Tellimya tenella* and *Arctica islandica.* Based on value criteria, *T. tenella* is considered as '*medium*' environmental value, and *A. islandica* as '*low*' environmental value. Based on the seabed area impacted in relation to the extent and density of the population in the wider area, the two species could be affected at the individual level, but not at the population level, therefore the extent of influence of the CO_2 plume is '***Incidental***" for both species.

Degree / **Value**		**Environmental value**		
		Low	**Medium**	**High**
Degree of impact	**Small**	*Arctica islandica*	*Tellimya tenella*	
	Moderate			
	Large			

For the other identified valuable resources there is no overlap; indicating that these resources and areas will not be directly affected by a potential leak, when considering pH change.

Limitations of the case study are discussed, as well as recommendations for areas requiring more research and debate.

Propensity to Leak

Estimating leakage probabilities for geological storage sites is not currently feasible given the very small data set of actual storage site performance. However, even when the accumulated body of storage site operations becomes significant, it is not clear that it will be directly transformable to leakage statistics in the way that has been done with leakage from valves, pipes, process vessels, etc., which are represented by millions of data points for highly repeatable components and systems. This will never be the case for geological storage sites. Every geological storage site will likely have its own unique set of characteristics that are important for storage performance.

Instead of referring to leakage probability, the ECO2 project has chosen frame the risk component as propensity to leak (PTL). The distinction is subtle but important and is intended to remind users that the data and methods behind leakage assessment are much more heuristic in nature than other risk analysis processes which leverage large databases of factual system performance, i.e. offshore drilling rigs. The formalism applied to apply the heuristic framing of Propensity to Leak is the mathematics of Bayesian inference as implemented by modern, graphical-user-interface Bayesian Belief Net (or simply Bayesian Net, BN) software originally developed to more effectively process evidence of various degrees of ambiguity collected for health and disease diagnostics.

A prototype BN PTL model was produced for this case study and extensively described and documented in chapters 9-10.

The uncertainties associated with the estimates of propensity to leak (PTL) are dominated by geological uncertainties in the overburden and to a lesser extent the uncertainties in the target storage reservoir itself. To make a material decrease in these uncertainties implies significant and disproportionately increasing costs in data collection at the storage site. Therefore, the PTL scale is simplified in our case study to three discrete outcomes. In situations where data is more complete and uncertainties smaller, more probability and consequence discrete levels may be applied than the 3x4 matrix shown here.

Therefore a simple two-dimensional matrix model is considered as best practice to assess environmental risks related to leakage to the seabed from offshore CO_2 geological storage sites.

One specific subsurface feature was included in the case study PTL analysis. This feature is sourced from seismic survey data and commonly referred to as chimney 77. The BN PTL model main output for PTL from this feature are summarized in the table below.

Chimney 77	Bayesian Net estimate of propensity to leak to seabed
Very Unlikely	60.1%
Possible	38.5%
Very Likely	1.5%

Aggregating these values to a single propensity number gives 22%, which is in the 'Possible' category.

Risk

The final output risk matrix for the chimney 77 feature is shown below. The horizontal axis is output from the consequence assessment (chapters 4-8), while the vertical axis is output from PTL assessment (chapters 9-10). This is done in general for each discrete leakage pathway and leakage scenario identified for the storage site and based on the associated features, events and processes characterized for the site. The aggregate results will be a collection of risks labelled by a number or letter placed in the matrix below.

This will enable effective prioritisation of monitoring of specific storage site locations and potentially adjusting the injection programme to avoid the stored CO_2 from contacting high-risk features in the subsurface which may lead to leakage to the seabed.

The overall risk is assessed to the lowest category; Negligible/small negative for both Arctica islandica and Tellimya tenella, and summarized in the risk matrix below.

Table 1-1. Final Risk Matrix for the Sleipner ERA for the CO_2 geological storage project

Severity measured in Environmental Value / Propensity to Leak	Severity of environmental impact			
	Incidental	**Moderate**	**Major**	**Critical**
Unlikely				
Possible	*Arctica_islandica*$_{Chim77}$ *Tellimya_tenella*$_{Chim77}$			
Very Likely				

2. Introduction to Environmental Risk Assessment

The objectives of this study are to apply and “test” on the Sleipner CO2 storage site the Generic Environmental Risk Assessment methodology developed as part of the ECO2 project and presented within the Best Practice Guidance Document.

3. Main structure of this report

A generic approach for assessing consequence, probability and risk has been applied for the Sleipner Case Study as part of the ECO_2 project. The approach contains six main steps (Figure 3-1):

1. **EBSA methodology** (Ecologically or Biologically Significant Marine Areas). A description of marine resources within a defined area, and a site specific environmental value for each highlighted resource in that area.
2. **Overlap analysis of plume and valued resource.** A quantification of the potentially affected population or habitat expressed as a proportion, number of individuals, or size of an area.
3. **Vulnerability and degree of impact**. An assessment of the vulnerability of, and the impact on the valued environmental resource.
4. **Consequence.** Combination of the “environmental value” and “degree of impact” for each valued environmental resource expressed as consequence categories incidental, moderate, major or critical
5. **Propensity to Leak.** Estimated for each site-specific leakage pathway and leakage scenario.
6. **Risk matrices** for valued environmental resources

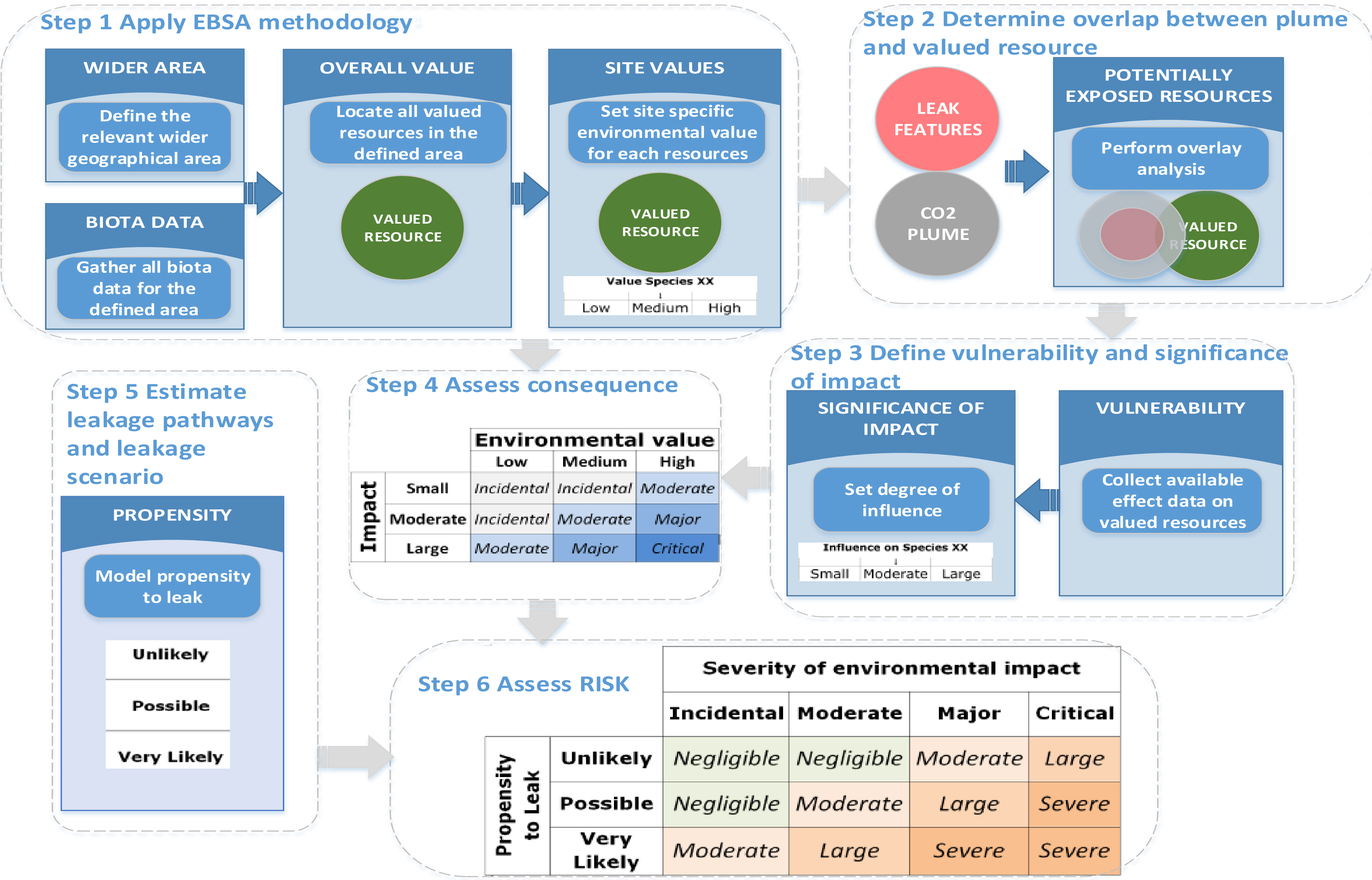


Figure 3-1 *This shows the overall ERA approach applied for assessing consequence.*

4. Introduction to Consequence Assessment

The Environmental Risk Assessment (ERA) for carbon dioxide storage sites is designed to be as transparent, repeatable, and adjustable as possible. There are many knowledge areas concerning leak features, flux rates, biological responses to carbon dioxide, species distribution and ocean carbon chemistry, which are expanding and deepening all the time. There are also areas where knowledge may be sorely lacking, such as the interplay between carbon dioxide release and heavily contaminated seabed areas. A risk assessment must therefore use the most up-to-date knowledge in these fields, and be open for expert discussion. Wherever possible, recognised international, national, and regional frameworks for assigning value to biological resources should be used, as well as published literature. All data and literature sources used, as well as assumptions made, should be documented and traceable. In this way each step in the process can be assessed in light of new knowledge or information. This method does not exclude resources which are considered valuable by a particular sector, but not universally recognized as such because all sources of information are documented, any resource can be taken through the process and brought forward for consideration and discussion.

Within the ERA case study, a number of assumptions have been made which are outlined below and include

- a CO_2 leak will be persistent
- Due to the continuous nature of the release species restitution time is not applicable
- features leak from point sources
- pH change is a good proxy for pCO_2

The assumption on a persistent CO_2 leak is very conservative because it is known from actual, natural CO_2 seepage sites offshore that seepage is periodic, i.e. leaking a period and then not leaking, and repeating

Sleipner is located in one of the busiest maritime areas in the North East Atlantic, in OSPAR Region II (Greater North Sea). Region II opens into the Atlantic Ocean to the north and, via the English Channel, to the south-west, and into the Baltic Sea to the east. Depths do not exceed 700m. The seabed is mainly composed of mud, sandy mud, sand and gravel. The variety of marine landscapes is considerable: fjords, estuaries, sandbanks, bays, intertidal mudflats. Major activities in the area include fishing, extraction of sand and gravel and offshore activities related to oil and gas reserves. Biological systems in the Greater North Sea are rich, complex and highly productive (OSPAR, 2014). The Quality Status of Region II, assessing the pressures and threats to the area is described in the OSPAR Greater North Sea Quality Status Report 2010 (OSPAR, 2010).

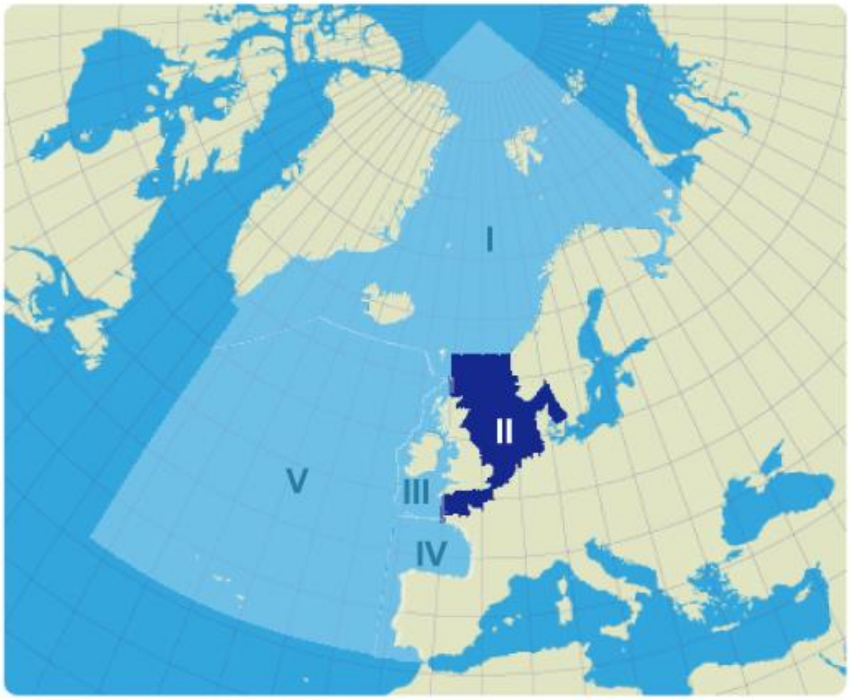


Figure 4-1 OSPAR Region II, the Greater North Sea, within the North East Atlantic (OSPAR 2014).

The Sleipner area embraces the Sleipner East and Sleipner West gas and condensate fields. As part of the required environmental monitoring associated with oil and gas activities on the Norwegian continental shelf, the soft bottomed benthos and sediment contaminant concentration at the Sleipner area has been monitored every 3 years since 1997, with the latest survey carried out in 2012 (Nøland et. al. 2013).

A total of 143 stations were sampled during this survey with a total of 715 benthic grab samples. The fields surveyed are shown in Figure **4-2**. The water depth in the survey area ranged from 78m to 130m. The fauna in the region is divided into 3 sub-regions which correlate with the sub-regions identified by sediment and bathymetric parameters. The sediments are dominated by sand and fine sand, while the total organic material content of the sediments in the shallow southern sub-region where Sleipner is located varied from 0.54-1.01%. The benthic fauna showed no disturbance in any of the fields, and there is some natural temporal variation in benthic diversity throughout the southern sub-region. Benthos at the Sleipner field was dominated by the detritus feeding polychaete *Spiophanes bombyx*, while the polychaetes *Paramphinome jeffreysii*, *Galathowenia oculata*, *Owenia fusiformis* and the tube dwelling sea anemone *Cerianthus lloydii* were common. Diversity (Shannon-Wieners, H’) was high, ranging from 3.8-4.3. This diversity falls within or slightly below the ‘Natural Reference value’ based on undisturbed reference stations in the wider area (H’=4.6±0.5).

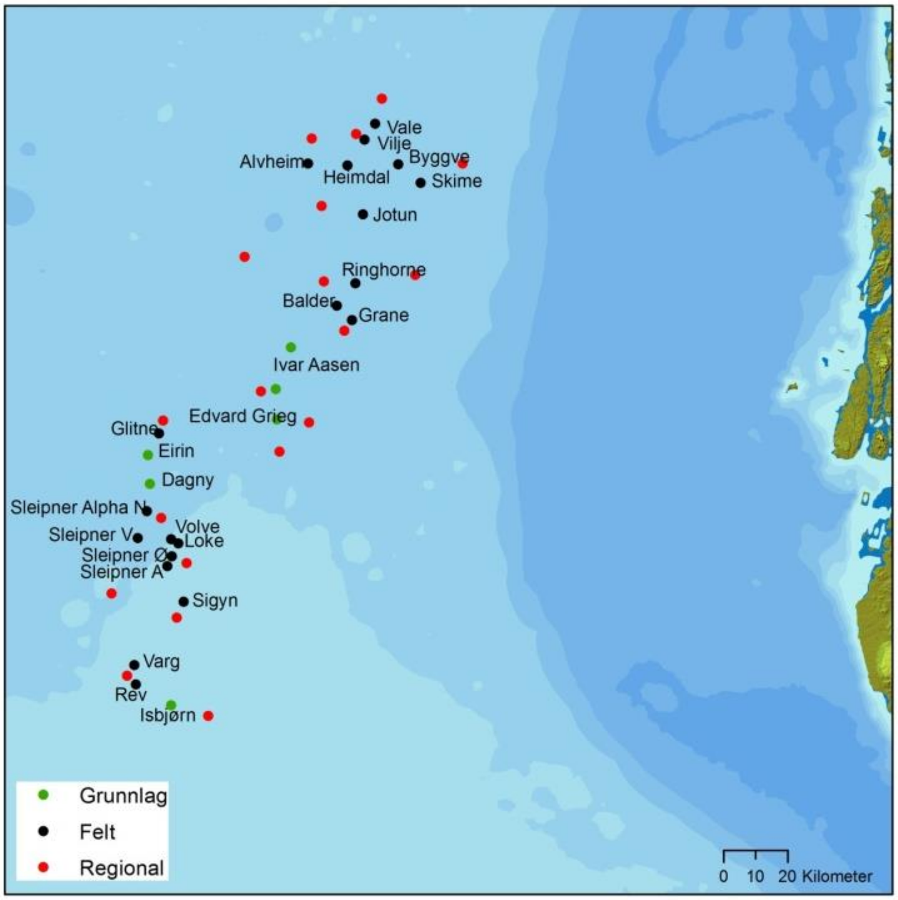


Figure 4-2 Overview of fields included in the monitoring of the Sleipner Area in 2012, and baseline surveys in the region. • Existing fields • Baseline surveys • Regional stations. From Nøland et. al. (2013). The Sleipner fields can be seen toward the west.

5. Methodology for the Consequence Assessment

Steps in the approach

Figure 3-1 presents the overall approach applied to the risk assessment. A Site and Species Specific approach was applied in order to determine the value and vulnerability of the key species and habitats. The site specific risk assessment takes into account the ecological and biological significance ('value') of the resources in the area of interest, and derives consequence assessments for each unique environmental benthic resource. The value of the resource is ultimately evaluated in the context of the wider geographical area. The approach contains four main steps further applied in this assessment:

Step	Content	Purpose
1	Apply EBSA methodology	To describe site specific marine resources within the defined area in question and set site specific environmental value for each highlighted resource in that area.
2	Determine overlap between plume and valued resource.	To identify potential leak sites, model the leak from identified leak sites and determine the overlap between the CO2 leak and valuable resources identified in Step 1.
3	Define vulnerability and significance of impact	To put measure of value on the identified environmental resource, to assess the vulnerability and assess the degree of impact on the valued environmental resource identified in Step 1.
4	Assess consequence	To assess the consequence for each valued environmental resource into one of four categories (negligible, moderate, large or severe) by combining the "environmental value" and "degree of impact".

Step 1 – Apply EBSA methodology

For the purpose of assessing risk, an already established approach is applied, first initiated at a high end level, by the Convention on Biological Diversity (CBD). This is known as the EBSA approach and is transparent and logical, and aims to ensure no resources of value are overlooked. A set of seven criteria to identify ecologically or biologically important areas in the sea (see CBD COP 9 Decision IX/20) are proposed to use as the basis for the environmental value assessments. These criteria are:

- Uniqueness or rarity
- Special importance for life-history stages of species
- Importance for threatened, endangered or declining species and/or habitats
- Biological productivity
- Biological diversity
- Vulnerability, fragility, sensitivity, or slow recovery
- Naturalness

The different criteria for generating the environmental values system can be up-weighted if they are considered more important than other criteria. If weighting is carried out, a description of the rationale behind it should be described.

It is recommended that the criteria 'naturalness' is treated separately from the other six. The concept of naturalness and its potential impact on the consequences of a disturbance is discussed later in this document. See Table 5-1 for the different criteria and their definitions. In order to assess the criteria in an objective and transparent way, four main steps are suggested (Clark et al. 2014).

1. Identify the area to be examined
2. Determine appropriate data sets to use in the evaluation
3. Evaluate data for each area/habitat against a set of criteria
4. Identify and assess valued resources

There are various sources of literature describing and evaluating the EBSA scheme (Clark et al. 2014; Convention for Biological Diversity, 2014) and it is currently being developed and refined into a transparent and logically sequential selection process which is conceptually transferable to different scenarios. The EBSA criteria are primarily used today through the Convention on Biological Diversity to identify marine areas in need of protection, but the method is equally applicable and valuable when identifying important resources in areas of potential impacts.

Table 5-1. The seven criteria used to identify ecologically or biologically important areas in the sea (see CBD COP 9 Decision IX/20)

CBD COP 9 Decision IX/20)		
Criteria	**Definition**	
Uniqueness or rarity	(i)	unique ("the only one of its kind")
		rare (occurs only in few locations)
		endemic species/populations/communities
	(ii)	unique/rare/distinct habitats
		unique/rare/distinct ecosystems
	(iii)	unique/unusual geomorphological features
		unique/unusual oceanographic features
Special importance for life history stages of species	Those areas required for a population to survive and thrive.	
Importance for threatened, endangered or declining species and/or habitats	Area containing habitat for the survival and recovery of endangered/threatened/declining species.	
	Area with significant assemblages of endangered/threatened/declining species.	
Vulnerability, fragility, sensitivity, or slow recovery	Relatively high proportion of sensitive habitats/biotopes/species that are functionally fragile	
	Habitats/biotopes/species with slow recovery	
Biological productivity	Area containing species/populations/communities with comparatively higher natural biological productivity	
Biological diversity	Area contains comparatively higher diversity of ecosystems/habitats/communities/species/diversity.	
Naturalness	Area with a comparatively higher degree of naturalness as a result of the lack of or low level of human-induced disturbance or degradation.	

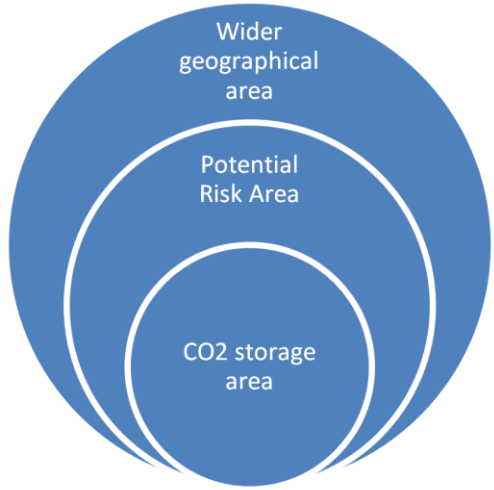
Identifying the area to be examined

Potential Risk Area

The seabed area potentially at risk from CO_2 leakage should be defined based on the location of the CO_2 storage reservoir, and of leak features and pathways such as chimneys and conduits. The process of defining the potential risk area is described chapters 9 - **Error! Reference source not found.**.

Wider geographical area

The potential risk area is placed in the context of its location and importance in the wider geographical area. Marine areas are characterized by particular bathymetric conditions, human impacts and ecosystems, and they can be classified into distinct entities at different geographical scales. It is this wider area that is assessed for *Valued Resources* in an ERA methodology. All sources of 'value' information available for the wider area are consulted and documented to ensure a comprehensive assessment.



Determine appropriate data sets and identify valued resources in the wider area

All valuable resources in the wider area are identified. This refers principally to biological resources (biota), such as benthic species and important habitats. Wherever possible, existing, recognized frameworks which assign value to marine species, habitats and areas can be applied. These include international, national and regional frameworks, such as the OSPAR list of threatened or declining species, and national Red Lists of threatened habitat and species. As many sources of 'value' information as possible can be used and documented to ensure a comprehensive assessment. This method does not exclude resources which are considered valuable by a particular sector, but not universally recognized as such: because all sources of information are documented, any resource can be taken through the process.

The outcome of this step within the overall process is an overview of the ecological and biological components along with an environmental map for each identified species/habitat describing the spatial distribution.

Assessment of environmental value

Each identified valued resource within the anticipated influence area should be valued descriptively according to the following criteria:

Low value: Area with *local* importance for species and habitats

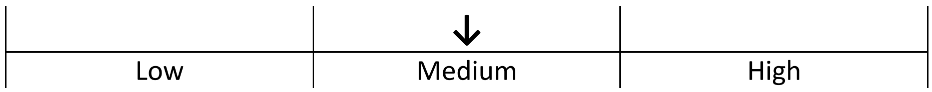
Medium value: Area with *regional* importance for species and habitats, and/or having national Red List species/habitats classified as data deficient (DD) or nearly threatened (NT).

High value: Area with *national* importance for species and habitats, and/or having national Red List species/habitats classified as vulnerable (VU), endangered (EN), critically endangered (CR) or regionally extinct (RE).

As a starting point, the value assigned by recognized frameworks (international, national and regional) are applied. If higher resolution data on abundance and distribution of the valuable resource in the wider area are available, these can be used to adjust the assigned value. The value derived would thus be case-specific. The rationale behind assigning a value to a resource, and the sources of data used, must be clearly documented and traceable.

For a given species which e.g. has been assessed to have “medium value” the outcome would be as illustrated below.

Environmental value Species XX



Step 2 - Determine overlap between Plume and Valued resources

Model of leaks and plumes

In general the report by Alendal et al. (2014) describes the environmental conditions and possible leak scenarios relevant as input to the Sleipner ERA. There are three classes of models; a marine chemistry model, two different Near-field two-phase plume models, NFTPM, and a regional scale general circulation model (BOM, Bergen Ocean Model). They all have different needs with regards to data for calibration and validation. The models are all described in depth by Dewar et al. (2013), including a general discussion on model parameters.

Near-field multiphase model (NFMPM) is the model to predict the impact of leaked CO_2 on the marine environment. The outputs from this NFMPM, such as the pH/pCO_2 changes, can be applied for prediction of acute biological impacts and as input data to the up-scale model (regional scale OGCM) for impact predictions on a larger scale.

Sub-seabed Leak features

In order to assess environmental consequences one has to identify potential leak features that can connect the CO2 stored in the target subsurface geological formation with the seabed. There are different types of leak features such as faults, fractures, chimneys or leaky wells. The leak features identified in the Sleipner area are shown in Figure 5-1. The basis and data for these features are described in chapters’ 9**Error! Reference source not found.**. The locations and characteristics of these leak features were imported to a Geographical Information System (GIS) in order to combine this information with modelled leak results enabling analysis and visualization of environmental consequences.

The identified leak features have a non-zero likelihood of leakage of CO_2 in a case where CO_2 is stored in the reservoir at Sleipner (yellow area in the figure). The likelihood is expressed as a Propensity to Leak Factor described in detail in chapters’ 9**Error! Reference source not found.**.

The features included in the environmental assessment are shown in Figure 5-1. These are the features which are considered to be potential pathways of CO_2 migration from the reservoir to the sediment in the upper layer of the sea floor and to the water masses above the sediment surface (above the sea bottom) at Sleipner.

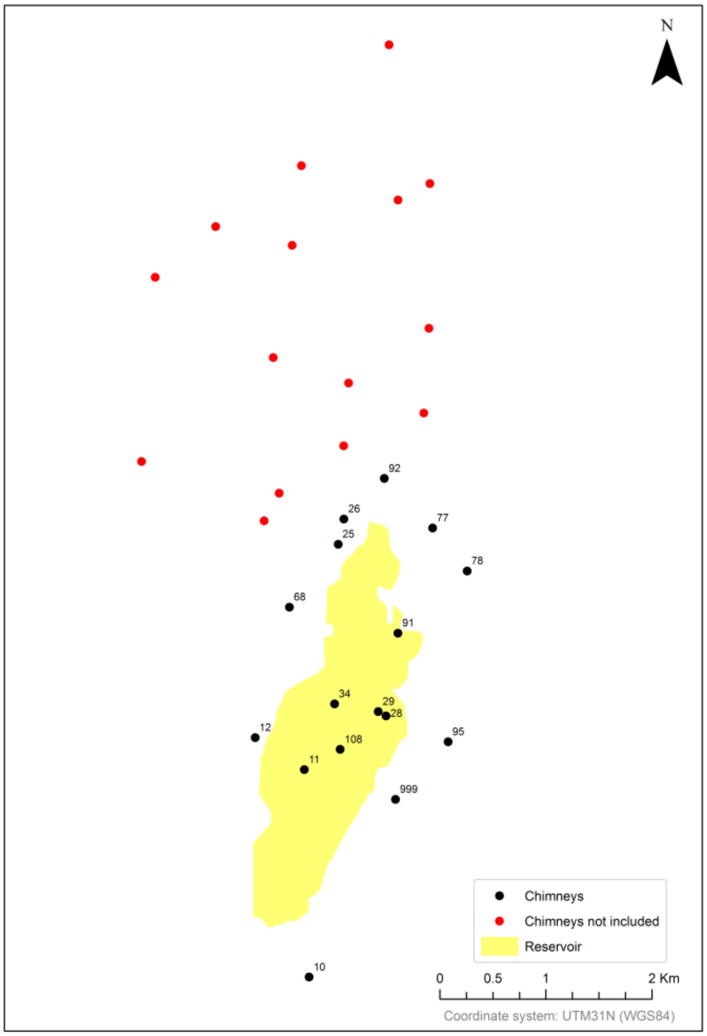
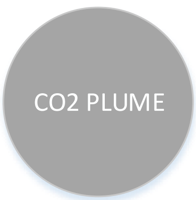


Figure 5-1 Identified potential leak structures in the Sleipner area. Black symbols represent leak feature included in the assessment. The yellow area represents the outermost extent of CO_2 at the top of the storage target reservoir as indicated by time-lapse acoustic seismic survey data.

Each leak feature has a set of estimated characteristics, such as diameter, form, orientation etc. As each leak features is unique, the potential leakage should be modelled for each individual feature based on its specific characteristics and location relative to the stored CO2 and the overall operation of the storage site, e.g. injection rates, cumulative stored, movement of the stored CO2, changes in reservoir pressure due to injection, etc. This was the subject of ECO2 WP1, which constructed numerical simulation models of CO2 injection into the subsurface at the Sleipner site. These reservoir simulation models were observed to be somewhat unstable, required very long times to complete, and were not able to represent all subsurface features with the level of detail possible in static geological models.

This ERA does not directly use a reservoir simulation model tailored to a specific leakage feature at a specific storage site to represent leakage scenarios. The modelled results provided to the ERA are from a generic gas chimney. Therefore the modelled footprint of the pH change at the seabed (affecting benthic species) from a generic gas chimney has been overlaid on the other relevant features in order to get an overall footprint of potential impacts due to the pH change. This is a coarse simplification in many ways, but is considered the best option available at this time in order to perform an ERA, given the very large software and computing resources required to dynamically model a fully coupled subsurface CO2 storage formation with leakage up through the overburden to the seabed.

CO2 Plume



The modelled results used in this assessment were produced by Near-field multiphase model (NFMPM), see Dewar et al (2013) for details. The Near-field multiphase model can be used to predict the local extent of leaked CO_2 on the seabed. The spatial scale ranges from centimeters to several kilometers and on a time scale from seconds to days. Data on porosity of the sediments, the topography of seafloor, the vertical (and horizontal if available) distribution of local current, temperature, salinity and background pCO_2, are requested for reconstruction of a near-field scale turbulent ocean. These data can be provided from field observation data or data predicted from the up-scale model (regional OGCM). The CO_2 leakage flux and sites (area) are the data required for the generation of plume of dispersed phase. The outputs from this NFMPM, such as the pH/pCO_2 changes, can be applied for prediction of biological impacts and as the input data to the up-scale model (regional scale OGCM) for impact predictions on a larger scale.

The scenario modelled and used in this environmental assessment can be described by the following general characteristics:

- Generic Gas Chimney 19: 50m diameter circle
- Max flux rate (at seafloor): ~100T/d
- Depth: 100 m – Sleipner
- Season: Summer
- Bubble sizes: Predicted from sediment data from Ardmucknish bay – provides bubbles from 1mm to 6.4mm
- Current: For worst case, no current is applied.
- Domain: 800m x 800m
- Scenario: Blowout (largest leakage rate per unit area)
- Background pH: 8.3

Background pH at Sleipner

Some data on carbon parameters in the North Sea are shown in Figure **5-2**. For the purposes of the ERA it is important to have information on the natural variation in carbonate parameters that species are regularly subject to. Based on data on short term variations of bottom water pH in the North Sea in 2012 (Abdirahman and Johannessen, pers. comm. 2014), historic data, and literature (Talmage and Gobler, 2010), the background pH in Northern North Sea is taken as pH 8.15 ±0.15.

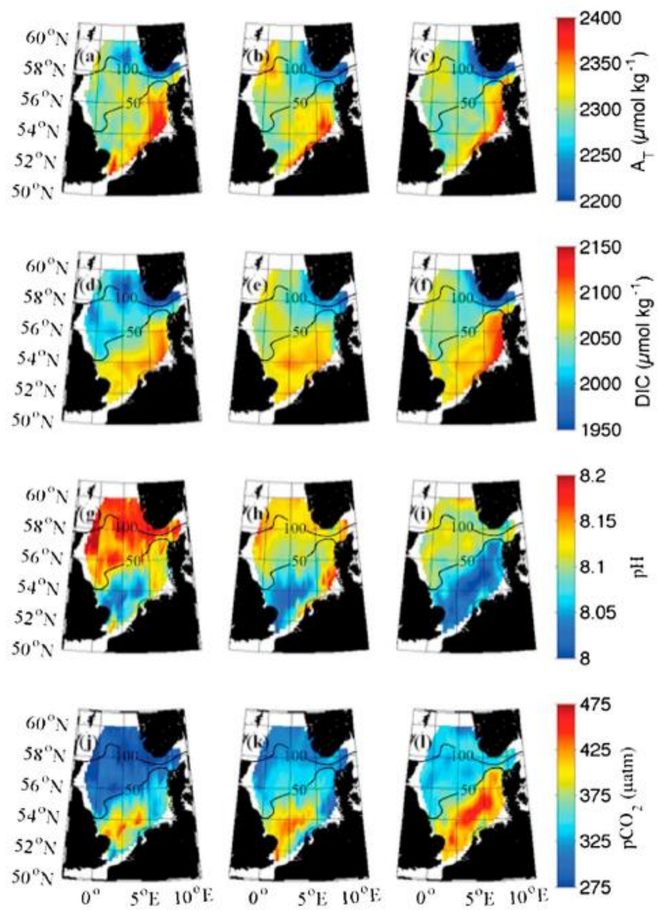
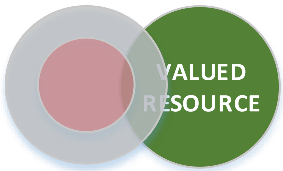


Figure 5-2 Reproduced from Salt et al, 2010. Surface layer distribution of carbonate parameters with 50 and 100m depth contours. Sleipner is located at the Northern edge of the illustrated area. (a-c) Total alkalinity A_T (μmol kg^{-1}) for the years 2001, 2005, and 2008, (d-f) dissolved inorganic carbon (μmol kg^{-1}) for the years 2001, 2005, and 2008, (g-i) pH for the years 2001, 2005, and 2008 and (j-l) partial pressure of CO_2 (pCO_2; μatm) for the years 2001, 2005, and 2008. A_T and pH are calculated parameters from DIC and pCO_2, using carbonic acid dissociation constants of Mehrbach et al., 1973, refit by Dickson and Millero, 1987, and pH is given on the total scale. Average values for 2001, 2005, and 2008 are 2299, 2298, and 2291 μmol kg^{-1} for A_T, respectively, 2014, 2052, and 2055 μmol kg^{-1} for DIC, 8.129, 8.105, and 8.079 for pH, and 323, 344, and 369 μatm for pCO_2.

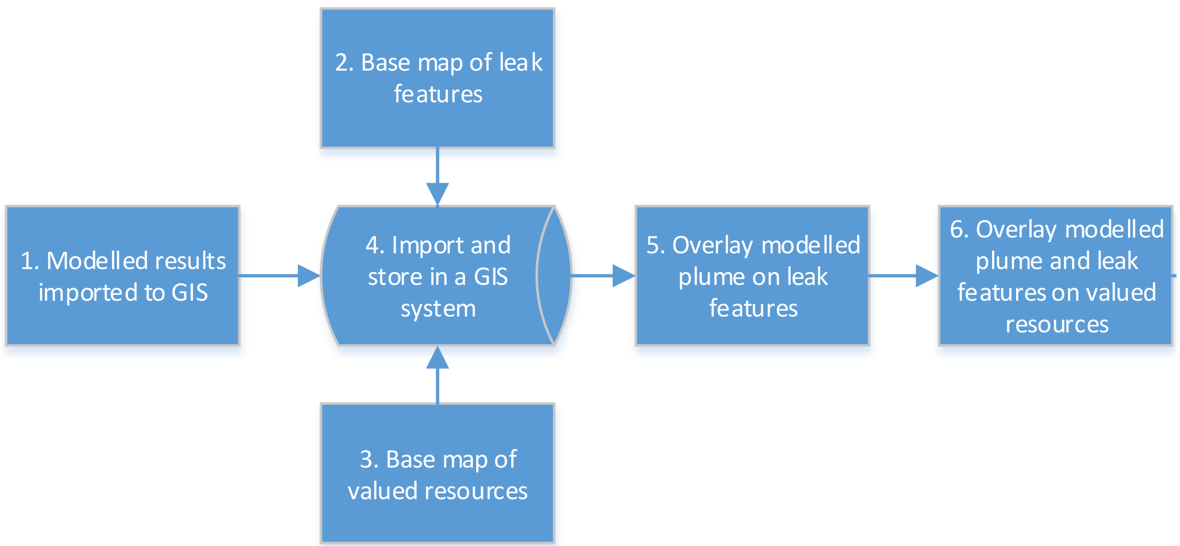
There is an anomaly between background pH (8.3) used in the plume model, and the expected background pH at Sleipner (8.15±0.15). This introduces a few m^2 uncertainties in the footprint of the plume. The effect of this uncertainty is discussed in 0.

Overlap analysis



The scenario is considered to be a worst case scenario with a rate of 100T/d and no ocean current. Since the modelled results are from a generic gas chimney, the results have to be applied for all leak features identified as relevant. In this case study each leak feature was treated as if it had the characteristics of the generic chimney, i.e. having the same diameter and the same leakage characteristics.

The modelled results were delivered as netCDF files, the agreed format in ECO2. The main analysis was carried out in GIS and contains the following general steps.



Point 1-4: Modelled results (1), base map of leak features (2), and base map of valuable resources (3) are imported to GIS.

Point 5: The modelled plume representing changes in pH in two dimensions are overlaid on each leak feature assessed as potential pathways of CO_2 leakage.

Point 6: A map of the environmental resources assessed as valuable based on EBSA criteria are overlaid on the map layers containing leak features and the modelled pH change for the leak features.

Step 3 - Define vulnerability and significance of impact

After valued resources have been identified, an environmental value for each has been generated, leak features have been identified and CO_2 modelling results are available, consequences need to be described and defined for the source of influence (i.e. pH change). This description should refer to results from research available for the public. If there is no published research available on effects, a precautionary principle should be applied.

The consequence can be expressed as:

Vulnerability

Research on the ecological impacts of CO_2 or other factors associated with ocean acidification has become a high priority in recent years, and research on the topic is expanding at an exponential rate. Over 403 studies investigating ocean acidification were published between 2010 and 2012, which more than tripled the number of studies available (Kroeker et al. 2013). The most up-to-date and comprehensive data available on organisms' vulnerability to increased levels of carbon dioxide at the sea bed should be gathered for the ERA. As new information from research becomes available, the ERA can be updated. All sources of data should be documented clearly to ensure traceability and reproducibility of the ERA, and to enable policy decisions based on particular information to be traced back to source.

The following source of species effects data should be used in the ERA in the following order of preference:

1. Specially designed experiments on the particular species of interest from the population in the potential risk area.
2. Published data on the species of interest from a different population
3. Published data from closely related taxa that are matched for life history, traits and physiology
4. Published data on less closely related taxa, matched for life history, traits and physiology
5. Expert judgment based on knowledge of the organisms' physiology and life history traits
6. Apply precautionary approach: if there is a suspected risk of causing an effect to the species, in the absence of scientific consensus that the action is not harmful, the burden of proof that it is not harmful lies with those taking the action.

Defining the degree of the impact on the valued resource

Threshold values from the literature are obtained for the identified valuable resources (see 0). These threshold values are added to the pH plume to indicate the zones of effect on the particular valuable resource. As part of the ERA, the degree of the impact (i.e. the magnitude of the effect on the species) on each identified resource can be descriptively assessed according to the following criteria:

Small degree: The impact can impair/reduce species and habitats on an individual level.

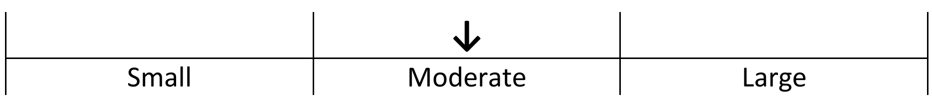
Moderate degree: The impact can impair species and habitats at the population level.

Large degree: The impact can reduce/remove species and habitats at the population level.

The method for defining degree of impact will depend on the particular valuable resource being assessed: whether it is a discrete entity which has an individual value, whether it is a valuable habitat which must cover a certain area of sea bed, etc.

For a given species, which for example has been evaluated to be impacted to a "moderate degree" the outcome would be as illustrated below:

Degree of impact on Species XX



Step 4 – The consequence matrix

The assessment of environmental value and the degree of impact are further compiled in a consequence matrix (see below). The results from the consequence matrix are a direct input to the risk matrix for the given resource.

Degree \ Value		Environmental value		
		Low	**Medium**	**High**
Degree of impact	**Small**	Incidental	Incidental	Moderate
	Moderate	Incidental	Moderate	Major
	Large	Moderate	Major	Critical

For each valued resource identified as part of Step 1, the above steps are followed.

Resource data from the area

Data regarding resources are from the following sources:

Norwegian Environment Agency:

- Administrative areas
  - Downloaded from http://kartkatalog.miljodirektoratet.no/map_catalog_dataset.asp?datasetid=700&download=yes
- Particularly Valuables areas
  - Downloaded from http://kartkatalog.miljodirektoratet.no/map_catalog_dataset.asp?datasetid=703&download=yes&language=

Havmiljø – Environmental values in Norwegian marine areas (http://www.havmiljo.no/):

- Data on herring – Larvae, April
- Herring – 0 group
- Mackerel spawning area
- Sandeel areas

Institute of Marine Research - Mareano project

- North Sea Cod Spawning Area
  - Source: Institute of Marine Research
  - Downloaded from http://maps.imr.no/geoserver/web/;jsessionid=923iu6j94lyf?wicket:bookmarkablePage=:org.geoserver.web.demo.MapPreviewPage

MOD (Environmental Monitoring Database):

- Data on benthos from the Norwegian continental shelf as part the compulsory long-term environmental baseline and monitoring program for oil and gas activities in Norway

6. Results and discussion for the Consequence Assessment

Modelled pH changes

The modelled result presented at pH change just above the sea bottom for the generic gas chimney (see scenario description above) is presented in the figure below. The model results represent a single case scenario based on the input provided; hence it is not a stochastic model. In addition a steady state is achieved after a period of time so the steady state situation may represent a long term scenario.

In this case study the assumption has been made that the leak features all leak in the way predicted by the generic chimney, and that the diameter of the feature does not affect the plume characteristics i.e. the feature leaks from a point source. This assumption is based on the uncertainties around the diameter, extent, and location of leak features which are input data to the case study.

As can be seen the pH change is modelled to be very local. The plume extends about 130m from the epicenter of the chimney with the following characteristics:

1. pH change of -2 to -2.2 extending about 40 m
2. pH change of -1.5 to -2.2 extending about 50 m
3. pH change of -1.0 to -2.2 extending about 67 m
4. pH change of -0.5 to -2.2 extending about 92 m
5. pH change of -0.2 to -2.2 extending about 130 m

If current were applied, the footprint of the plume would be larger, with smaller pH changes over a larger area. Modelled results are dependent of the quality of the input parameters. Small changes in numerical model parameters can have a great effect on the overall result, especially close to the leakage location, and this highlights the need for accurate in-situ data (such as ocean turbulence data to determine viscosity) when modelling different locations rather than using generic values. Overall the results indicate very local pH changes.

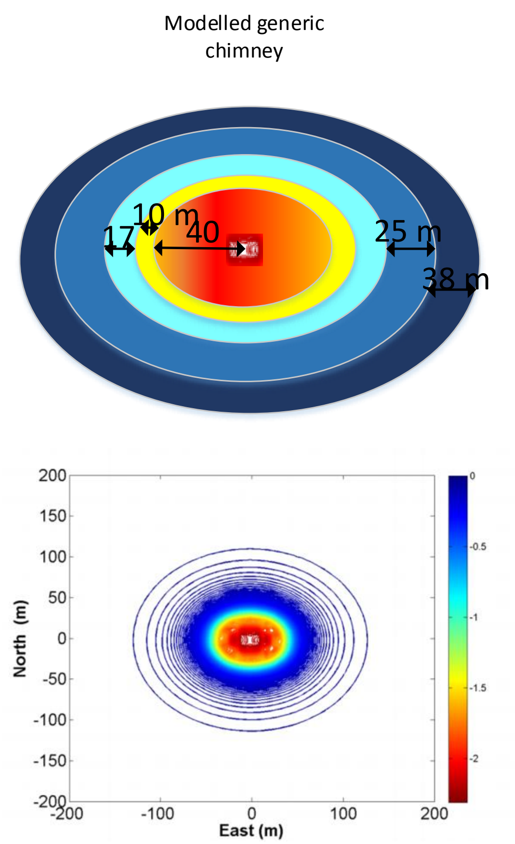


Figure 6-1 Modelled pH change just above the sea floor for the generic gas chimney. Dewar 2014.

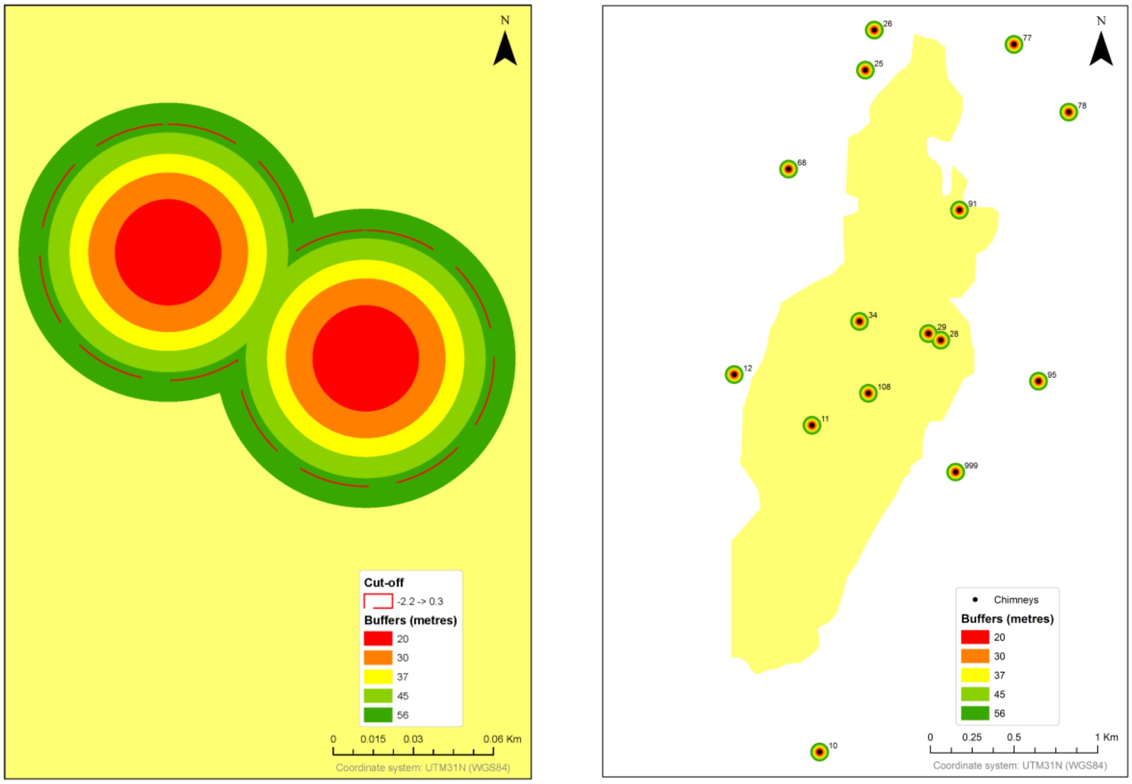


Figure 6-2 *Left*: Detail of the modelled plume, based on the generic model. This image shows the plume at a location where two chimneys are in close proximity and the plumes could potentially overlap. The broken red line demarks the influence cut-off, at a pH change of -0.3. This is the natural variation in pH at Sleipner. Outside this cut-off, any pH change is considered to be within natural variation. *Right*: Modelled pH plume for a generic gas chimney overlaid on the potential leak features, Sleipner.

Assessment of Ecological and Biological Significant areas (EBSA) and assessment of value for Sleipner

The potential risk area is placed in the context of its location and importance in the wider geographical area. The North East Atlantic is divided into 5 regions according to OSPAR as shown in **Error! Reference ource not found.**. Each region is characterized by particular bathymetric conditions, human impacts and ecosystems. The Sleipner field is located in OSPAR Region II (Greater North Sea). It is this wider area that is assessed for Valuable Resources in this ERA methodology. In the case of Sleipner all sources of 'value' information available for Region II are consulted and documented to ensure a comprehensive assessment.

Based on the collation of data from Region II, areas fulfilling criteria (i) uniqueness or rarity, (ii) special importance for life-history stages of species and (iii) importance for threatened, endangered or declining species and/or habitats, have been identified (

Table **6-1**). The region is considered to have a low degree of naturalness due in particular to shipping-, fishing- and petroleum activity.

For the Sleipner case, the criteria are used to document:

- sources of information on species and habitats which fulfil the various criteria
- data sources used for generating distribution maps of given species and habitats
- identified species

Regarding the category DD (data deficient) used in the Norwegian Red List for Species: Data deficient does not necessarily mean that it is a rare or vulnerable species but simply that there are lack of data to assess the status of the species properly. The species listed as DD in

Table **6-1** have been treated here as being rare or unique, following the precautionary approach.

Table 6-1 Evaluated sources of information on species and habitats within Region II which fulfil the various criteria, data sources used for generating distribution maps of given species and habitats and identified species (DD: Data deficiency).

Criteria	Identified criteria used	Data sources used	Identified species and areas	EBSA within Region II
Uniqueness or rarity	• OSPAR • Norwegian Red List for Species • Norwegian Red List for Habitats • Havmiljø.no	MOD 2012 Havmiljø.no Mareano.no	**Benthic compartment:** *Apherusa bispinosa* (DD) *Tellimya tenella* (DD) *Thyasira dunbari* (DD) Sand eel **Pelagic compartment:** None	X
Special importance for life-history stages of species	• Norwegian Red List for Habitats • Norwegian Red List for Species • St. meld 37	Havmiljø.no Mareano.no	**Benthic compartment:** Sand eel **Pelagic compartment:** North Sea cod Mackerel Herring	X
Importance for threatened, endangered or declining species and/or habitats	• Norwegian Red List for Habitats • Norwegian Red List for Species • OSPAR	MOD 2012 Havmiljø.no Mareano.no	**Benthic compartment:** *Arctica islandica* **Pelagic compartment:** North Sea cod	X
Vulnerability, fragility, sensitivity, or slow recovery	• Norwegian Red List for Habitats • OSPAR • Havmiljø.no	MOD 2012 Havmiljø.no Mareano.no	**Benthic compartment:** None **Pelagic compartment:** None	-
Biological productivity	• Havmiljø.no	Havmiljø.no	**Benthic compartment:** Sand eel **Pelagic compartment:** None	X
Biological diversity	NA	MOD 2012	**Benthic compartment:** None **Pelagic compartment:** None	-

Species description

Arctica islandica

The mussel ocean quahog (*Arctica islandica*) is not listed in the Norwegian Red List for Species, but has been defined by OSPAR as being a species under threat and/or in decline within the Greater North Sea (Region II).

Assessment of value

Witbaard and Bergman (2003) described the distribution and population structure of *Arctica islandica* in the North Sea. *A. islandica* has a widespread distribution in the North Sea north of 53°30'N, and in the northern North Sea (Fladen Ground) east of Sleipner abundance peaked at 28,600 individuals per $100m^2$. The population structure here was bimodal in shape and dominated by juveniles. The average density of adult *A. islandica* in the central Fladen ground is 12 individuals per m^{-2}.

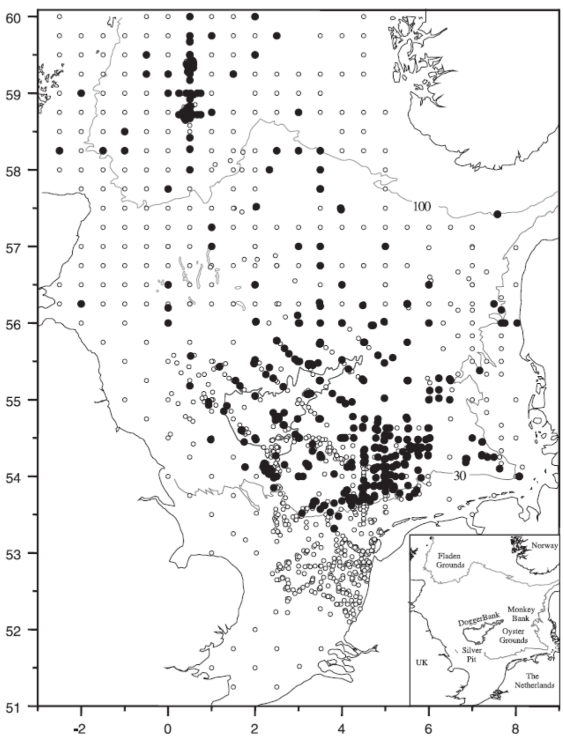


Figure 6-3 Presence absence data of *A. islandica* (>10mm) within the North Sea. Filled dots represent stations where one or more specimens were found in sample. Open circles represent stations where, despite sampling, no living *Arctica* was found. Map based on 1520 records from NIOZ sampling operations between 1972 and 2000 as well as from literature. *From Witbaard et al. 2003.* Sleipner is located to the east of the Fladen Grounds.

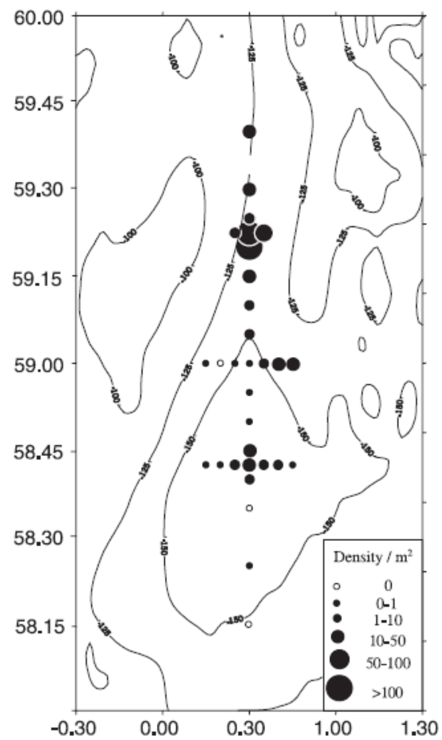


Figure 6-4 Distribution and abundance (m^{-2}) of *A. islandica* (>10mm) in the Fladen Ground along the 00°30' E transect in the northern North Sea as measured during a cruise with RV' Pelagia in July 2000. From *Witbaard et al. 2003.* Sleipner is located to the east of the illustrated area.

Data from the regional monitoring survey carried out in 2012 revealed highest densities north west of the Geitungen location (4 ind per $0.5m^2$). The results may indicate a patchy distribution), related to preferred grain size of medium to fine grain sand, sandy mud and silty sand, at depths where suspension feeding on phytoplankton is possible (Cargnelli *et al.* 1999).

Based on the assessment by OSPAR defining *Arctica islandica* as a species under threat and/or in decline within the Greater North Sea the initial environmental value is set as 'high'.

Environmental value *Arctica islandica*

		↓
Low	Medium	High

As described in the method, if higher resolution data on abundance and distribution of the valuable resource in the wider area are available, these can be used to adjust the assigned value. The value derived would then be case-specific.

It is apparent from the distribution pattern of *A. islandica* that the densities of specimens in the Sleipner area are low and that the Sleipner area is outside of the epicenter of the Fladen bank A. islandica population. Hence, the environmental value for A. islandica at Sleipner is assessed as "Low" value.

Case Specific: Environmental value *Arctica islandica*

↓		
Low	Medium	High

Assessment of effects

Threshold values

Two studies have been reported in literature on the consequence of high pCO_2 on *A. islandica*. Neither of these has been carried out on the North Sea population relevant to Sleipner. The studies (Stemmer et al, 2013; Hiebenthal et al, 2012) involve the Baltic population (Kiel Fjord) where high seawater pCO_2 levels occur regularly. Surface seawater pH in the estuarine Kiel fjord can vary between 8.2 (385 µatm pCO_2) in winter and 7.6 (2300 µatm pCO_2) in summer (Thomsen et al, 2010). Temperature is considered to have an important effect on bivalve shell characteristics. Witbaard et al. 2003 describe an upper temperature limit for *A. islandica* of 18 °C, and Hiebenthal (2012) describe higher mortality at >20°C. Temperature in the Kiel Fjord varies from 0.15 °C to 23 °C (all-year mean 10.5 °C ± 6.1 SD).

Stemmer et al. (2013) report that growth experiments with *A. islandica* from the Western Baltic Sea kept under different pCO_2 levels (up to 1120 µatm, pH 7.75 for 3 months) indicate no effect of elevated pCO_2 on shell growth, indicating that *A. islandica* shows an adaptation to a wider range of pCO_2 levels than reported for other species.

Hiebenthal et al. (2012) investigated whether a combination of warming and acidification leads to increased physiological stress (lipofuscin accumulation and mortality) and affects the performance (shell growth, shell breaking force and condition index) of young *A. islandica* from the Baltic Sea. They found shell stability, shell growth and tissue lipofuscin accumulation to be unaffected by high pCO_2 (up to 1655 µatm, pH 7.63, for 3 months). Temperature increases, rather than increases in pCO_2, were shown to have a negative effect on the shell stability, shell growth and tissue lipofuscin of *A. islandica.*

Arctica from the Baltic undergoes regular high pCO_2 levels, and may be adapted to these conditions. Hiebenthal et al. (2012) proposed that relatively low metabolic rates allow *Arctica* to live without a pH-sensitive oxygen binding pigment in the haemolymph, as well as biologically controlled calcification contributes to their robustness to elevated seawater pCO_2. Hiebenthal et al. (2012) consider it reasonable to assume that *Arctica* are robust against acidosis without being able to actively acclimate to it. *A. islandica* is known to regularly keep its shells closed for days during which it stays buried. During these periods the haemolymph pH decreases from 7.64 ('normal' value) to 7.47 (Taylor et al. 1976).

Several studies have demonstrated that beam trawl fisheries affect *Arctica* populations by inducing direct mortality due to physical damage. Witbaard et al. 2003 surmised that an *A. islandica* population density of 10 ind $100m^{-2}$ population could be considered severely decimated.

Table 6-2 Summary of CO_2 exposure studies on *A. islandica* reported in [1] *Stemmer et al.* 2013, and [2] *Hiebenthal et al*. 2012. As reported by [3]Thomsen et al, 2010 the natural pH in the Kiel fjord from which specimens were collected varies widely between winter and summer [3]Thomsen et al, 2010

Ref.	Exposure (days)	Seawater pCO_2 (µatm)	Total DIC (mmol kg^{-1})	pH	Temp. °C	End point	Effect
1	90	524	2193	8.07	10	shell growth (height and thickness)	none
	90	800	2263	7.90	10		none
	90	1140	2309	7.75	10		none
2	91	391	1940	7.98	25	shell growth, breaking force, tissue stress	none
	91	869	1980	7.82	16		none
	91	1655	2102	7.63	7.5		none
3 Natural variation	Winter/Summer	385-2,300		8.2-7.6	15-23		

It must be noted that the Baltic population of *Arctica* which is exposed to strong environmental fluctuations, i.e. low and variable salinity, periods of low oxygen availability and fluctuating pCO_2 levels, differs from *Arctica* from fully marine environments. Compared to *Arctica* from the North Sea or Iceland, the Kiel fjord animals have a shorter life span and are generally smaller with thinner shells. This may itself be a consequence of the fluctuating environment. This consequence has not to date been quantified in the literature and the consequence values used in this case study of Sleipner are based on the best available information.

Therefore, for this case study

- the pH range tolerated by *Arctica islandica* is taken to be 0.6.

The consequences to *A. islandica* outside this pH variation are undocumented. Following the precautionary principle, any pH change outside this range is assumed to have an effect on *A. islandica* individuals, in the absence of scientific information proving the contrary. Therefore when assessing the consequence to *A. islandica* the modelled plumes have a cut off at -0.6pH. Within this cut off contour there is considered to be an effect on *A. islandica*.

In Figure 6-6 the interpolated distribution of *A. islandica* based on findings from regional monitoring in 2012 is shown. In

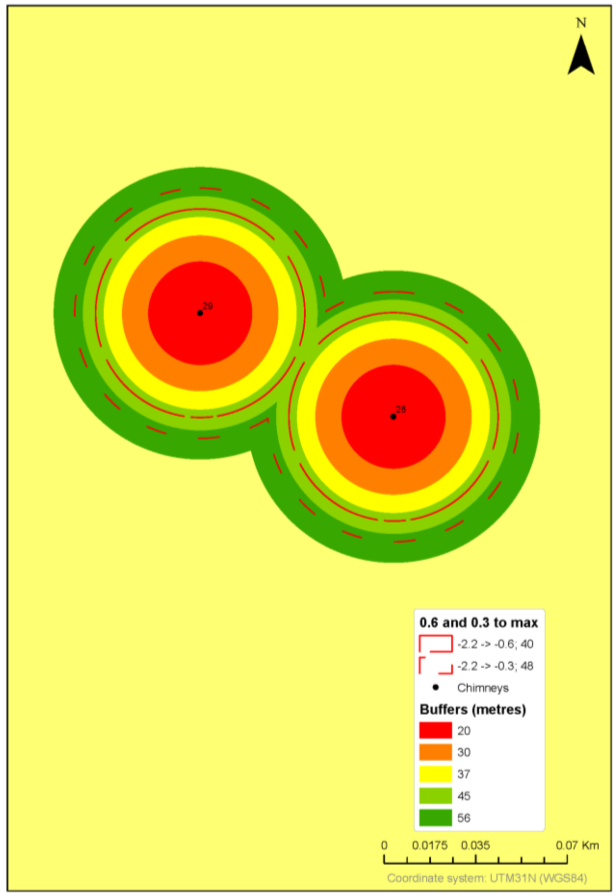


Figure 6-5 Detail of the modelled plume, based on the generic model. The innermost broken red line demarks the species specific cut-off for *A. islandica*, at a pH change of -0.6. Based on the reviewed effects data this is considered to be the pH change which *Arctica* withstands with no effects. Inside this cut-off, the effect on *Arctica* is unknown and following the precautionary principle is considered to be the area of *A. islandica* impacted.

Table 6-3 the number of individuals of *A. islandica* affected by a pH change larger than 0.6 is presented. The estimated numbers of individuals affected are 214 000 (total for all leak features). Estimated numbers of individuals within the interpolated area (Figure 6-6) are 9 million, so the fraction affected are estimated 0.023 %. *A. islandica* has a wider distribution as described above for the Fladen ground so there is strong evidence for that the fraction affected is even smaller. Based on this the extent of influence on *A. islandica* is set to small.

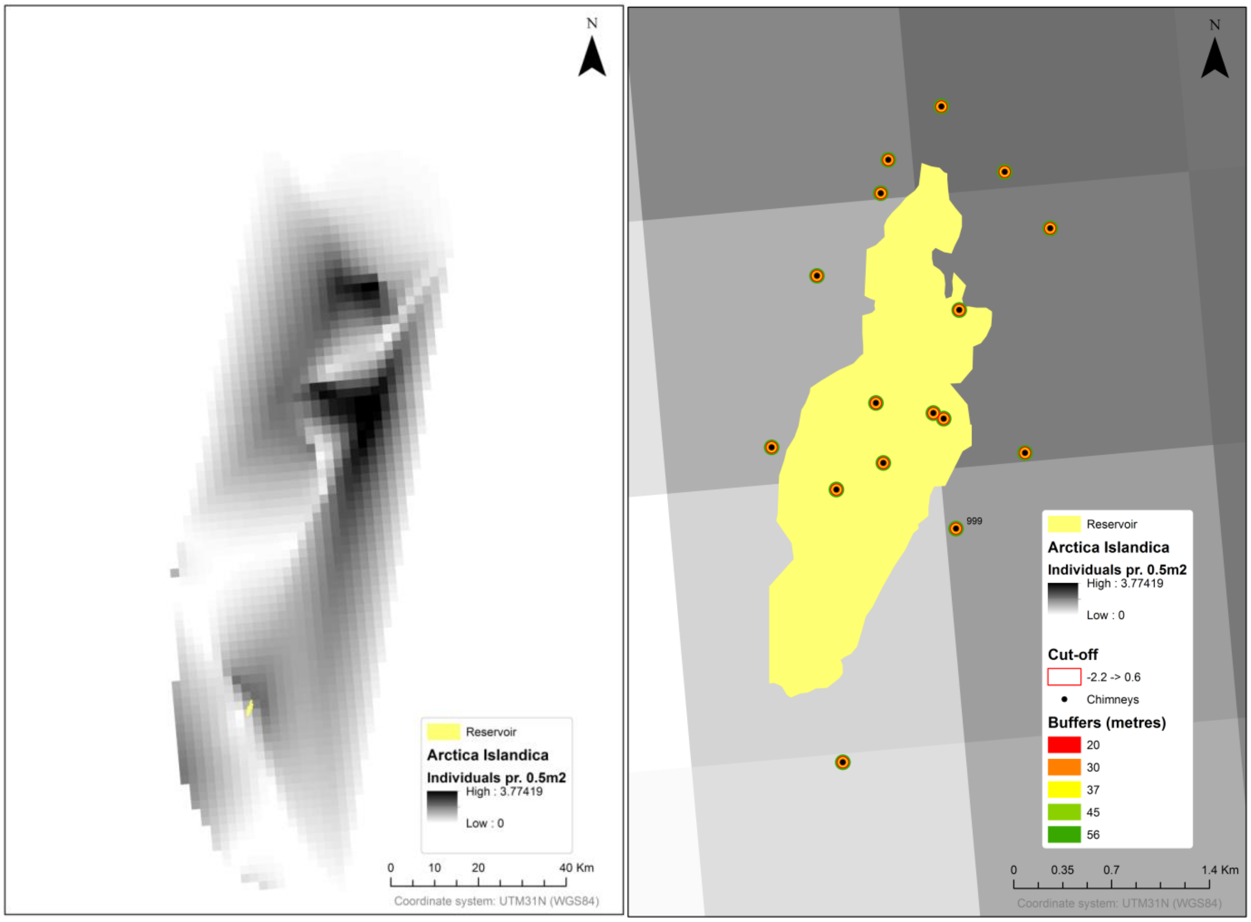


Figure 6-6 Large scale (left) and close up (right) map of *A. islandica* i distribution and density overlaid on the reservoir, Sleipner. The reservoir can be seen in the left image as a small yellow area to the south. *A. islandica* distribution in the area is interpolated based on recorded findings from regional monitoring survey in 2012.

Table 6-3 Calculated numbers of individuals of *A. islandica* within the area of a modelled pH change of 0.6 for each leak feature, Sleipner.

Chimney no.	Area (m^2) within a pH change of 0.6	Density *A. islandica* (1 m^2)	Number of individuals
10	5027	0.9	4435
11	5027	1.1	5618
12	5027	2.1	10433
25	5027	3.2	15970
26	5027	3.2	15970
28	5027	3.4	17130
29	5027	2.1	10433
34	5027	2.1	10433
68	5027	2.1	10433
77	5027	3.8	19342
78	5027	3.4	17130
91	5027	3.4	17130
92	5027	3.8	19342
95	5027	3.4	17130
108	5027	2.1	10433
999	5027	2.5	12855
Sum	80432		214221

Based on the data assessed and presented here, the extent of influence on *Arctica* is assessed as small.

Small degree: The impact can impair/reduce species and habitats on an individual level.

Moderate degree: The impact can impair species and habitats at the population level

Large degree: The impact can reduce/remove species and habitats at the population level.

Degree of impact on *Arctica islandica*

↓		
Small	Moderate	Large

Tellimya tenella

Assessment of value

The mussel *Tellimya tenella* is listed as a data deficient (DD) species in the Norwegian Red List for Species. According to the Marine Species Identification Portal its distribution within OSPAR Region II is limited to the Scandinavian shelf and the northern North Sea. Data from the regional survey carried out in 2012 (Nøland et al 2013) revealed highest densities far west in the Norwegian economic zone, and if at all, single to few specimens at the other sampled locations.

As mentioned, the category DD (data deficient) used in the Norwegian Red List for Species does not necessarily mean that the species is rare or vulnerable but simply that there are lack of data to assess the status of the species properly. The species listed as DD are treated in this methodology as being rare or unique, following the precautionary approach.

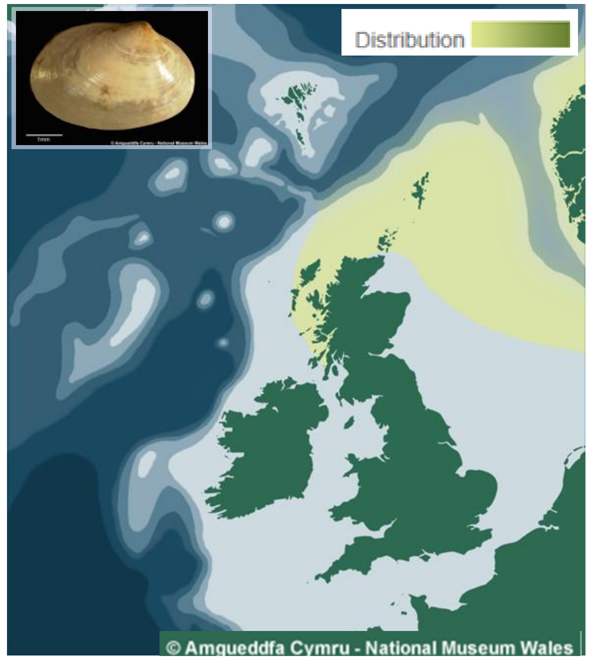


Figure 6-7 Distribution of *T. tenella* in the northern North Sea. The species is data deficient and precise abundance distribution is not collated for the wider area.

No recent detailed maps of *T. tenella* distribution and abundance are available at the wider geographic scale. The environmental value set in this case is therefore based on the Norwegian Red List classification for the species (DD), which is an environmental value of 'medium' and this value, has not been adjusted further.

Low value: Area with *local* importance for species and habitats

Medium value: Area with *regional* importance for species and habitats, and/or having national Red List species/habitats classified as data deficient (DD) or nearly threatened (NT).

High value: Area with *national* importance for species and habitats, and/or having national Redlist species/habitats classified as vulnerable (VU), endangered (EN), critically endangered (CR) or regionally extinct (RE).

Environmental value *Tellimya tenella*

	↓	
Low	Medium	High

Assessment of effects

No data were found from experiments on the effect of carbonate parameters on *T. tenella* from the Sleipner area, nor from other geographic populations of this species.

The closest related species for which laboratory results are reported is a species also belonging to the order Veneroida: *Mercenaria mercenaria*. However, this species is taxonomically so far from *T. tenella* that it is not suitable to apply effect results for this species.

In the absence of suitable effects data for *T. tenella*, the recommended approach is to apply the precautionary principle and document any changes to pH which are above the natural variation experienced by the species. As discussed, in this study the background variation in pH in the northern North Sea is taken as pH ±0.3. Any change in pH greater than 0.3 is greater than the normal pH variation experienced by *T. tenella* and thus considered to have a possible effect at the individual level. The pH plume overlaid on the leak features is therefore the generic one illustrated in Figure 6-2, with an effect cut-off at 0.3 pH change.

- The area impacted by each plume to the 0.3 cut-off is 7235 m^2
- Considering all the leak features identified, the total area impacted if all 16 features leaked at once would be 7235 X 16 chimneys = 115 753 m^2

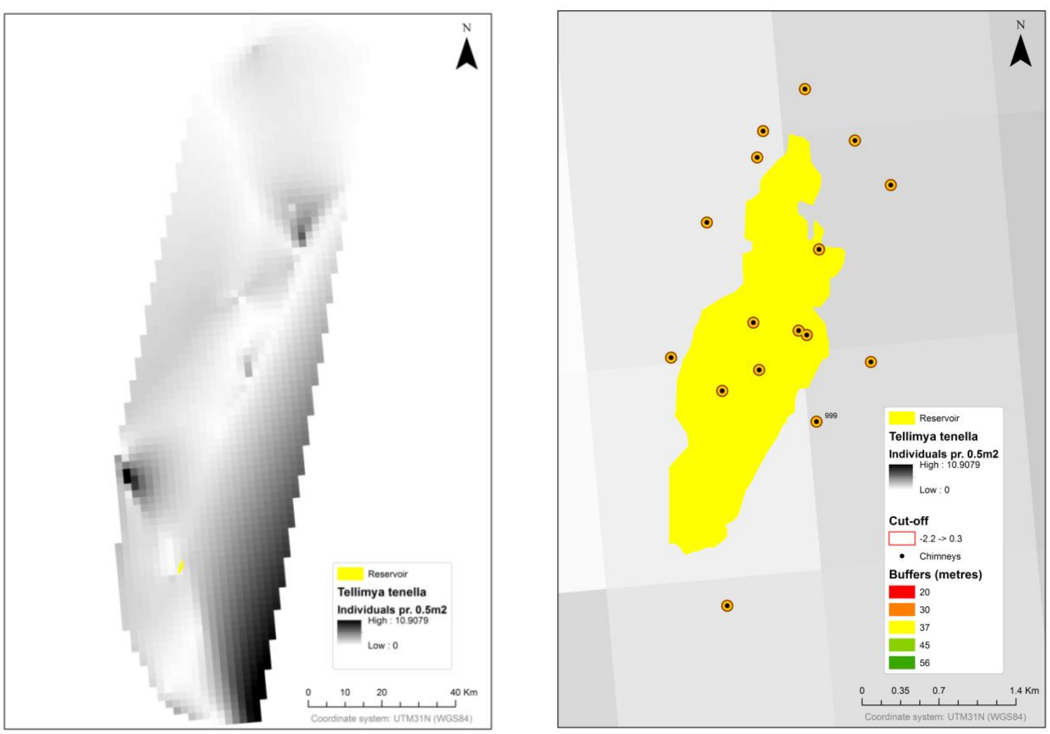


Figure 6-8 Large scale and close up of maps illustrating *Tellimya tenella* interpolated distribution and density overlaid on the reservoir, Sleipner. The CO2 reservoir can be seen as a small yellow area to toward the bottom of the left image. *T. tenella* distribution in the area is interpolated based on findings from regional monitoring survey in 2012.

The interpolated distribution and density of *T. tenella* based on recordings from the 2012 environmental monitoring survey in the Sleipner area (DNV 2013) is shown in Figure 6-8. The CO_2 reservoir lies within an area of low density of *T. tenella* at a distance >30 km from the maximum density epicentre (10.9 individuals 0.5 m^{-2}) of the population, located in the western perimeter of the surveyed area. Based on this, the extent of influence on *T. tenella* is considered to be small, as defined below.

Small degree:	The impact can impair/reduce species and habitats on an individual level.
Moderate degree:	The impact can impair species and habitats at the population level
Large degree:	The impact can reduce/remove species and habitats at the population level.

Degree of the impact on *Tellimya tenella*

↓		
Small	Moderate	Large

EBSAs not further assessed

The other valuable species and areas identified with the EBSA approach are shown in Figure 6-9. The records of *Apherusa bispinosa* and *Thyasira dunbari* are located north of the reservoir and based on the modelled results these locations will not be affected by a pH change due to leakage from the leak features. The identified areas for cod, mackerel, sand eel and herring are also located outside the reservoir. Further, the size of these areas in relation to the modelled area of pH change is much larger, supporting a conclusion that these fish stocks will not be affected.

Thyasira dunbari

Only three specimens of the bivalve have been recorded at one station located far to the north west from the Sleipner area. *T. dunbari* is listed as data deficient (DD) in Norwegian Red List for Species. Since it has not been recorded near Sleipner it's not further assessed.

Apherusa bispinosa

Only one specimen of this amphipod was recorded at the Dagny field, to the north west of Sleipner. *Apherusa bispinosa* is listed as data deficient (DD) in Norwegian Red List for Species. Since it hasn't been recorded at Sleipner it is not further assessed.

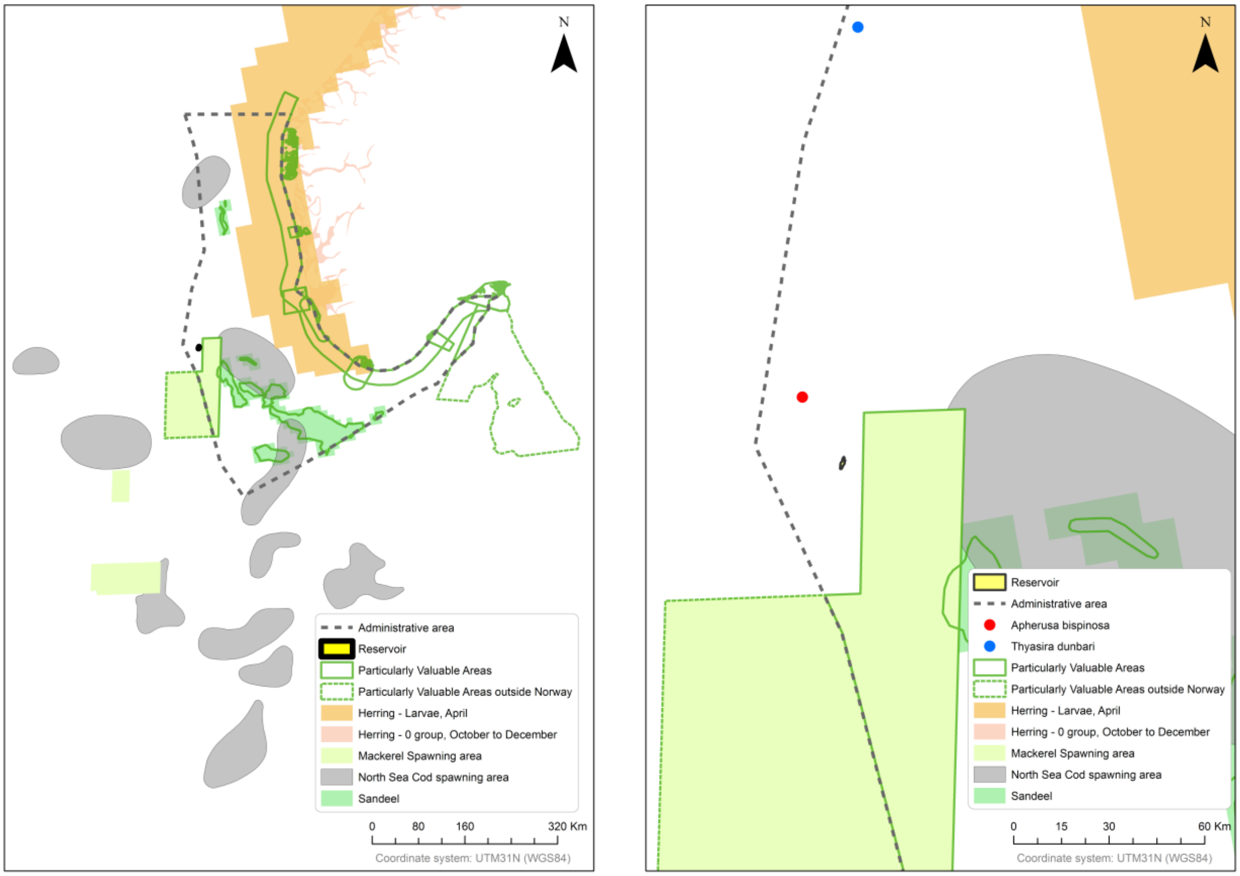


Figure 6-9 Valuable resources and areas identified but not further assessed, Sleipner. Left: overview, indicating North Sea cod and mackerel spawning areas, herring and sand eel areas and areas defined as '*Particularly Valuable*' (data sources shown in

Table 6-1). Right: Detail from left, including locations of records for *Apherusa bispinosa* (●) and *Thyasira dunbari* (●), environmental monitoring survey 2012 (DNV 2013).

Sand Eel

High fishing intensity on sand eel over the last decades has resulted in negative impacts on the spawning population. As a consequence, area specific management plans were implemented in 2010 to secure a sustainable spawning population at all historical important sand eel locations. Sand eels are known to be grain size selective, and in addition to fishing pressure, also vulnerable to activities resulting from altering the grain size composition. The sand eel area does not overlap with the potential risk area at Sleipner therefore is not further assessed in this case study.

North Sea cod

The Norwegian Red List for Species classifies the cod population (including the North Sea population) to be in very good to good ecological condition, resistant to influence without risk of significant change. However, according to Stortingsmelding 37 (2013), the North Sea cod stock has over a long period of time been overexploited and the population is considered to be below critical spawning size (Figure 6-10). The North Sea cod spawning area does not overlap with the potential risk area at Sleipner, and is therefore not further assessed in this case study.

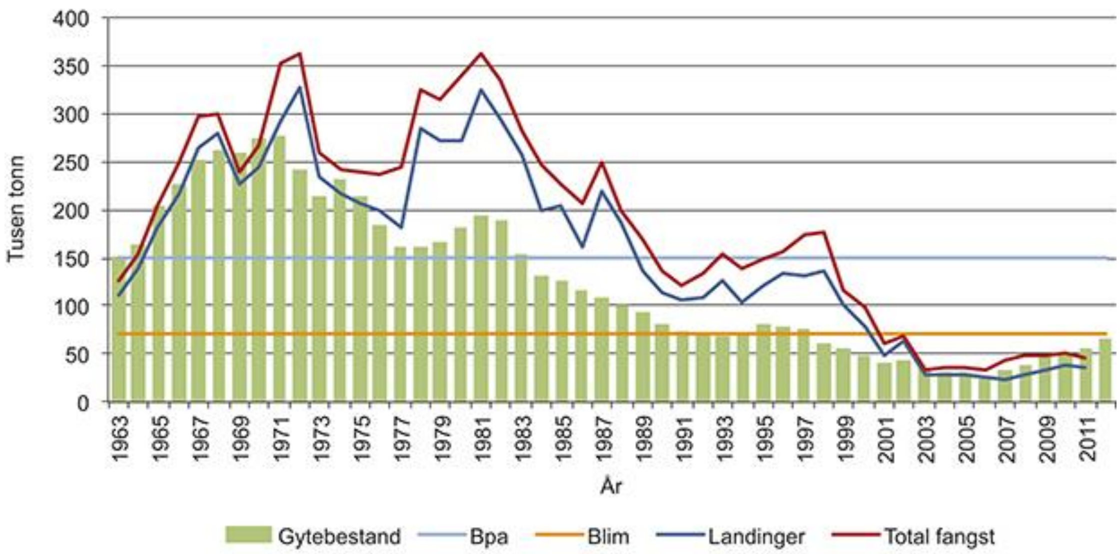


Figure 6-10 Development of the spawning population and catches of North Sea cod (Source: IMR).

Mackerel

The North Sea mackerel is the smallest stock of the Atlantic population. The spawning grounds are located in Skagerak and central North Sea. During the 1970s the population was overexploited and has yet to recover. As a consequence, strict regulations and prohibited fishing areas have been implemented. The potential risk area at Sleipner is located outside the area defined as important for mackerel, as shown in Figure 6-9. The consequence to mackerel is therefore not further assessed here.

North Sea herring

The autumn spawning herring dominates the North Sea and is considered a key species both as predator and prey. High exploitation and low recruiting over many years has led to strict regulations. The areas important for larvae and juvenile fish are found more than 100 km east of Sleipner (Figure 6-9). The consequence to North Sea herring is therefore not further assessed here.

Summary of EBSAs, value assessments and extent of influence at Sleipner

A total of four EBSA criteria have been identified within Region II. When carrying out overlay analysis between identified environmental resources and pH dispersion simulation results, a more refined picture is revealed (Table 6-4).

A change in pH concentration may influence the bivalves *Tellimya tenella* and *Arctica islandica*. The other benthic species identified as valuable are only registered with a few specimens far from the Sleipner field. Hence, they are not expected to be present within the potential risk area and are not further assessed.

Table 6-4 Identification of species within the risk area revealed from overlay analysis between EBSA identified and plume footprints

EBSA Criteria	EBSA within Region II	Overlay analysis between EBSA identified and simulation results for the Sleipner field		
		Benthic compartment	Assessment of Environmental value	Assessment of effects
Uniqueness or rarity	X	***Tellimya tenella***	**Medium**	**Small**
Special importance for life-history stages of species		-		
Importance for threatened, endangered or declining species and/or habitats	X	***Arctica islandica***	**Low**	**Small**
Vulnerability, fragility, sensitivity, or slow recovery	-	-		
Biological productivity		-		
Biological diversity	-	-		
Naturalness	-	-		

The data are further compiled in a consequence matrix (see below). The results from the consequence matrix are a direct input to the risk matrix for the given EBSA.

Table 6-5 Consequence matrix for valuable components at Sleipner.

Degree \ Value		Environmental value		
		Low	**Medium**	**High**
Degree of impact	**Small**	*Arctica islandica*	*Tellimya tenella*	
	Moderate			
	Large			

7. Evaluation and considerations of the approach for the Consequence Assessment

Sources of uncertainty

Use of a generic plume on all leak features

In this case study the assumption has been made that the leak features identified all leak in the way predicted by the modelled 'generic' chimney, and that the diameter of the feature does not affect the plume characteristics, i.e. that the feature leaks from a point source. This assumption is based on the uncertainties around the diameter, extent, characteristics and location of leak features which are input data to the case study.

The results presented in this document are based on modelled results from a generic gas chimney applied directly to several leak features identified in the Sleipner area. This can be a source of error as the plume footprint could be under- or over- representative. Ideally each relevant leak feature would be modelled in order to get specific leak feature results. Nicoll (2014) has proposed diameters for the potential leak chimneys at Sleipner. The chimneys with the suggested diameter of the features are shown in Figure 7-1 below. Applying these dimensions, and assuming a leakage over the whole area of the chimney, the plumes could potentially cover large areas. Based on the information available, the footprint of the pH change from these features is unknown. More details, input, and discussion from the plume and leak feature research areas would be required to ascertain the best method of overlaying and extrapolating plumes on leak features for the purposes of an environmental impact assessment.

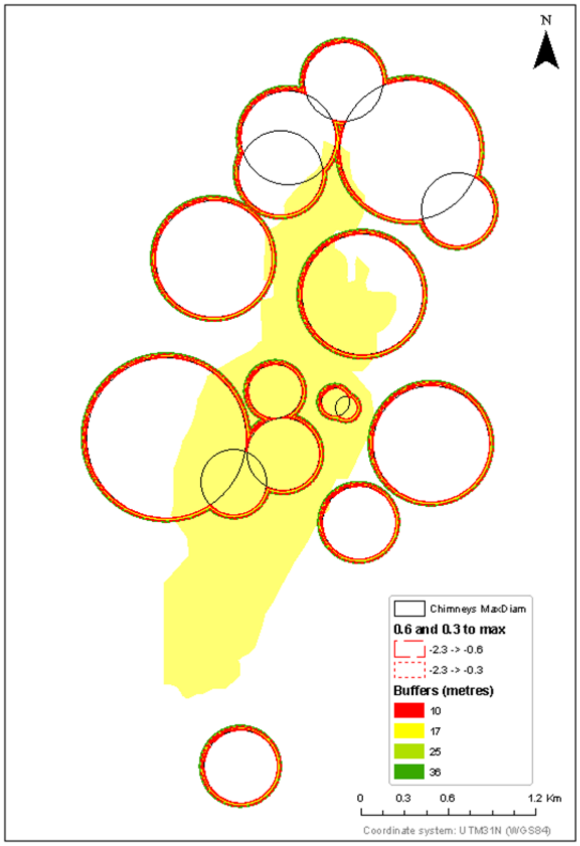


Figure 7-1 The footprint of plumes if the diameter was taken into consideration, and if it was assumed that the feature leaks all over. Diameter of leak features and chimneys proposed by (Nicoll, 2011; and Karstens, 2014 (feature 999 only). The plume from each feature is shown extending some meters from the edge of the chimney. The position of the underground CO_2 reservoir is shown in yellow.

In order to take into account the diameter of the chimney, one could extrapolate the modelled results from the generic gas chimney, and expand it, as illustrated in the figure below.

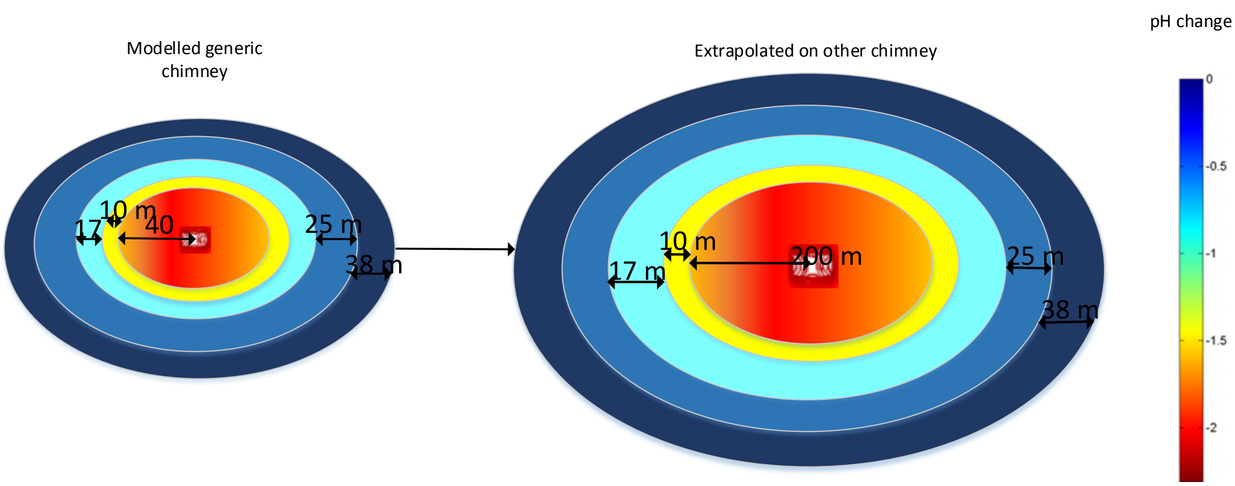


Figure 7-2 Extrapolating the modelled chimney over different sized features.

Such an approximation was considered to be unsatisfactory in this case study. Nothing is known about the leak details from these features and by introducing a concept with leakage from the whole diameter of each feature some very debatable results would be produced. It would be preferable if a plume was modelled for each leak scenario.

High dependence on plume- model input parameters

As mentioned, the plume modeling results are affected by uncertainties and are highly dependent on the input parameters to the model. Small changes in numerical model parameters can have a great effect on the overall result, especially close to the leakage location, and this highlights the need for accurate *in-situ* data (such as ocean turbulence data to determine viscosity) when modelling different locations rather than using generic values.

Uncertainty is also introduced due to an anomaly between background pH (8.3) used in the plume model, and the expected background pH at Sleipner (8.15±0.15). This introduces a few m^2 uncertainties in the footprint of the plume. This difference alters the expected area of sea-bed impacted and thus the estimated number of individuals of a species (or proportion of a community) potentially affected, but it does not affect the final consequence matrix for the community nor for the valuable species.

Areas for discussion

Assessment of Community

Research on the topic of the effect of high pCO_2 on marine organisms in general, including at the community level, has expanded rapidly in recent years. There are a number of first-rate studies assessing, collating and summarizing the impact on different taxonomic levels, including Kroeker et al. (2013), Fabry et al. (2008), Hendriks et al. (2010) among others, as well as within the ECO2 project Widdicombe et al. (in prep.)). A sensitivity index specifically designed for CO_2, based on the expanding body of information about species sensitivity will facilitate site specific assessment of effects at the community level. As described by Widdicombe et al (in prep.), such CO_2 indices are currently in development, and will eventually be widely applicable in the way that indices such as AMBI (Muxika et al., 2005) are applied globally for assessment of other anthropogenic pressures such as organic enrichment, sand extraction, petroleum activities, engineering works, dredging and fish aquaculture. As part of this study of Sleipner the effect on the benthic community was assessed by applying the AMBI index. This is not presented here as correlation between AMBI and pH change are not causative, and any conclusions about consequence at Sleipner could be misleading. The use of the AMBI index would have to be further validated by thorough testing along gradients of CO_2 before it could be applied widely. A higher priority is the generation of a specific CO_2 sensitivity index.

The benthic community in the Sleipner area is diverse, and a pH change at the magnitude modelled here would probably affect species abundance, number and diversity. At the lowest pH it is likely that all individuals are wiped out. Based on the size of the modelled plume, this effect would be locally limited to areas near the leak location. The magnitude of this effect, in relation to the area of impact on the benthic community, is considered small.

Naturalness

As part of the EBSA process which is applied by the Convention on Biodiversity to identify areas in need of protection, the criterion *naturalness* defines areas with a comparatively higher degree of naturalness as a result of the lack of, or low levels of human disturbance or degradation. In that context, a higher naturalness bestows a higher score on an area, and increases the argument for protection. However when applying the criteria of naturalness as part of a risk assessment of CO_2 leakage, a higher naturalness score could potentially *favour* the selection of a site for storage. This is because the interaction between a CO_2 plume and, for example, heavy metals in the sediment is poorly understood. It is possible that CO_2 leakage could mobilise pollutants. The area around Sleipner is considered to have a low degree of naturalness, as illustrated in Figure 7-3. This figure shows different usages of the area, and it can be seen that shipping-, fishing- and petroleum activity is high in the area.

In light of this, the *naturalness* criterion has not been assessed in terms of consequences of a leak at Sleipner, and the significance of this element will not be discussed further.

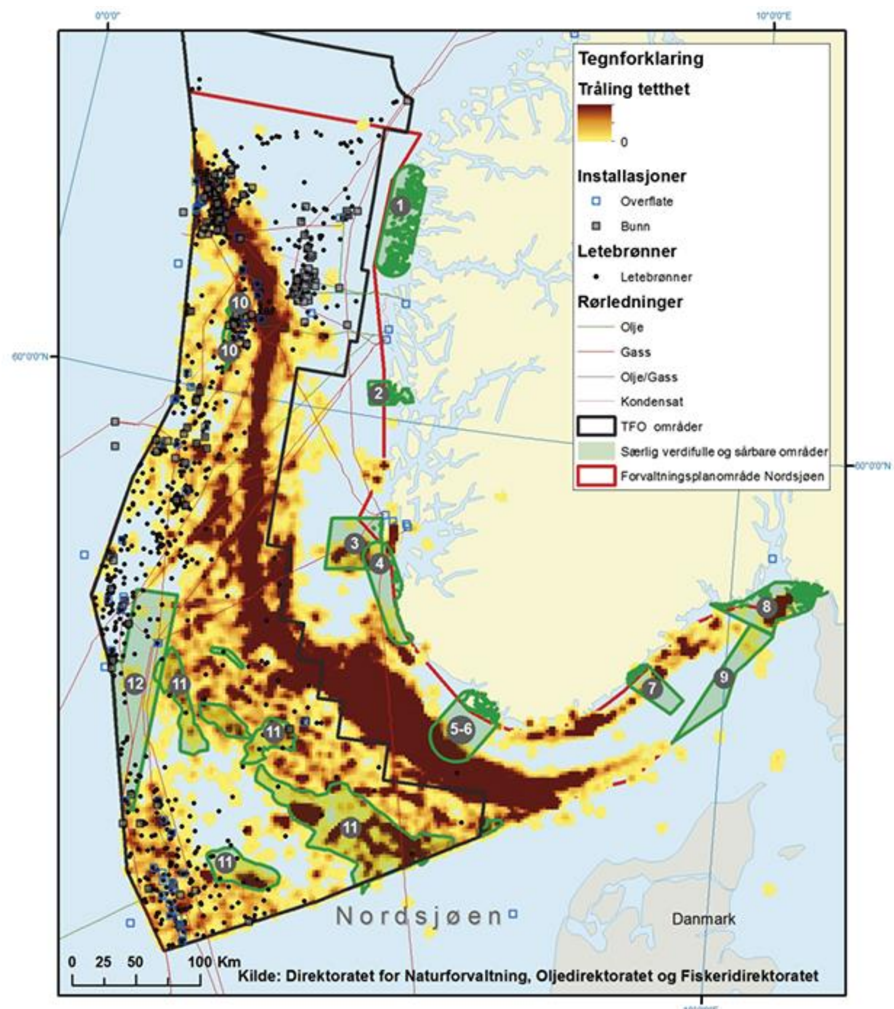


Figure 7-3 Extent of various anthropogenic activities in the area around Sleipner, including trawling intensity (brown areas), and exploration wells (●). From Direktorat for Naturforvaltning, Oljedirektorat and Fiskeridirektorat, accessed October 2, 2014.

8. Conclusions for the consequence assessment

EBSAs: A total of four EBSA (Ecologically or Biologically Significant Marine Area) criteria were identified in the wider geographical area, bringing to light eight components/ species deserving special attention. These include:

- The benthic species *Apherusa bispinosa*, *Eteone suecica*, *Tellimya tenella*, *Thyasira dunbari*, all listed in the Norwegian Red List for Species under Data Deficiency (DD). *Arctica islandica* is defined by OSPAR being a species under threat and/or in decline within the Greater North Sea.
- Sand eel areas (spawning and foraging area)
- Spawning ground for North Sea cod
- Mackerel spawning area
- North Sea herring larvae and juvenile area

Leak features and modelling: A total of 16 leak features/chimneys of interest were identified at Sleipner. Each leak feature/chimney was overlaid with a generic modelled 'worst case scenario' plume of carbon dioxide, expressed as a plume of pH change. The leak features are assumed to leak perpetually. A worst case scenario is also assessed, in that the consequence of all leak features leaking at the same time is presented. This allows an understanding of the scale of the consequence, in the context of the wider geographic area. The pH change is modelled to be very local. The plume extends maximum about 130m from the epicenter of the chimney.

Assessment of consequence: In the assessment of consequence it was identified that a change in pH concentration from leakage points may influence the bivalves *Tellimya tenella* and *Arctica islandica* on an individual level. On a population level only a very small fraction may be influenced. The other benthic species identified as valuable are only registered with a few specimens far from the Sleipner field.

The data are compiled in a consequence matrix (see below). The results from the consequence matrix will be a direct input to the risk matrix for the given EBSA. The consequence is **"Incidental"** for both species.

Consequence matrix for valuable components at Sleipner.

Degree \ Value		Environmental value		
		Low	Medium	High
Degree of impact	Small	*Arctica islandica*	*Tellimya tenella*	
	Moderate			
	Large			

9. Leakage Probability Assessment

About 850 thousand tons of CO_2 have been injected yearly into the Sleipner Utsira formation since 1996. The level of stakeholder support has been very high for basic and applied research on how this CO_2 is moving and evolving in its target reservoir. Data collection from the subsurface, mapping of the storage volume, visualisation of the stored CO_2, reservoir modelling and laboratory experiments have been performed on numerous projects supported by the EU Thermie Programme, 5th, 6th and 7th FP, national research councils in Norway and other countries. The project has provided unique access to Sleipner Utsira site datasets to many researchers and graduate students and the number is historically high of peer-reviewed and popular publications resulting in dissemination of knowledge for a single geoscience project.

Introduction and Motivation

Yet some important issues on storage performance still inspire new enquiry and paths of discovery. It is also common knowledge in the geosciences of the subsurface, that the more time and effort used to collect data, survey and to investigate, the more that is observed, revealed and learnt. The ECO2 project confirms this.

The primary question regarding CO_2 geological storage on the minds of both specialists and the general public alike is

"What happens to the CO_2 once it is stored in the underground?"

There are many physical and chemical processes of flow in porous and permeable rocks. These include the chemistry of rock-fluid interaction, geomechanical stress state changes due to increasing reservoir fluid pressures and natural seismicity, and thermodynamics acting over time scales from days to millennia and spatial scales of micrometres to kilometres involved in answering this question. Representing all of this in a single, integrated numerical model for the entire storage complex is still not a feasible task, although some progress has been made on integrated simulation models with simplified physics and coarse discretisation in space and time. Therefore the more risk-based focus is on the **subsidiary** question:

"What is the likelihood that the stored CO_2 will leak and return to the sea bed (surface) or contaminate some protected formation

A first comparison of the two questions would indicate only subtle distinctions between them, but the differences become much clearer when trying to answer these using geoscience and risk analysis methods and tools. The ECO2 WP5 approach has been to focus on the **subsidiary** question addressing directly the leakage propensity, the reasoning of which is explained below. The risk-based approach combines the likelihood of undesired events with their potential impacts or consequences. The scope of this section is on likelihood only. Sections __ discuss potential impacts and combine likelihood estimates to produce risk estimates.

The first question (*"What happens to the CO_2 once it is stored in the underground?")* involves rigorous multi-process coupled physics, mathematics, numerical methods, advanced software and complex analysis combined with comprehensive mapping and characterisation of the subsurface from the millimetre scale to the kilometre scale based on a variety of proxy measurements in wellbores, acoustic seismic surveys and direct measurement on rock and fluid samples in laboratories. The level of effort required from a wide range of specialists is daunting and the need for software capabilities and computer capacity substantial. In practice, a number of simplifying assumptions are made to “tailor” the modelling scope such that more commonly used, commercially tested software packages can be applied.

One such simplifying assumption is that the cap rock[1] is effective, i.e. it is hydraulically sealing and will not leak. This assumption allows the reservoir simulation model to comprise the storage target formation alone, which is the approach most commonly applied in reservoir simulation of oil and gas recovery and production. It has also been the starting point of several studies and forecasts of the Sleipner Utsira CO2 geological storage.

The assumption that the cap rock is leak-tight essentially pre-empts the whole assessment of propensity to leak and subsequent impacts. Therefore, the approach taken here is to assume that the cap rock can potentially leak at discrete locations given specific combinations of rock and fluid factors and conditions. The main evidence for these combinations is provided by the

- mapping and characterization of the subsurface volume referred to as the “storage complex”
- time-lapse 3D (4D) acoustic seismic images over the target reservoir where CO_2 is stored and moving (the ‘plume’ in the subsurface)
- calibration of dynamic reservoir models to re-produce the observed 4D and potentially observation well data
- forward modelling of the movement of CO_2 within the target storage formation based on the calibrated reservoir simulation model
- Reports of original conditions and subsequent inspections of wellbores that may be contacted by the stored CO2 and which may not be perfectly sealed, which is also connected to forward modelling of the movement of the CO2 and reactions therewith in case of contact with the affected wellbores.

It should be noted in all cases that there is currently no empirical, conclusive evidence from the original Utsira baseline survey and seven repeat seismic surveys[2] that CO_2 has escaped from the target storage formation (Utsira).

The body of acoustic seismic survey data collected over the Sleipner area does show however that natural leakage vertically through the overburden has occurred hundreds and thousands of millennia ago, long before the start of CO_2 injection. Evidence of ancient leakage is seen at various discrete locations

[1] The cap rock is the barrier preventing buoyant movement of the stored CO_2 upward through to shallow zones and the surface. In most storage sites there are of series of cap rocks that form a barrier system.
[2] Pre-injection baseline seismic survey collected in 1994, repeat surveys in 1999, 2001, 2002, 2004, 2006, 2008 and 2010.

throughout the geological record, which is seen as the sequence of sediments above the Utsira formation.

The starting point for this study can be summarized by the three main observations on the Sleipner Utsira CO_2 geological storage site that

- The geological record as evidenced mainly by the proxy data of acoustic seismic surveys over the Sleipner area shows in the area including and around the CO_2 storage site ancient features, events and processes that can be labelled as signatures of ancient leakage, but that
- There is currently no evidence in the seven repeat seismic surveys of the entire stored plume of CO_2 in the Utsira that it is leaking from the target storage formation.
- The seven repeat seismic surveys over the Sleipner area show that internal movement of stored CO_2 within the Utsira formation has breached a number of thinner (<2 m) mudstones and one thicker mudstone (5-10m) on a vertical line extending above the injection point or nearby to this line.

Section 11 explains the motivation for the methodology chosen for estimating propensity to leakage.

Section 12 presents the main Features, Events and Processes (FEPs) for the Sleipner Utsira CO2 geological storage.

Section 13 describes in detail the event related (in the context of FEPs) to leakage propensity estimates called "exceeding the local capillary entry pressure" at the base cap rock on the Sleipner Utsira storage.

Section 14 describes in detail the Bayesian Net sub-model that represents the feature (in the context of FEPs) referred to as a "chimney"[3], which for this study also represents similar features identified by the acoustic seismic survey data, e.g. "pipes".

Section 15 describes the Bayesian Net (BN) model features.

Section 16 summarizes BN model inputs and section 17 main BN model outputs and discussion.

Motivation for using Bayesian Belief Net (BN)

A Bayesian network (BN) is a graphical tool that applies Bayesian probability methods to aid risk-based decision-making under conditions of uncertainty. The versatility of BN application is illustrated by the very wide range of risk analyses encountered in a variety of publications (Bolsover, 2013, examples provided in Appendix A). The general framing of testing a hypothesis, e.g. that a CO_2 geological storage might leak in the future, by applying the Bayesian method is described in Appendix B.

[3] The terms seismic chimney and pipe are used in interchangeably in many examples in the literature. Following Andresen (2012), some publications use the term seismic pipe for narrow, strictly columnar anomalies associated with stacks of high amplitudes, and seismic chimneys for dimmed or distorted amplitude anomalies that may have a complex shape and much larger dimensions.

Kjaerulff and Madsen (2008) give a comprehensive description of the mathematics and numerical techniques involved in creating, solving and applying BN models to practical problems that involve representing and handling uncertainty and ambiguous evidence, including

- diagnosis of symptoms to determine conditions of sickness and disease
- exploration for oil and gas and the value of collecting pre-drill data
- decisions related to investment in agricultural projects
- fraud detection

Features of a BN which distinguish it from other decision-support tools are described here. A BN is uniquely suited for application to problems which have a high level of *inherent* uncertainty, which is different from the type of uncertainty typified by well-defined but random processes, e.g. the throw of fair dice. Bayesian net models can handle both inherent uncertainty and the well-defined statistics of completely described random processes.

The distinctive advantage of the BN is that it can represent processes which may contain some degree of poorly understood bias. “Inherent uncertainty” refers to situations where the probability of an event is not clearly defined, but might be indicated by a variety of experience, expert opinion and evidence, some of which may be conflicting or ambiguous. It is considered particularly appropriate for the situation of interpreting acoustic seismic survey data, which is characterized by a locally variable mixture of signal and noise, may be biased by processing, and ultimately requires some subjective interpretation of signal morphologies for which there may be multiple, equally plausible but mutually exclusive explanations. It is a widely recognized fact that seismic data forms a large part of the basis of identifying conventional oil and gas exploration prospects, and that the overall discovery rate (after drilling the prospects) for this industry varies from year to year but is generally <40% (Sandrea and Sandrea, 2007). In other words, seismic data can be indicative, but are seldom conclusive and are sometimes misleading given the complex nature of what influences the return signals and noise from the subsurface collected during a survey.

To illustrate the ability to handle decision and risk assessment problems with inherent uncertainty it is notable that:

− Bayesian models can be run with missing data

− Bayesian models can use uncertain data and quantify the effects of uncertainties

− Bayesian models can handle situations where the level of knowledge and understanding is low

In short, the situations where use of BN in a risk analysis may be preferred are summarized by John Tukey (1962): *“Far better to find an approximate answer to the right question, which is often vague, than an exact answer to the wrong question, which can always be made precise”.*

A BN has the ability to perform both forward and reverse inference. A conventional QRA uses input data and modelling to estimate the future likelihood of an undesirable outcome, such as a fire or a fatality.

This is an example of a forward inference - from the causes to the effects. A Bayesian network can make this type of inference, but it can also make a reverse inference – from the effects to the causes. For example, a Bayesian network would be capable of ranking the probability of possible causes of a fire or fatality that have already occurred. The capability to perform reverse inference means that a BN also finds application in systems for medical diagnosis. Key features are therefore:

− BN models can be used to estimate the probabilities of future outcomes

− BN models can also diagnose the probable causes of each realised outcome

A BN converges typically in seconds. The software solutions engines for Bayesian network are very quick. This means that Bayesian networks can be suitable for reassessment of situations that change from day to day, or even minute to minute. The speed of solving a Bayesian network depends on its complexity, but for many types of problems it is realistic to expect software run times in the order of 1-100 seconds. When combined with the characteristics of BN as listed above, they have potential for application in real-time monitoring of the evolving risk state of complex systems, which for the case of offshore geological CO_2 storage, would be to reflect the tendency of a site to leak to the sea floor and create negative impacts to local ecosystems.

Specific Motivation for using BN for CO2 Storage Site Leakage Propensity Estimates

Two contrasting chains of logic can be applied when analysing acoustic seismic survey data for mapping and predicting leakage pathways from CO_2 geological storage site. These are summarized in the tableTable 9-1 below.

Table 9-1. Two contrasting chains of logic for evaluating the leakage propensity of a seismic anomaly identified as a "chimney"

Chain of Logic supporting the "leakage pathway" hypothesis	Chain of Logic weakening the "leakage pathway" hypothesis
The acoustic seismic morphology looks like a seal bypass feature, e.g. chimney, pipe or leaky fault.	**If the acoustic seismic morphology is unclear due to noisy data, it may not in fact be a seal bypass feature.**
This feature indicates that a rapid, vertical migration of fluid (likely CH_4) occurred in the geological past.	**If it is in fact a seal bypass feature, the permeability within it may actually be "healed" meaning it has permeability close to or even lower than the background permeability.**
The identified feature is therefore concluded to be at present a higher-permeability conduit that can promote CO_2 leakage if the stored plume intersects it, i.e. comes into contact with it.	**If this acoustic seismic feature is intersected by the stored CO_2 plume, it may therefore not promote leakage any more than the background rock.**

One strategy to provide mathematically consistent estimates of leakage propensity would be to represent the entire storage complex and all its relevant characteristics using a digital model, and based on this, model specific scenarios of CO_2 injection and different plausible descriptions of the storage complex, including those directly or indirectly related to the two chains of logic above.

The level of software, hardware and expert user input to perform this in a way that represents all relevant flow physics, geochemistry and thermodynamics (including phase behaviour and heat flow) is daunting, and inevitably, the process is made feasible by

- reasoned assumptions that significantly simplify the physics, and
- reducing the outcome space to only a few scenarios which are then modelled as to represent all the uncertainty and design choices, e.g. number and location of injection wells (and in some cases water production wells for reservoir pressure management) and their injection (or production) rates.

The opportunity for a BN approach for leakage propensity estimation is therefore to allow for a wider range of plausible scenarios to be represented in a much simpler, more leakage-focused calculation framework which allows for more qualitative, subjective input from experts, in combination with more “hard” physical or model-based evidence.

Main Features, Events and Processes (FEPs) for the Sleipner Utsira CO_2 geological storage

The initial phase of any study of the long-term performance of a CO_2 geological storage site has been comprehensively described by Wildenborg et al. (2009) and Savage et al. (2004).

The Sleipner Utsira site has been the subject of multiple collaborative research projects, graduate student theses and commissioned studies. Given its (soon) 20 years of CO_2 injection operations, 8+

acoustic seismic and geophysical surveys, and numerous reservoir simulation and history-matching processes, the Utsira CO_2 injection no longer needs screening tool results that the FEPs database and workflow are intended to serve.

So although no formal FEPs profile has been published for the Sleipner Utsira, most if not all of the various Features Events and Processes relevant for long-term storage have been inventoried by pre-ECO2 work (e.g. Nicoll, 2011) and within the ECO2 project. These are briefly summarized here.

A formal Area of Review (AoR) was chosen for this study. It is defined as a rectangle with the corner in the southwest at UTM (428600, 6460000) and far corner in the northeast at UTM (443600, 6480000). This rectangle is 15 km wide (east-west) and 20 km long (north-south).

It is seen on Figure 9-1 that the current footprint of the CO2 in the target Utsira formation is less than 1% of the AoR. Thus the AoR is considered an absolute maximum for modelling and investigation. A smaller subset may be optimal in practice.

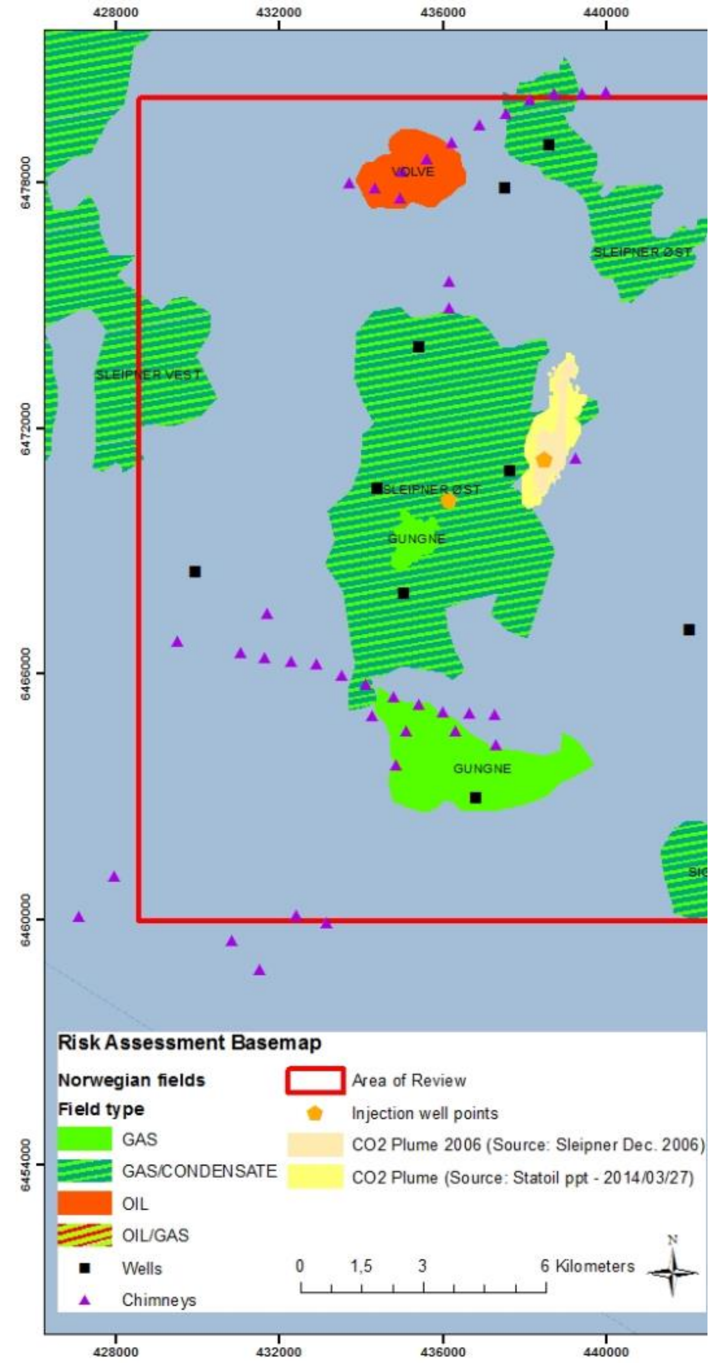


Figure 9-1. Area of Review (AoR) for this study. Data compiled from WP1, Karstens (2014), Nicoll (2011) and the Norwegian Petroleum Directorate website. The CO_2 plume is its extent at the top Utsira formation and this does not refer to a leaked CO_2 plume.

Features

These are generally classified into wellbores, faults, intrusions and seal bypass features.

Wellbores

A single plugged and abandoned exploration wellbore, 15/9-13 is within 5 km of the outermost edge of the stored CO_2 as indicated by repeat seismic surveys. A total of 9 wellbores penetrate the Utsira formation in the AoR. All these are "down slope" of the local structural top where CO_2 is currently observed to be accumulated. The only mechanism by which the stored CO_2 can contact these wellbores is by "fill and spill", meaning local structural traps will have to fill with CO_2 to the point its "spills" across local structural low points, and then proceed to fill neighbouring structural highs.

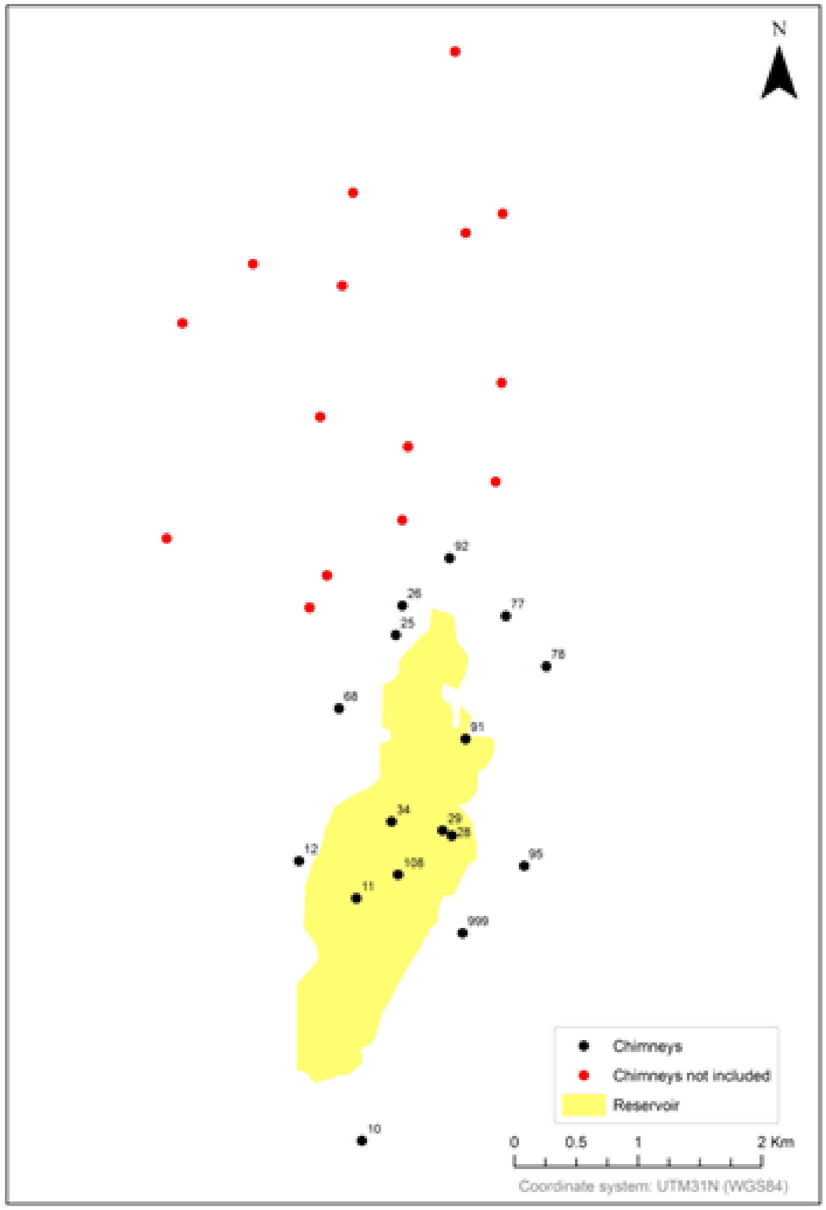


Figure 9-2. Identified potential leak structures in the Sleipner area. Black symbols represent leak feature included in the assessment. The yellow area represents the outermost extent of CO2 at the top of the storage target reservoir as indicated by time-lapse acoustic seismic survey data.

The important parameter to note for the wellbore table below is that the top Utsira for all wellbores in the AoR are deeper than for the CO_2 injection well, with the exception of 15/9-11, which is about 4 km from the edge of the stored CO_2 at the top reservoir level. This means that that all wellbores are "down dip" and that CO_2 must either flow downhill against buoyancy or the structure must fill with stored CO_2 on a regional scale in order for CO_2 to contact these wellbores and potentially leak. It is considered virtually impossible for either the Utsira top structure to fill with CO_2 or for stored, buoyant CO_2 to flow "downhill", and therefore none of these wellbores are considered at risk of leaking stored CO_2.

Table 9-2	Wellbores within the AoR, not including platform gas production wells drilled from the Sleipner platform	
Well number	Location description in the AoR	Top Utsira/Sand Wedge mMSL
15/9-A16	CO_2 injection well	800 (directly above injection point)
15/9-17	most northern	810
15/9-19	2nd most northern	818
15/9-11	3rd most northern	800
15/9-13	closest to the CO_2 injector	822
15/9-16	west of Sleipner platform	818
15/9-18	most western	842
15/9-09	south of Sleipner platform	819
16/7-08	most eastern	851
15/9-15	most southern	859

Faults and related

Seal Bypass Features

Cartwright et al. (2007) document their taxonomy for different subsurface features that can allow buoyant fluids to migrate vertically through or around sealing cap rocks. The top-level taxonomic types (with the number of sub-types in parenthesis) are

1. Faults (2)
2. Intrusions (4) and
3. Pipes and chimneys (4).

The term “chimney”[4] has also been introduced to describe seismic anomalies which are believed to be caused by seal bypass events or processes that occurred in the geological past. ECO2 work package 1 plan includes extensive mapping of seal bypass features in an area larger than the AoR for this WP5 activity. The term seal bypass feature includes any long, narrow, vertical morphology on the seismic survey data that is indicative of rapid movement of fluid from deeper zones to shallow zones, and any seismic data “anomaly” that indicates collection of gas at different formations in the subsurface in connection with seal bypass events in the geological past. Karstens and Berndt (2015) describe a further classification of chimneys into sub-types (2015).

When gas migrates from deep source rocks, residually trapped gas stays behind and generates a vertical noise trail on seismic data. These noise trails are known as chimneys and they indicate were migration has taken place. By detecting and studying these chimneys a qualitative assessment of the risk of gas migrating through a (sealing) formation can be made (Ligtenberg, 2005).

[4] The terms defined by Andresen (2012) are used here. A ‘seismic pipe’ is a narrow, strictly columnar seismic anomaly associated with stacks of high amplitudes. A ‘seismic chimney’ is a dimmed or distorted seismic amplitude anomaly of complex shape and much larger dimensions.

Several studies (Barthold et al., 2003; Heggland et al., 2000; Meldahl et al., 2001) reported examples of gas chimneys and described their observable characteristics on seismic data. Chimneys can be detected on seismic data based on their shape and energy characteristics. They are characterized by:

1. a vertically cylindrical and elongated shape (circular on horizontal slices and elongated on sections);
2. lower energy compared to its surrounding area and the disturbance of lateral continuous layers;
3. their association with bright spots at shallow depths;
4. they can terminate at seabed anomalies such as mud-volcanos and pockmarks.

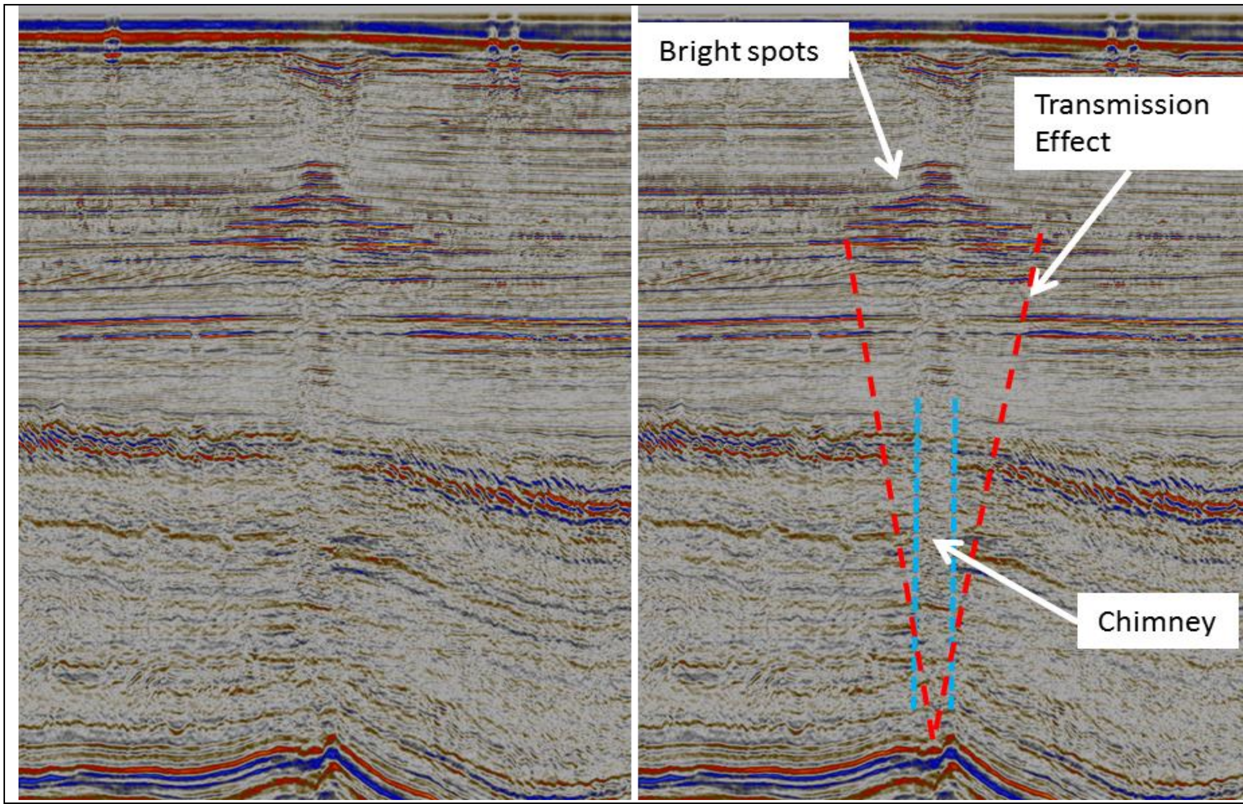


Figure 9-3. Example from the Dutch North Sea (A15) that shows a central chimney (in between the blue lines) that ends at several bright spots (Shallow gas), and the transmission effect (shadow zone) below the bright spots. Note the V shaped nature of the transmission effect.

Unfortunately, there is another seismic phenomenon that looks similar on seismic data: The transmission effect. This phenomenon is a cone shaped shadow below a bright spot (Figure 9-3). There is so much energy reflected upwards by the gas accumulation associated with bright spot that the layers below seems to have a lower energy compared to the same layers that are not overlain by the bright spot.

An important discriminating characteristic of the transmission effect is that it has a V shape appearance, which is caused by depth-varying illumination angle. Due to this, the seismic wave would better illuminate the deeper reflectors by incorporating more of incident angles close to the vertical via traveling from one side of the bright spot underneath the bright spot (undershooting) and be recorded at the other side.

It is often very difficult to discriminate a chimney from the transmission effect. However, when the dim zone has the same width of the bright spot and has a V shape it is most likely transmission effect. In previous studies, sometimes the transmission effect has been interpreted as chimneys.

Events

Detailed description of the event referred to as “exceeding capillary entry pressure” comes in section 13 .

Processes

There are three main processes relevant for the Utsira CO_2 storage characterization.

1. Change in reservoir pressure due to CO_2 injection and formation water production from hydraulically connected parts of the Utsira formation
2. Change in local pressure due to the presence of a buoyant column of CO_2 under a local top in the Utsira formation in which CO_2 can accumulate
3. The stored CO_2 displaces reservoir brine, which can flow through newly created or pre-existing leakage pathways, including pathways to the sea floor

The first process relevant for Sleipner Utsira is the change in reservoir pressure due to injection and production of fluids from the Utsira in the region including the AoR and nearby parts of the Utsira in which fluids are being injected and produced by other field developments.

The Volve field has been producing about 100 thousand barrels/day of water from the Utsira formation since 2007. It uses this water for injection into its oil reservoir for pressure maintenance and increased oil recovery. Although the water production wells on the Volve field are about 7 km from the CO_2 injection well, the Utsira formation has exceptionally high permeabilities due to its largely uncemented, well-sorted sand (Chadwick, et al., 2004), and because of this, pressure communication between the Volve water production and the CO_2 storage project is believed to be high. Therefore, it is believed that in the volume of the Utsira formation surrounding the CO_2 injection well, average reservoir pressure is most likely not increasing as long as water is produced from the Utsira formation at the Volve field at current rates.

The Sleipner gas field is depleting and is expected to stop producing before 2020. It is assumed that the injection of the associated CO2 into the Utsira formation will cease then and no further CO2 injection will take place in the Utsira formation.

However, near the injection point in the Utsira formation, a small overpressure of 1-3 bar may have developed due to local accumulation of injected CO_2. This cannot be confirmed or discounted based on pressure measurements at the wellhead due to the aggregate uncertainty in conditions in the coupled wellbore/fluid/overburden system which prevents precise calculation of sand-face injection pressures. No downhole pressure gauge is installed in the CO_2 injection well.

The second process is covered in detail in section 4.

The third process has been concluded by the ECO2 to be outside the scope of this project and is therefore not covered in WP5 or this case study.

Description of the event of exceeding the local capillary entry pressure at the base cap rock at Sleipner Utsira

The key process related to potential CO2 leakage at Sleipner Utsira is described here. As a first approximation, a mudstone/siltstone (which are often referred to as shale even if it is soft and not lithified) layer of a few meters thick can be considered a flow barrier. In other words, it will prevent a buoyant fluid from migrating vertically. However, there are numerous features and physical processes which can allow buoyant fluid to breach such a mudstone layer, and the leakage probability estimate question then becomes, what are those conditions which can allow buoyant fluid to breach the mudstone? If the mudstone layer is relatively “thin” (<2 meters) then it can be reasonably postulated that it is not continuous, and may have “holes” that can allow buoyant fluid to pass through. For thicker mudstones, the postulate of “holes” becomes less plausible as there are few sedimentary processes known to create such “holes” and are considered to occur rarely in such thick mudstones.

For the Sleipner Utsira case, it was known already from the first repeat seismic survey (1999) that a 5-10 meter thick mudstone separating the main Utsira formation from the “sand wedge” was breeched by the injected CO_2 migrating upward driven by its own buoyancy. This mudstone appears prominently in the seismic data sets and is considered correlatable over distances of tens of kilometres. The observation that it has been breached by upwardly buoyant CO_2 can be explained by other features and processes than “holes”, and these are briefly summarized here.

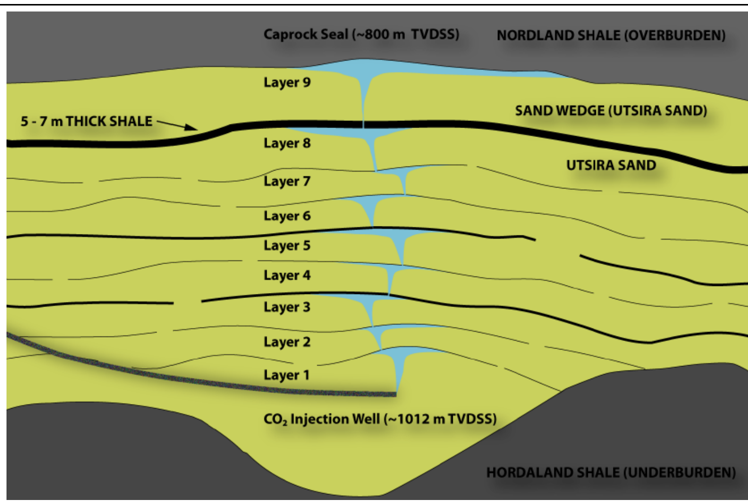


Figure 9-4. Side view conceptual description of movement of CO2 from the injection point up to top Utsira formation (Nicoll, 2011), based on detailed processing and interpretation of repeat acoustic seismic survey data

Several investigators have studied the breach of the mudstone at the base of the sand wedge. Nicoll summarized their findings in his PhD thesis (2011).

"Supercritical CO_2 has a lower density contrast with respect to pore water than natural gas, necessitating higher capillary entry pressures to overcome the threshold pressures of water-wet mud rocks. Laboratory experiments show that both natural gas and supercritical CO_2 require the presence of fractures or faults to ingress shales at low capillary entry pressures (Harrington & Horseman, 1999; Springer & Lindgren, 2006; Harrington et al., 2009). But only three years after CO_2 injection commenced at Sleipner, CO_2 was detected in the sand wedge underlying the Utsira caprock, having breached or bypassed eight internal mudstone barriers, including the ~5-7 m thick barrier immediately underlying the sand wedge. Various seal bypass mechanisms are proposed for these barriers within the Utsira Formation, including

- *micro-fractures,*
- *injectites*[5]*,*
- *carbonate cement dissolution,*
- *sub-seismic faults,*
- *lateral discontinuities,*
- *erosive holes created by high-energy deposition of overlying sands and*
- *chimney excavation (Zweigel et al., 2004a; Hermanrud et al., 2007, 2010).*

Similar mechanisms may also affect the overburden."

The mechanism of breach of the mudstone that Nicoll gives most probability is that the buoyant pressure of the CO_2 exceeds at a local location on the base mudstone its local capillary entry pressure. In other words, this is essentially the local pressure of the upwardly buoyant CO_2 creating its own leak path by forcing the opening of a larger, connected network of macro-pores in the mudstone that are hydraulically conductive, as illustrated conceptually in **Figure 9-5** below.

[5] Narrow, focused sand body that has penetrated the background mudstone layer at a time after the mudstone was deposited. Such a sand body may be created by continuously loading of new sediment on unconsolidated sands, such that geomechanical forces "squeeze" a semi-liquid sand formation upward after some threshold loading is realized.

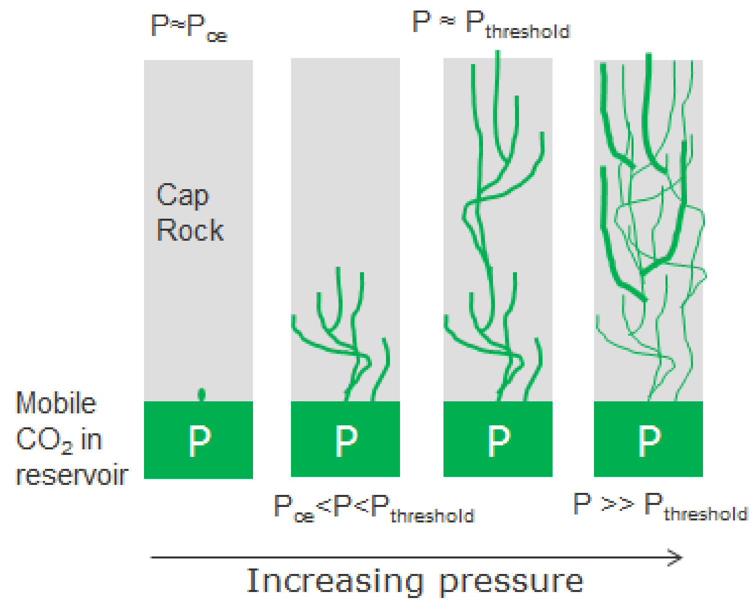


Figure 9-5. Stages of (green) non-wetting fluid breakthrough across porous media during a capillary drainage process (modified from Hildenbrand et al., 2004)

This study has therefore chosen to include in the overall leakage propensity estimate statement the potential to locally exceed the capillary entry pressure. This is done by applying a BN technique to the weighing of the available evidence for exceeding the local capillary entry pressure. This is considered relevant both

- where there is acoustic seismic survey evidence of ancient (pre-existing) leakage events (chimneys and pipes and related features)
- and where there is absence of such proxy evidence of ancient leakage events, i.e. anywhere a column of stored CO_2 is collecting below a cap rock

Additional considerations in this context are uncertainties in the future movement of the stored CO_2 within the target formation is due to uncertainty in mapping and characterizing the subsurface.

The platform for estimating leakage probability is now presented here. Instead of representing the leakage problem as a 3D digital map of the reservoir, fluids and general geological setting with flow governed by petrophysics, fluid flow and thermodynamics, the leakage problem is represented by an abstraction of linked probabilities of the features, events and processes considered to be directly influencing the potential CO_2 leakage. This is seen conceptually in the following sketch of a causation process of events in series. A loop structure is indicated for when a CO_2 leak must pass through alternating layers of reservoir lithologies and cap rock lithologies.

This is the basis of a BN model for estimating propensity for the CO_2 geological storage site to leak.

The core description of the leakage propensity question in the leakage risk assessment is shown below in **Figure 9-6**.

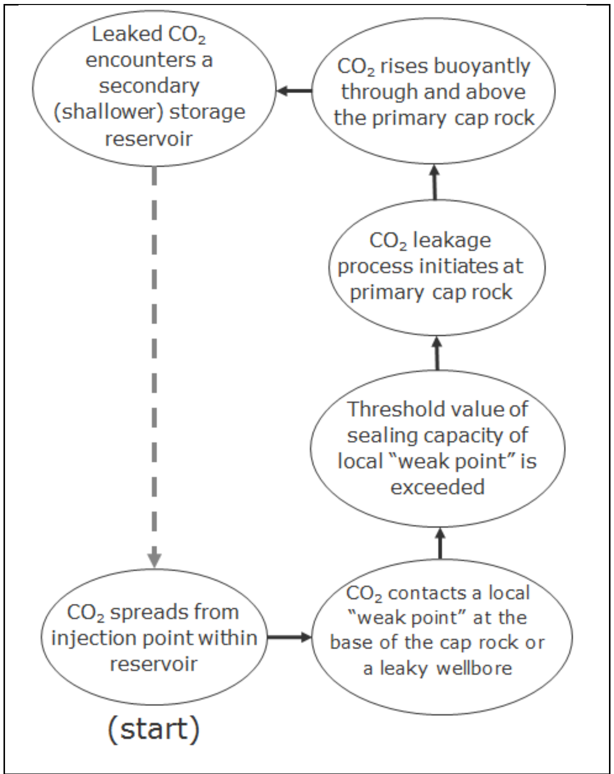


Figure 9-6. Conceptual sketch of causality in CO2 leakage from a storage reservoir

Capillary entry pressure is usually expressed as a maximum vertical column of buoyant fluid that can be "held back", implying that a "thicker column" buoyant fluid will cause the capillary entry pressure to be exceeded, leading to breach of the capillary seal of the cap rock and vertical flow upwards. The following equations are often applied.

$$P_{capillaryEntryPressure} = \frac{2\sigma cos\theta}{R_{maxPore}}$$

$\sigma = interfacial\ tension\ between\ brine\ and\ CO2\ at\ reservoir\ conditions$

$\theta = contact\ angle\ of\ CO2 - rock$

$R_{maxPore} = radius\ of\ largest\ pore\ throat\ at\ entry\ location\ of\ CO2$

The pressure exerted by a buoyant column of fluid is given by

$$P_{buoyantColumn} = (\rho_w - \rho_{CO2})gH_{CO2}$$

$\rho_w = in\ situ\ density\ of\ reservoir\ brine$

$\rho_{CO2} = in\ situ\ density\ of\ stored\ CO_2$

$g = acceleration\ of\ gravity$

$H_{CO2} = height\ of\ the\ CO2\ column\ at\ the\ top\ reservoir\ in\ the\ top\ of\ the\ local\ structural\ high$

Combining these two equations gives the expression for the maximum CO_2 column before exceeding capillary entry pressure for the case of no increase in reservoir pressure, i.e. reservoir pressure is equal to initial.

$$H_{CO2max} = \frac{2\sigma cos\theta}{(\rho_w - \rho_{CO2})gR_{maxPore}}$$

If there is an increase in reservoir pressure due to the injection process, which is very likely the case for Sleipner, the increase in reservoir pressure must also be included. This gives a modified version of the previous equation.

Total hydraulic load due to the pressurized, buoyant CO_2 at the maximum value, i.e. when the capillary entry pressure is reached, is then

$$P_{capillaryEntryPressure} = \Delta P_{reservoir} + P_{buoyantColumnMax} = \Delta P_r + (\rho_{brine} - \rho_{CO2})g\, H_{CO2max}$$

Re-arranging gives

$$H_{CO2\,\mathrm{max}=}\ \frac{(P_{capillaryEntryPressure} - \Delta P_r)}{(\rho_{brine} - \rho_{CO2})g}$$

And substituting into this the initial equation for capillary entry pressure yields

$$H_{CO2\,\mathrm{max}=}\ \frac{\left(\frac{2\sigma cos\theta}{R_{maxPore}} - \Delta P_r\right)}{(\rho_{brine} - \rho_{CO2})g}$$

This form allows uncertainties in all constituent parameters to be included directly. Some of these parameters are particularly sensitive to pressure and temperature, most importantly, in situ density of CO_2. Reservoir pressure and temperature are both estimated, i.e. not directly measured, in the Sleipner Utsira formation at the site of the CO_2 injection. Previous investigations have analysed the role of the uncertainty in reservoir temperature on CO_2 properties (Lindeberg et al., 2009; Chadwick & Noy, 2010, Nicoll, 2011).

A Monte Carlo approach to this uncertainty problem has been applied in a comprehensive study of leakage probabilities from the Utsira CO_2 storage site (Nicoll, 2011). This study leveraged all available laboratory measurements of fluid, rock and capillary pressure properties available on core material from the Nordland mudstones and similar rock types. However the very likely increase in background reservoir pressure near the CO_2 injection point in the Utsira formation was not represented.

A simple sketch of the main features of the buoyant effect of the stored CO2 in the Utsira formation is shown on **Figure 9-7**. A more comprehensive illustration of the equations discussed above regarding the process of exceeding the local capillary entry pressure is shown on **Figure 10-8**.

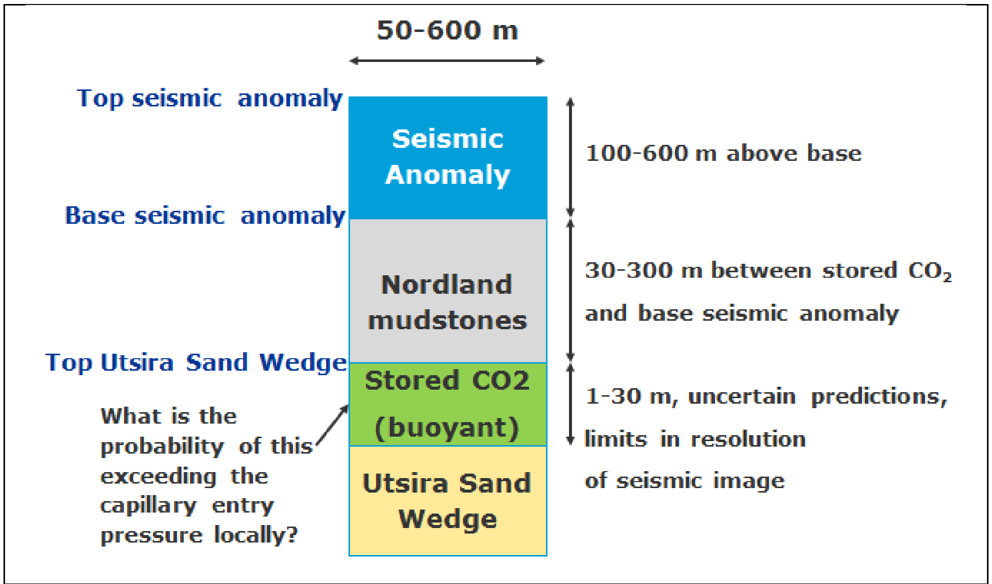


Figure 9-7. Conceptual model for risk of exceeding capillary entry pressure due to accumulation of buoyant CO2 at top the Utsira Sand Wedge

Description of the key fracture identified within the Sleipner assessment AoR

A fracture with connection to the seabed has been identified by the ECO2 project about 25 km northwest of the CO_2 injection well and has been referred to as the 'Hugin' fracture (ECO2 deliverable D1.1). Detailed analysis of shallow seismic data, seabed bacterial mats and seepage to the seabed indicates flow from a source of water with clearly different profile than the seawater in the area, and is suspected of being from a medium-deep zone. This fault is associated with potential leakage from deeper zones, however, it will **not** come into contact with the stored CO_2 due to its distance and location relative to the location of the stored CO_2 as deduced from time-lapse seismic surveys and forward reservoir simulation modelling.

Description of the feature "Chimney" in the context of estimating leakage propensity at Sleipner Utsira

The essential description of the BN framing of estimating leakage propensity due to features identified on acoustic seismic survey data, i.e. seismic anomalies, as being chimney structures was introduced in section 12. A 'seismic chimney' (or simply chimney) is a dimmed or distorted seismic amplitude anomaly of complex shape and relatively larger dimensions. A 'seismic pipe' is a relatively narrow, strictly columnar seismic anomaly associated with stacks of high amplitudes. For this text, only the term 'chimney' will be used to indicate either anomaly type in the terminology of Andresen.

For a chimney structure to form a vertical flow short-cut or conduit for stored CO_2, it must first be contacted by a part of the subsurface CO_2 plume at the top reservoir level of the target storage formation which has breached the primary cap rock seal.

Thus the BN sub-model for a specific chimney includes input as to the

- Macroscopic dimensions of the seismic anomaly
- Expert opinion on the nature of the rock within the chimney and
- The degree to which it is deemed possible that CO_2 has breached the primary cap rock seal by exceeding the capillary entry pressure locally.

The last bullet comprises a part of the chimney sub-model which is very similar to the BN sub-model discussed above in the context of stored CO_2 breaching the primary cap rock at a vertical point above the injection point, where there is no seismic anomaly identified. The BN sub-model for a seismic chimney is shown on Figure 10-1 below. Note some overlap in functionality with the BN for “competent cap rock (i.e. no seismic anomaly above) in figure 6. This was done to ensure that local parameter estimates specific to identified chimney are entered locally for each chimney included.

Karstens and Berndt (2015) describe a further classification of chimneys into sub-types (2015) as summarized in Table 9-3 below of the chimneys in the greater Sleipner area.

Table 9-3. Summary of chimney classification scheme by Karstens and Berndt (2015)

	Type A	Type B	Type C
Shape	Circular, aligned	Circular	Elongate, continuous
Triggering fluids	Gas	Gas	Gas, water
Migrating fluids	**Gas**, water, sediment	**Gas**	**Water, sediment**, gas
Formation character	Rapid (blow-out)	Potentially continuous	Rapid
Min. formation age	Holocene	Holocene or recent	Late Pleistocene
Max. formation age	Holocene	Early Pleistocene	Late Pleistocene
Evidence for ongoing activity	Ambiguous	Yes	No

The shape of the moving CO_2 in the target storage reservoir has been surveyed using time-lapse 3D seismic, and reservoir simulation models and analytical techniques have been applied to understand and predict its future evolution. This is important for estimating the probability that the CO_2 in the target reservoir will intersect any identified potential leakage pathways.

Numerous publications describe the situation at Sleipner Utsira as “stacked plumes”. This is deduced to be caused by a number of thin and persistent mudstone layers within the Utsira that are open to vertical flow at selected locations, allowing a cascading upward movement of the CO_2 from the point of injection to the top Utsira or the top Sand Wedge where this exists. This is illustrated on a schematic cross section Figure 9-4. A more three-dimensional view of the top layer (often labelled layer 9) shows that the CO_2 occupies only a narrow closure in the Sand Wedge, and appears to be migrating NNE. Thus CO_2 in lower layers is not contacting the cap rock to the Utsira due to "baffling" caused by the thin mudstones within the Utsira. A simple aggregate top-down view of the CO_2 plume within the storage reservoir does not show this and can be misleading when considering probability of intersection between the plume and leakage features.

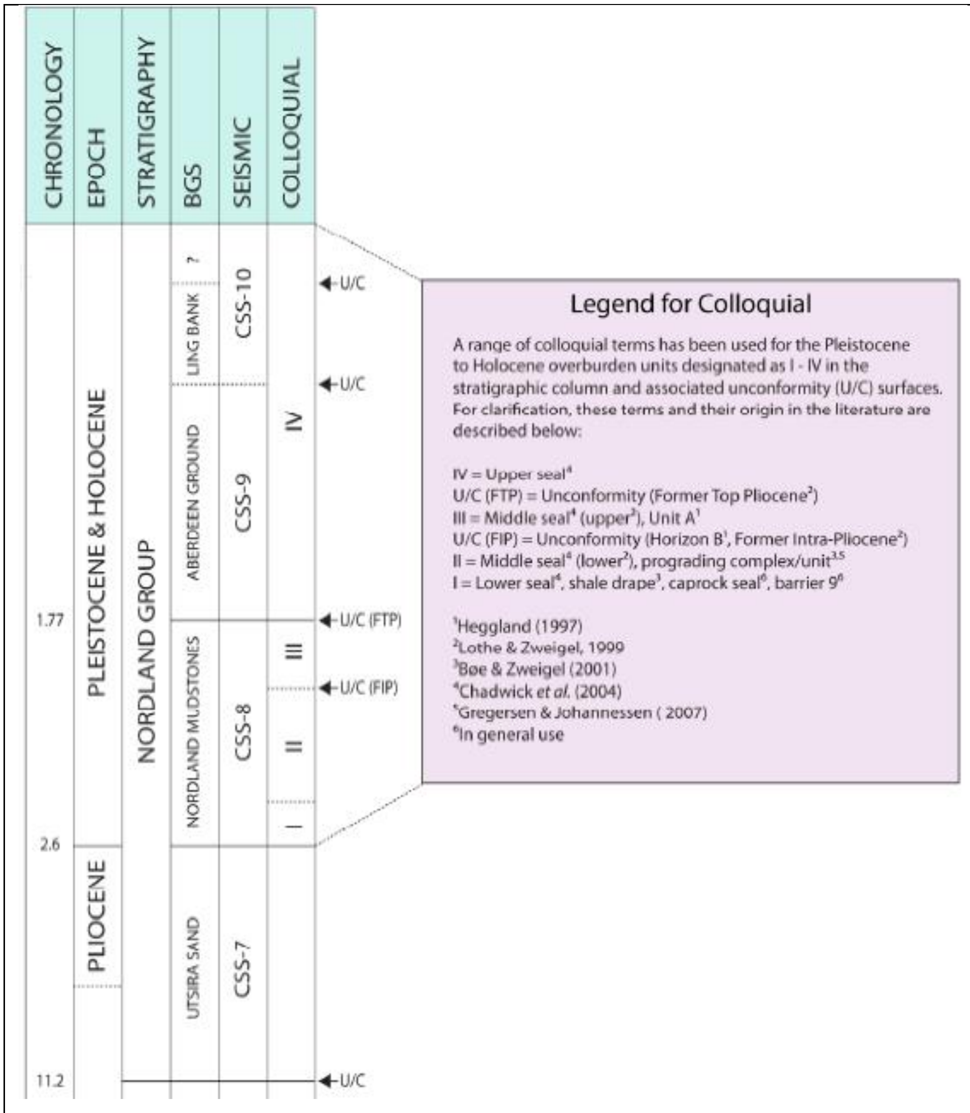


Figure 9-8. Relevant stratigraphy and nomenclature for the Sleipner area case study (after Gibbard and Head, 2010).

The closest chimneys to the stored CO_2 as identified by Nicoll (2011) and Karstens (2014) are summarized in **Table 9-4** below.

Several chimneys are confirmed to lie directly over the stored CO_2, (11, 25, 26, 28, 29, 34, 108) and none of them have shown any sign to have leaked CO_2 from the Utsira formation as evidenced by several repeat seismic surveys or other monitoring. These have therefore been excluded from further analysis.

Chimney A17 (999) lies to the east of what appears to be a linear barrier to eastward movement of the stored CO_2 at the top Utsira level. It has also therefore been excluded from further analysis.

Chimneys 10, 12 and 68 will most likely not be contacted by the stored CO_2 and have also been excluded from further analysis.

Chimneys 78, 91 and 92 have highest connection to the FTP (Former Top Pliocene). The simulation exercise by Nicoll (2011) did not generate buoyancy pressures in any of the Monte Carlo-generated scenarios that would indicate that these chimneys will leak further to shallower zones and to the seabed. They have therefore been excluded from further analysis.

Chimney 35, which is not included on the short list of this study, has been noted to extend from the storage formation to the seabed, where a $500m^2$ crater sits on its top at the seabed. The crater lies 6.5 km SW of the CO_2 injection point, but most importantly, the top Utsira at the location of Chimney 35 is far down dip from the injection point. It is considered virtually impossible that stored, buoyant CO_2 will flow ‘downhill’ to this location since the Utsira is essentially open to the north for several hundred kilometres.

The one remaining chimney for analysis is chimney 77. This has therefore been subjected to a more detailed review by WP5 and the results of this are described in the next section.

Chimney numbering and essential estimates from Nicoll (2011) and Karstens (2014)				Chimney lies above current reservoir CO2 plume or will be intersected with high certainty													
note that only chimney A-17 is sourced from Karstens				Chimney lies some distance from the edge of the reservoir CO2 plume and unlikely to be intersected													
			chimney														
	parameter		A-17 (999)	10	11	12	25	26	28	29	34	68	77	78	91	92	108
	horisontal distance to CO2 injection point, km	deterministic	1,0	1,6	0,3	0,8	2,5	2,5	1,0	1,1	0,9	4,3	2,8	2,6	1,7	2,9	0,5
SCAH=Supra-Caprock Anomalous Horizon																	
FTP=Former Top Pliocene	Chimney connection to top	(abbreviations on left)	FTP	SCAH	FTP	FTP	FTP	SCAH	SCAH	FTP	FTP	FTP	FIP/FTP	FIP/FTP	FTP	FTP	FTP
FIP=Former Iintra-Pliocene	Chimney Root (start or base)		UTS	UTS	UTS	UTS	TU	UTS	TU	TU	UTS	TU	UTS	TU	TU/SCAH	TU/SCAH	(strong)
UTS=Within the Utsira																	
TU=Top Utsira	Chimney horisontal distance to edge of CO2 plume inthe Sand Wedge, metres	0 m	1	0	100	80	85	85	85	80	85	1	50	50	55	25	90
		< 200 m	2	0,1	0	15	10	10	10	10	10	4	40	40	45	35	7
		200 m- 500 m	90	2,9	0	4	3	3	4	7	4	60	15	18	8	35	2
		>500 m	7	97	0	1	2	2	1	3	1	35	5	2	2	5	1
	Chimney Max.CO2 column below m	0 m	0,99	0,01	0,00	0,00	0,01	0,01	0,00	0,00	0,00	0,99	0,00	0,99	0,01	0,01	0,01
	note this is relevant only for the uppermost sand	0-2 m	0,01	0,98	0,00	0,80	0,05	0,05	0,00	0,00	0,80	0,01	0,80	0,01	0,05	0,05	0,05
	which is commonly referred to as the 'sand wedge'	2-6 m	0,00	0,01	0,02	0,15	0,70	0,70	0,19	0,19	0,15	0,00	0,15	0,00	0,70	0,70	0,70
		6-12 m	0,00	0,00	0,97	0,04	0,15	0,15	0,70	0,70	0,04	0,00	0,04	0,00	0,15	0,15	0,15
		12-20 m	0,00	0,00	0,02	0,01	0,08	0,08	0,10	0,10	0,01	0,00	0,01	0,00	0,08	0,08	0,08
		20-400 m	0,00	0,00	0,01	0,00	0,01	0,01	0,01	0,01	0,00	0,00	0,00	0,00	0,01	0,01	0,01
min. diam. From Nicoll	Chimney Diam., m		50	250	200	300	200	150	75	65	130	250	230	240	220	240	230
max. Diam. From Nicoll				500	450	1100	580	650	150	190	370	800	960	500	830	540	500
Type A chimney	Chimney seismic anomaly Evidence	ambiguous activity	0,8	0,2	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,2	0,17	0,2	0,2	0,2	0,04
Type B chimney		active	0,1	0,6	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,6	0,03	0,6	0,6	0,6	0,01
Type C Chimney		inactive	0,1	0,2	0,95	0,95	0,95	0,95	0,95	0,95	0,95	0,2	0,8	0,2	0,2	0,2	0,95

Table 9-4. Summary of chimneys from Nicoll (2011) and Karstens (2014). Only chimney labelled A-17 is from Karstens. The A, B, C chimney type is according to Karstens and Berndt (2015) and described in table . Assignment of discrete probability interval values based on several sources and expert judgement within ECO2. These discrete uncertainty distributions will be used in the Bayesian Net model described in section 10.

Detailed analysis of Chimney 77

A first assessment performed in the ECO2 project (WP5) suggests that a particular chimney, so-called Chimney 77 is the most critical in terms of the risk of CO_2 migrating out of the Utsira formation (see also Nicoll, 2012: Appendix 2.9 and Section 4.6.2). This report is the outcome of a quick scan investigation of seismic data of the Chimney 77 area with the objective to confirm the observation and asses the spatial extension of this particular chimney.

Surveys were shot to monitor the CO2 plume (Arts et al., 2004; Chadwick et al., 2004a). The CO_2 plume is clearly visible as bright spots on repeat seismic data. Several seismic volumes are available for this study; the 1994 and 2008 vintages were used.

The overburden consists predominantly of clays and comprises:

1. A zone of a higher seismic energy than the Utsira Formation.
2. A chaotic zone that contains several bright spots (Figure 9-9).

The present research focuses on these two intervals, plus the Utsira formation (Figure 9-9 and Figure 9-10) studied interval. For more information on the geological background see Chadwick et al., 2004b and Zweigel et al., 2004.

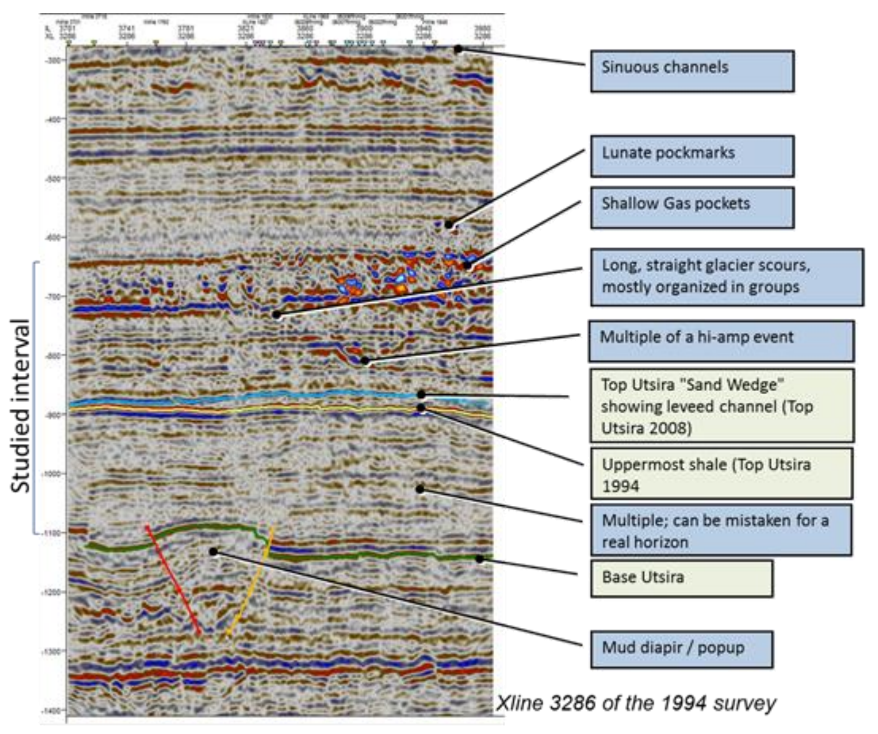


Figure 9-9: Seismic features and the studied interval at the Sleipner Utsira storage formation and overburden

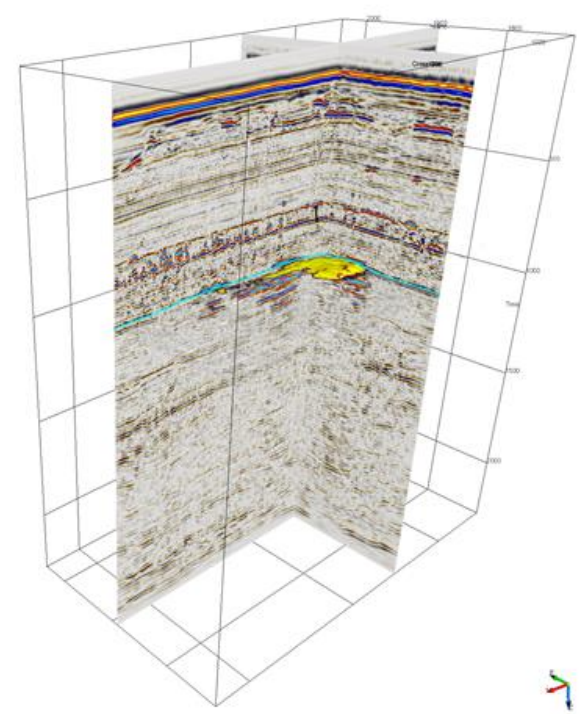


Figure 9-10: The Sleipner 2008 repeat seismic cube. In yellow the top of the injectedCO_2 plume is shown. The intersection of the Utsira top horizon with the seismic data is displayed in cyan colour.

This study chose to use a meta attribute, which is a combination of attributes to detect chimneys (OpendTect user manual). The meta attribute used is a blend of energy and similarity (lateral continuity of layers). The meta attribute indicated a high probability of a presence of a chimney when the energy and similarity is low over a vertically elongated area.

The output is a 'probability' volume (the size of the original seismic volume) that indicates for each seismic sample the chimney meta attribute measure. Next, the interpreter has to evaluate these results and differentiate them from other seismic phenomena and noise. Chimney attributes have been computed for the 1994 and 2008 seismic volumes and subsequently interpreted.

The seismic chimney attribute detects vertical noise trails characterized by low energy (Figure 9-11). In order to validate these vertical noise trails as chimneys their shape and relation with bright spots is evaluated. When a detected feature is elongated in cross sections, circular on time slices, they originate from a deep level and are linked to bright spots it is classified as chimney.

One of the reasons we think the attribute is not likely to pick up the transmission effect, but chimneys, is because bright spots are in many cases wider than the chimneys. In several cases, the chimneys appear to be related to features that indicate mud diapirism (pillows) below the Utsira Formation.

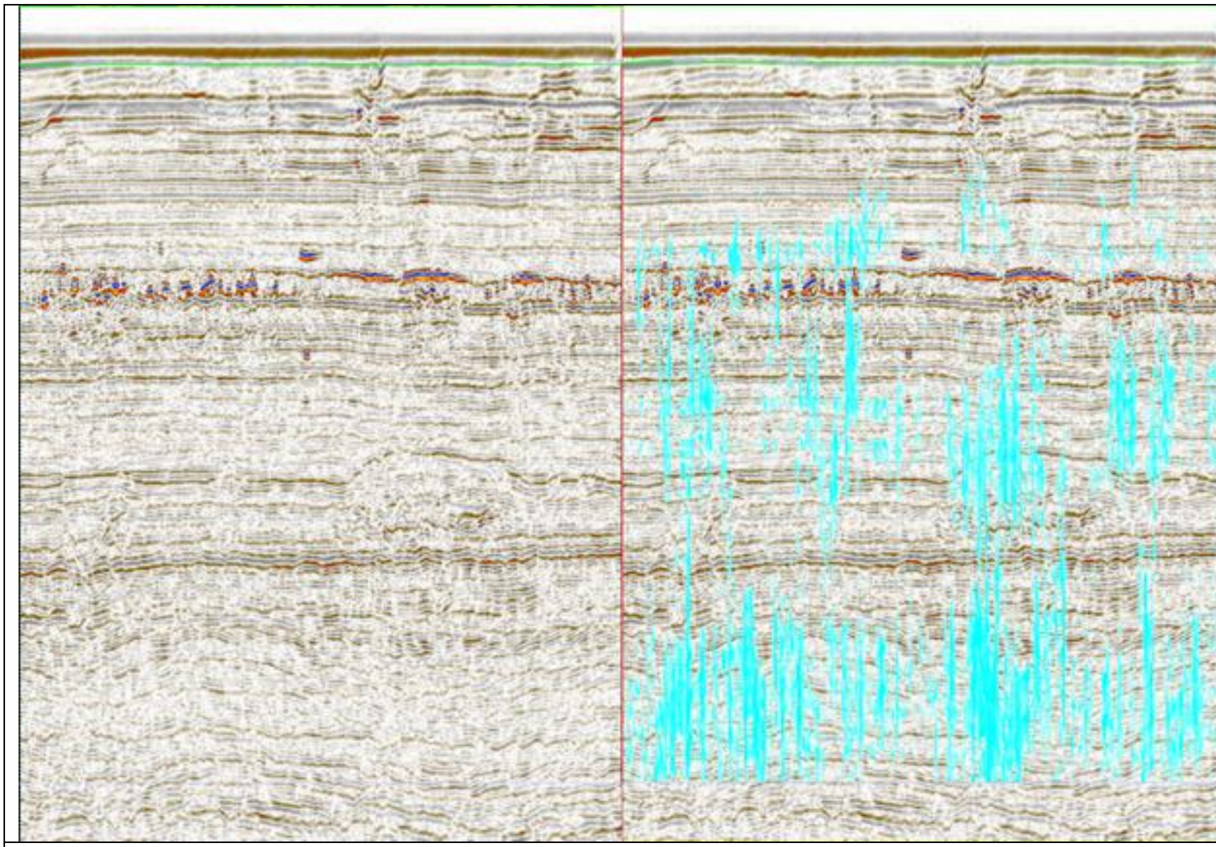


Figure 9-11: - inLine 3893 of 1994 vintage overlain by the chimney-fingerprint attribute (cyan)

Chimney 77 is located on the North-Eastern edge of the CO_2 plume. It was originally identified in the PhD study of Grant Nicoll (2011) as “Two tapered (carrot-shaped) interconnected vertical discontinuities…” located at UTM x= 439588.61 m and y = 6473824.77 m. The chimney intersects crossline 1329 and inline 1926 according to Nicoll. He interpreted the bottom at 889 m TVDSS and the top at 570 m TVDSS and he estimated the diameter between 230 and 960 m.

The main direction of extension of the CO_2 plume is towards Chimney 77 (**Figure 9-12** and **Figure 9-13**Figure 9-12) and is therefore of interest for leakage risk analysis. The figure shows that the CO_2 plume is very close to Chimney 77.

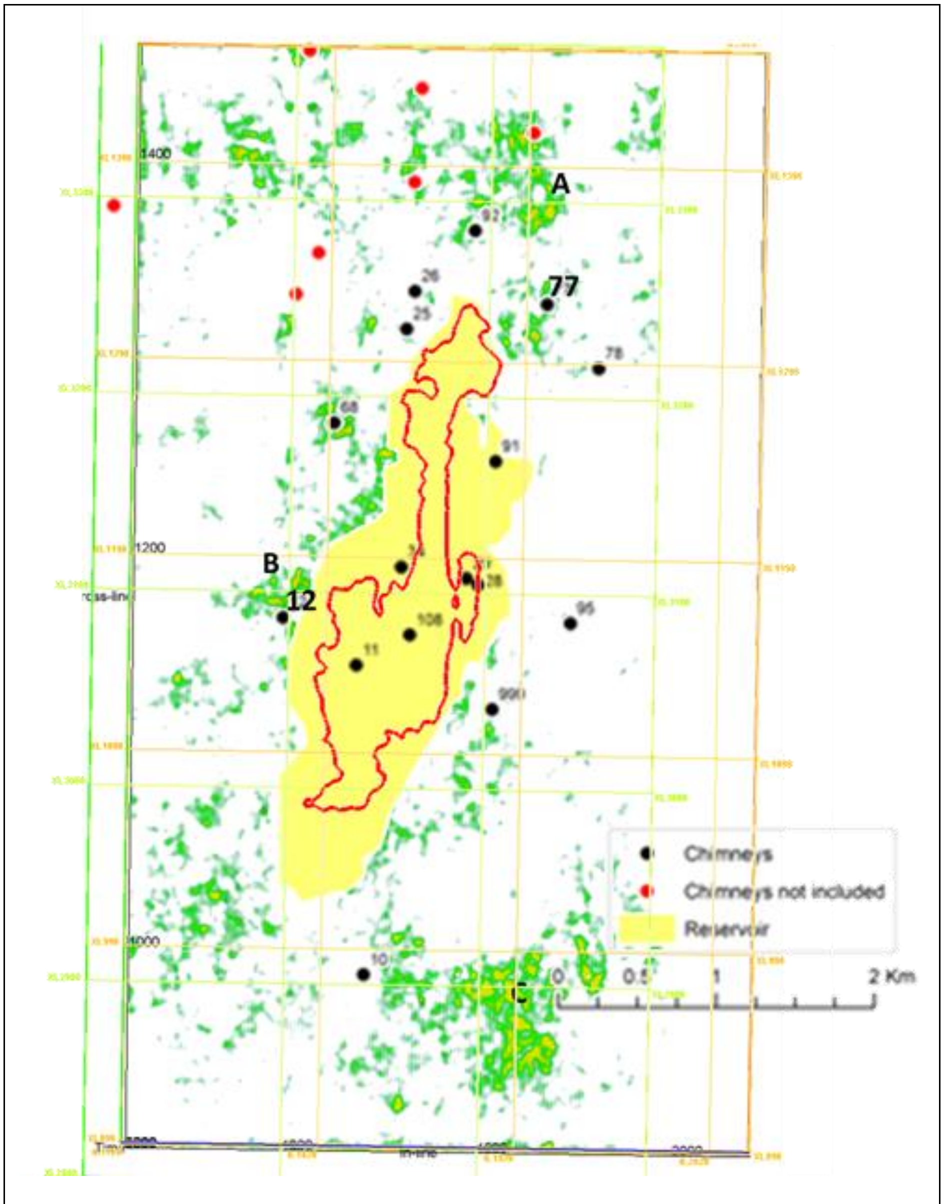


Figure 9-12: Location map of chimneys identified by DNV (black and red dots) overlain onto TNO's Chimney Attribute Map (green-yellow). The yellow area overlapped by red contour line display the CO_2 extension at level (internal) 5 and 9 (top sand wedge) respectively that are picked on 2008 seismic vintage

The shape of Chimney 77 is characteristic for a gas chimney (see **Figure 9-14**). It originates from a deep level, and runs through the Utsira reservoir and the overburden (see **Figure 9-15**). It is linked to shallow gas pockets (marked by the bright spots "BS"), characterising it as a gas chimney. The chimney is visible on the pre CO_2-injection seismic data and, therefore, its presence cannot be related to the current CO_2 injection and is likely to be related to gas or fluid migration that have taken place earlier in geological history. Since the migration has penetrated the seal it is considered to be a seal breach feature and, hence, a potential seal-risk for the CO2 storage site.

Comparison between the baseline (1994) and monitor (2008) seismic data (see **Figure 9-16**) show a similar chimney pattern. The observed differences are likely to be related to repeatability noise, arising from differences in acquisition and/or processing of the data. Chimney features that are persistent between repeat seismic surveys suggest that these features are not noise related. The comparison also shows that there are no indications of developments in chimney activity or bright spots extent.

Therefore, there is no indication that gas/fluid migration has been taking place at Chimney 77 between 1994 and 2008.

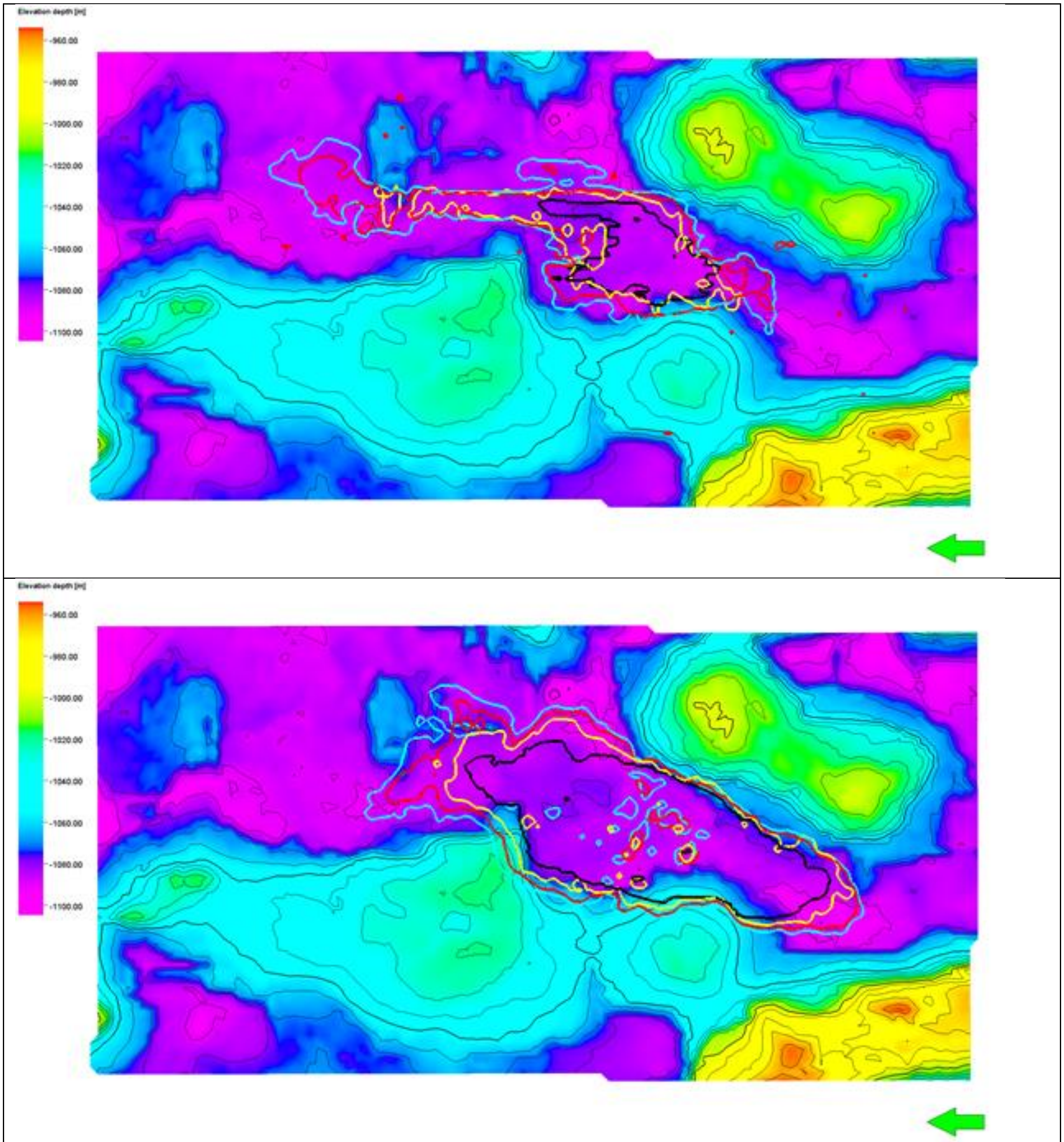


Figure 9-13: Base Utsira overlain by CO_2 plume boundary at level-9 (top) and level-5 (below) observed on repeat surveys of 2001 (black), 2004 (yellow), 2006 (red), and 2008 (cyan)

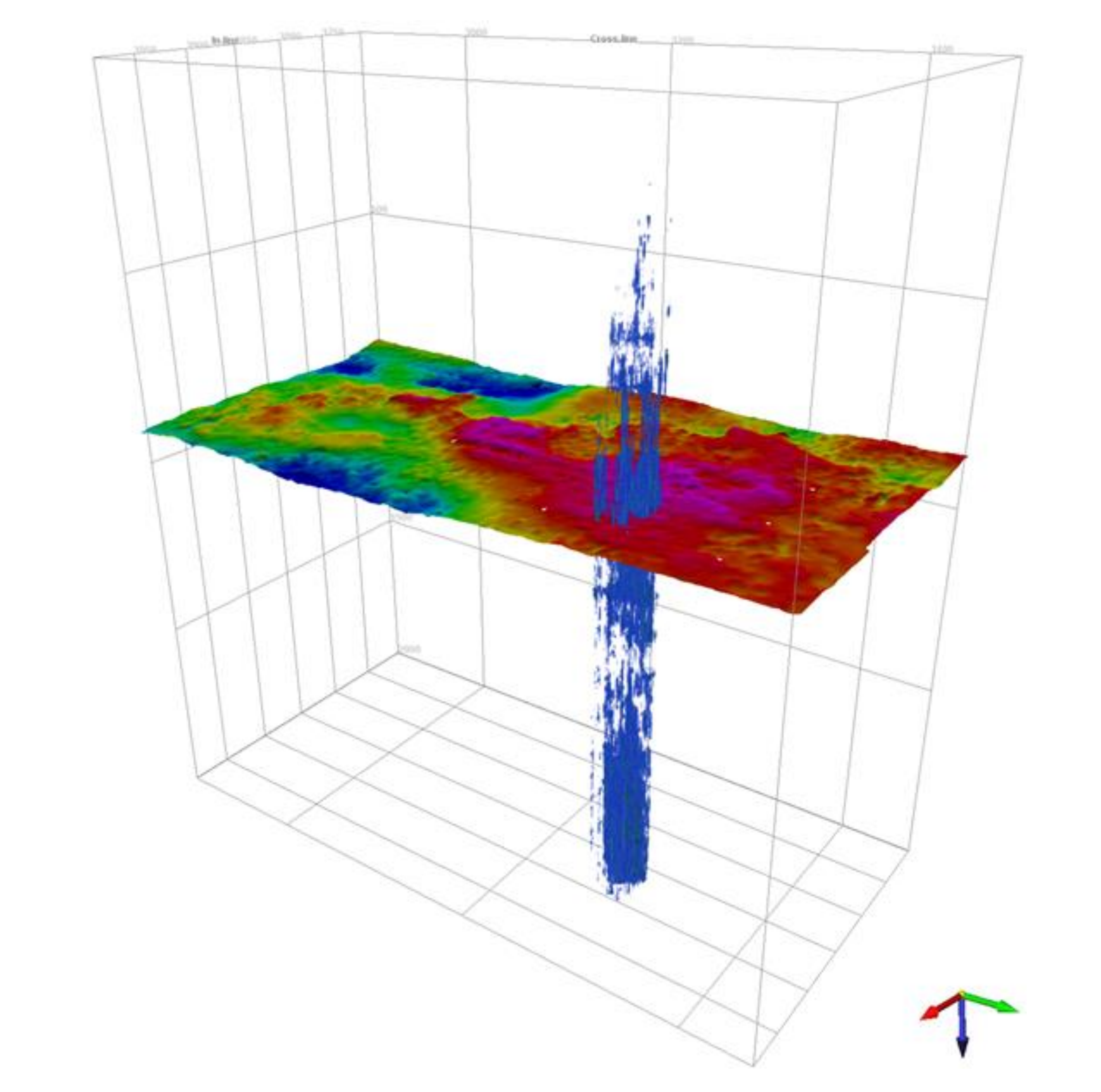


Figure 9-14 Chimney 77 is shown as a isolated 3D body (blue). Note the vertical elongated shape, which is characteristic for chimneys. It is clear that the chimney is passing through the Top Utsira (Base Seal) indicating that migration of gases has taken place in geological history

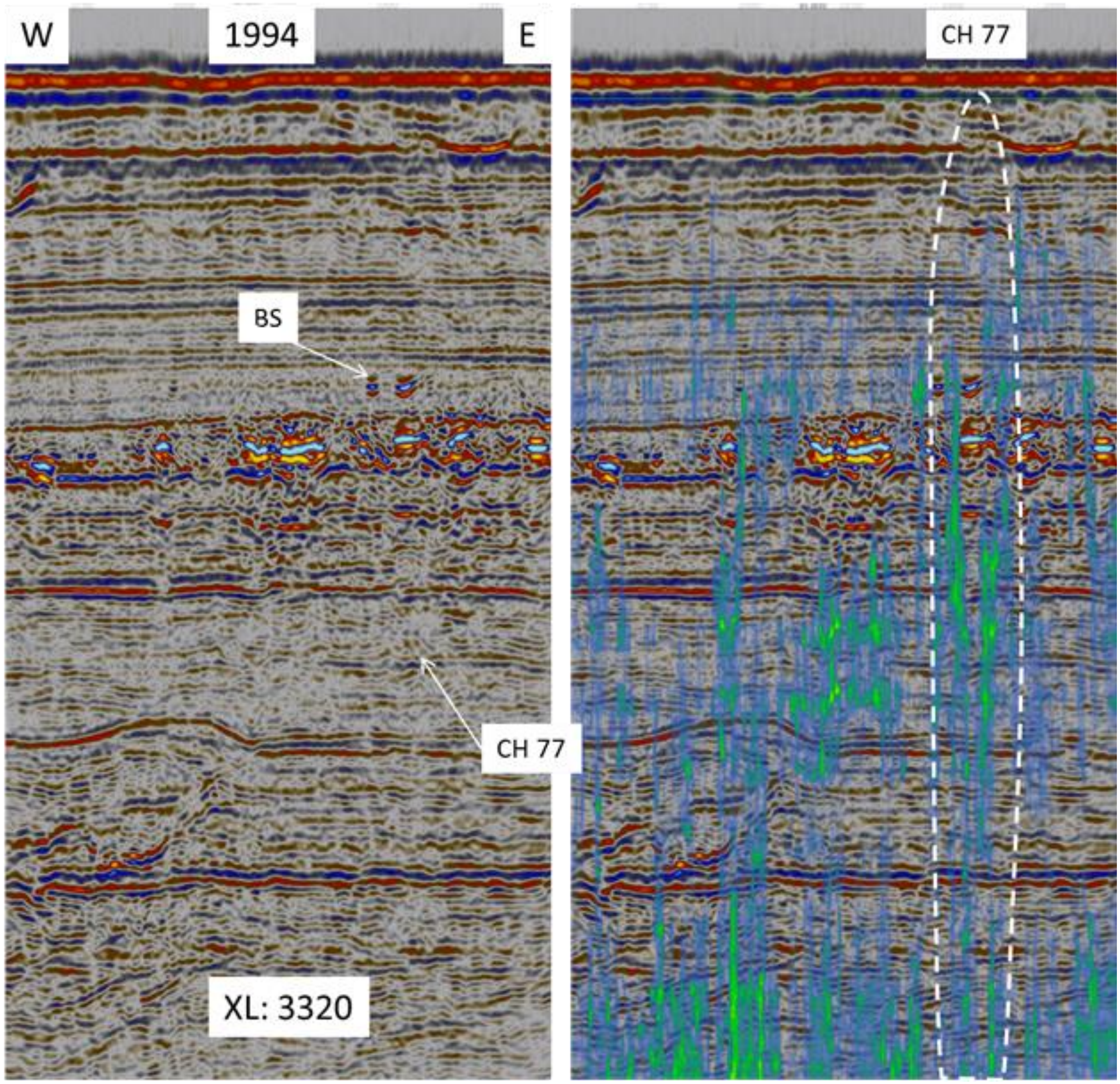


Figure 9-15: Chimney 77 (indicated by the white dashed line) is a gas migration structure that runs through the Utsira reservoir and overburden (The Utsira formation TWT interval is roughly located between 900 to 1100 ms). It is linked to shallow gas pockets (marked by the bright spots "BS") validating it as a gas chimney. The results shown here are from the pre-injection seismic data and therefore, they can only be caused by natural occurring migration of gas that has taken place in the geological history. Since signs of gas migration indicate that the seal is transected, it is considered to be a seal breach feature, which represents a potential seal risk for the CO_2 storage site.

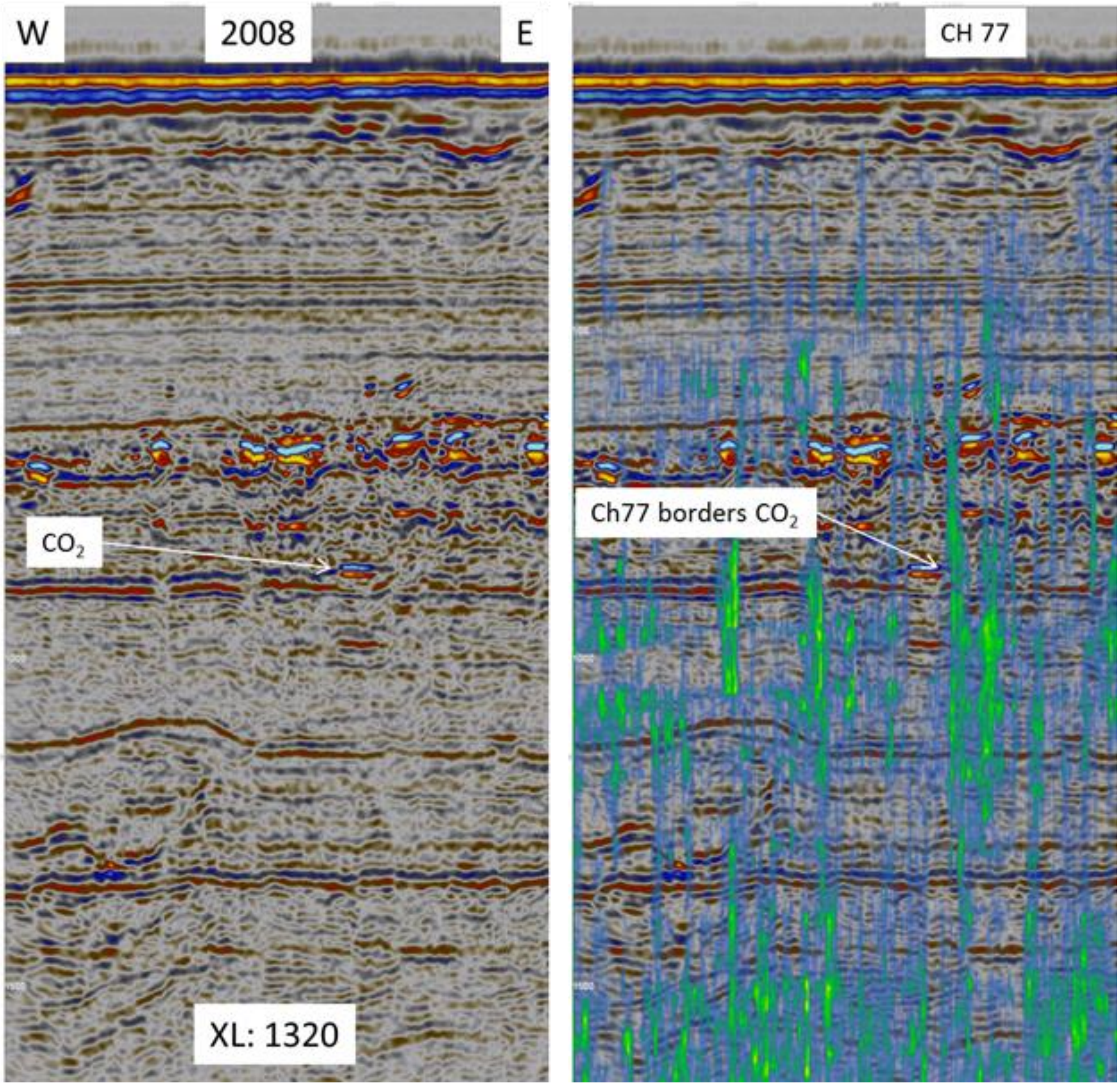


Figure 9-16: Chimney 77 is also visible on the post-injection seismic data, eliminating the possibility of these features to be noise related. Comparison between the pre-injection (1994) and post-injection (2008) seismic data does not reveal indication of increased chimney activity or new bright spots. Therefore, there is no evidence that migration of CO_2 has been taken place at chimney 77

In conclusion, regarding the evaluation of Sleipner Utsira chimney features, the following points are noted.

1. Our interpretation has confirmed Chimney 77 to be a gas migration feature predating the CO_2 injection.
2. Chimney 77 penetrates the seal and overburden, indicating that (natural) gas has migrated through both seal and overburden in geological history. The presence of shallow gas pockets (associated with the chimney) within the overburden (above the CO_2 plume), supports this conclusion.
3. Comparison between the baseline (1994) and repeat seismic data (2008) does not indicate any change in chimney activity or bright spots extent since the start of the CO_2 injection in the Utsira formation in 1996. Therefore, there is no evidence that Chimney 77 is a migration pathway for the CO_2.
4. Since gas migration has passed through the seal in geological history, Chimney 77 is considered to be a seal breach feature. Hence, it is a potential seal risk for the CO_2 storage site.

Long-term evolution of the Sleipner CO_2 plume

Simulation of CO_2 injection at the Sleipner site and its difficulties in terms of calibration against monitoring time lapse seismic data has been well studied and published (Singh et al, 2010; Cavanagh, 2013; Cavanagh et al, 2014; Lindeberg et al., 2002; Chadwick et al, 2010). One of the challenges amongst all is mimicking the northerly elongated CO_2 anomaly at the uppermost sand wedge layer, which is observed on the repeat seismic surveys (**Figure 9-17**). To our best knowledge, almost all published models display much less northerly extension of CO_2 at the uppermost sand wedge layer. This leads to a considerable uncertainty in simulation of the CO_2 spread fate, which is of great importance for risk assessment studies. Lateral growth pattern of the injected CO_2 are steered by several factors including acting drive forces, petrophysical properties, and structural features. Driving forces are weighted combination of viscous, buoyancy, and capillary forces. Majority of the simulation models developed around the Sleipner CO_2 injection are based on Darcy flow approach that fails to mimic the elongated feature completely.

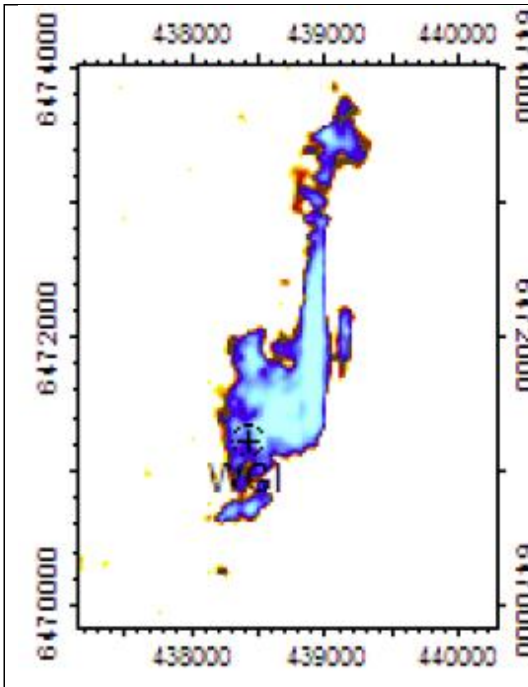


Figure 9-17. CO_2 anomaly observer on the 2008 seismic vintage data at the uppermost layer

Cavanagh (2013) has shown that the capillary flow approach can better explain the elongated CO_2 migration at the uppermost level. Nonetheless, the capillary flow simulation results display less CO_2 flow towards the southern part (around the injection area) and exaggerated CO_2 growth towards the northern part, at all survey vintages (**Figure 9-18**). Log evaluations of more than 100 wells penetrating the Utsira formation and available core measurements revealed that the Utsira Sand is a homogenous unconsolidated clean fine grained sandstone with isotropic properties (Best Practice for the Storage of CO_2 in Saline Aquifers, 2008). This provides confident estimation of porosity and permeability parameters. Probably the most uncertain steering parameter is structural features, namely, cap rock topography, general dip trend and sealing faults. It is basically due to imperfect velocity model, seismic resolution, and low reflectivity of intra reservoir layers. The intra reservoir layers play an important role in migration pattern and entrapment of CO_2 within the reservoir (Chadwick R.A. et al, 2004). The CO_2 flow characteristics within the reservoir will influence the CO_2 flux into the uppermost sand wedge layer. In order to avoid ambiguities related to the intra reservoir CO_2 flow, common practice is to model merely the uppermost sand wedge layer, instead of whole Utsira formation (the Sleipner CCS reservoir). This approach suggests the need for estimation of the CO_2 flux into the uppermost layer over the history period and also prediction of future fluxes to forecast the CO_2 spread. The in-situ CO_2 volume per layer, and flux based

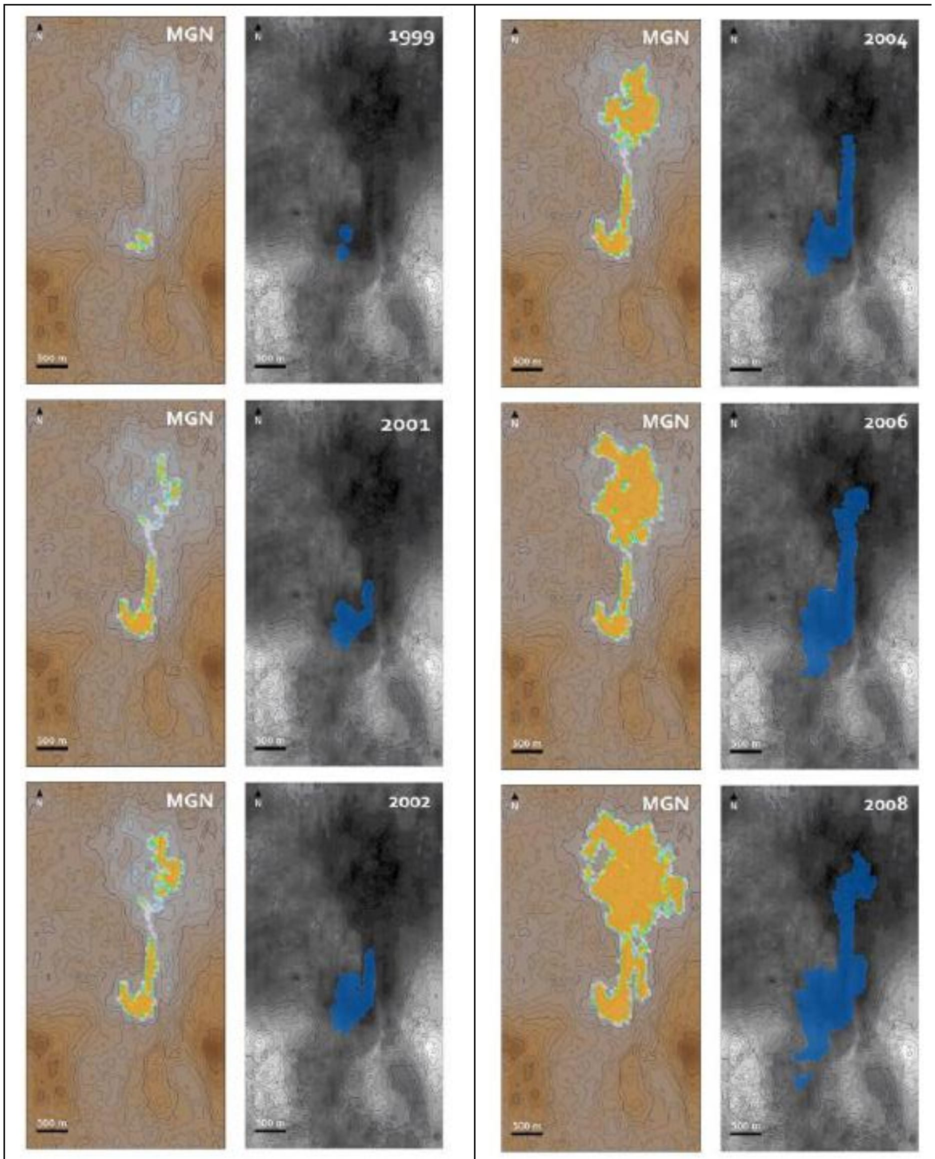


Figure 9-18- Uppermost CO2 anomaly observed on repeat surveys of 1999, 2001, 2002 2004, 2006 and 2008 and their corresponding capillary flow simulation results. Cavanagh et al. (2013).

on volume changes over time, can be estimated via the time-lapse seismic data, based on tuning amplitude-thickness relationship and velocity time pushdown observations on seismic data [Chadwick R.A. et all, 2005].

An alternative sand wedge model

The morphology of the uppermost CO2 anomaly is primarily guided by the cap rock topography. However, the lateral extension of the sand wedge could also play a key role on the CO2 flow diversion by physically limiting the pathways at the sand wedge. We have further investigated this aspect starting from detailed interpretation of the sand wedge layer. In order to enhance the seismic resolution, various volume attributes have been examined and eventually combination of derivative and structural smoothing attributes were selected and applied on 1994 data. The attributes were picked from the Petrel library and were applied in order as follow:

1. First Derivative: first time derivative of the input seismic trace that honours the signal changes rather than the amplitudes.
2. Structural Smoothing: spatial smoothing based on a Gaussian weighted filter to sharpen discontinuities.
3. Second Derivative: This is second time derivative of the input seismic trace and shows all reflecting interfaces visible within seismic band-width.
4. Amplitude Gain Control (AGC): scales the instantaneous amplitude value with the normalized RMS amplitude over a specified window.
5. Derivative attributes cause phase shift and polarity reversal that brings ambiguity in interpretation of reflectors. As long as the structural interpretation is planned, the interpreter can compensate for these changes. **Figure 9-19** displays an seismic cross section example before and after application of attributes (enhanced seismic image) on the 1994 vintage and corresponding interpretations of the same top sand wedge horizon. The enhanced seismic image tracks the pinch-out locations better compared to the old interpretation carried out on seismic data before attribute application. **Figure 9-20** illustrates map view of the interpreted top sand wedge using the enhanced seismic image overlapped by the CO2 boundaries in 2006 and 2008. Interestingly, the interpreted pinch out edge fairly well matches with CO2 boundary that seems to be stopped after 2006 (**Figure 9-20** - top). Moreover, the 2D high resolution 2006 seismic data also confirms our interpretation in respect to the sand wedge extension based on the enhanced seismic image (**Figure 9-20** - bottom).

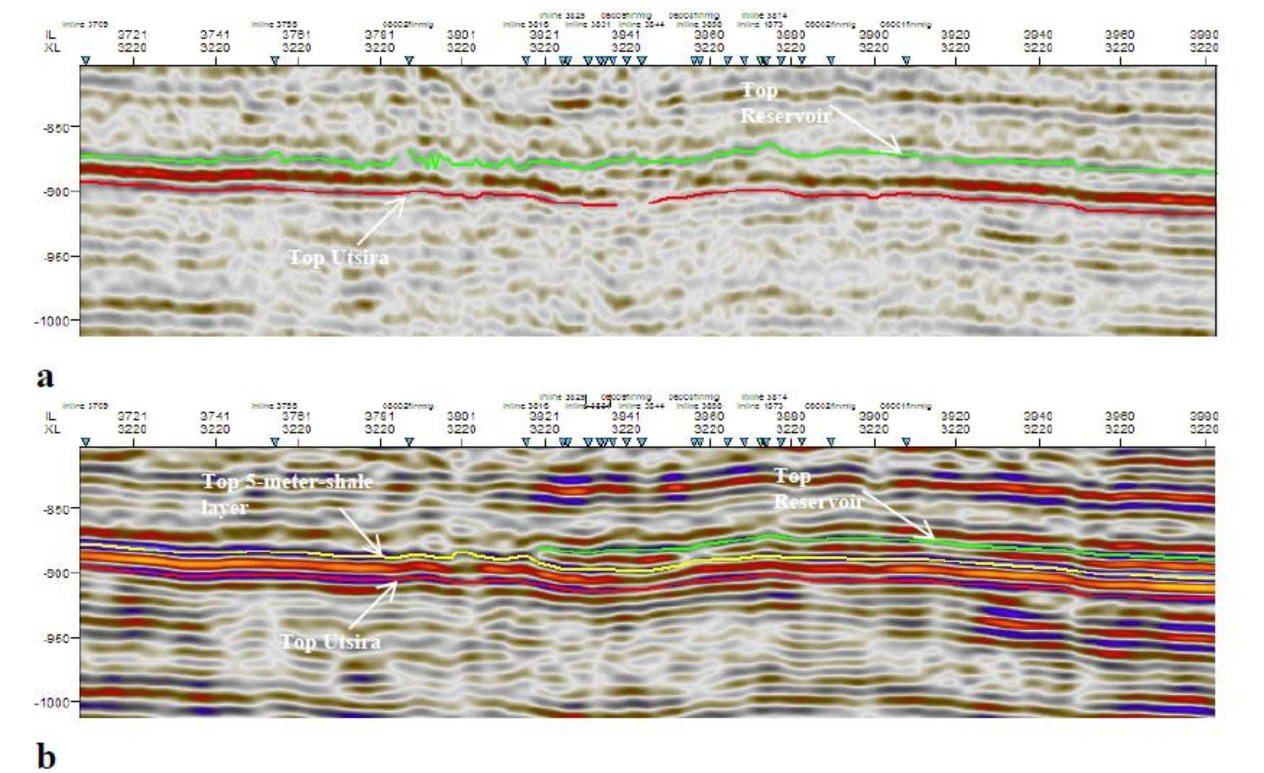


Figure 9-19- xline example of the Sleipner 1994 vintage before and after application of attributes on the data.

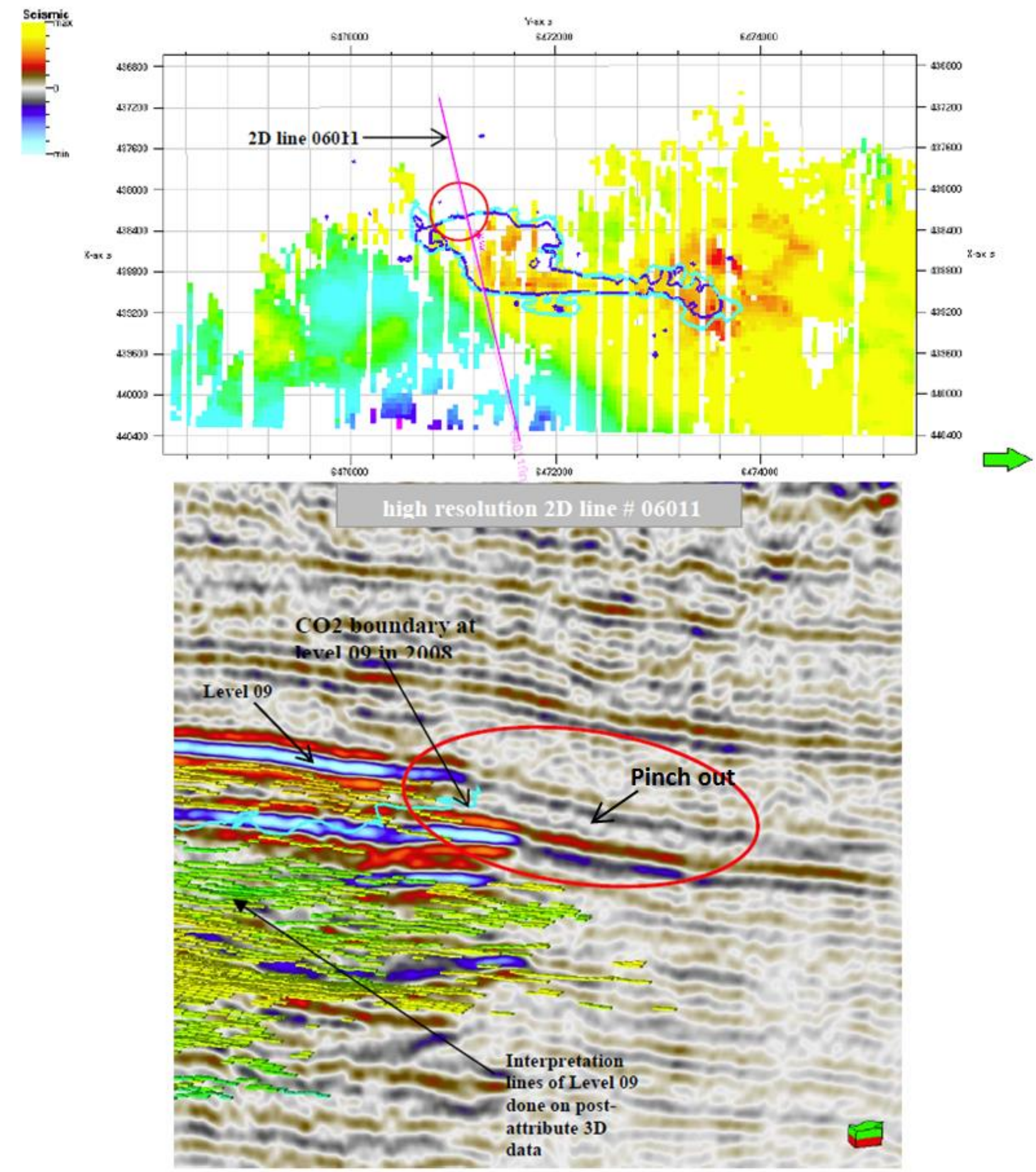


Figure 9-20- Relative position of CO2 anomaly at the uppermost layer (2006 and 2008) in respect to the sand wedge top picked on post-attribute seismic data. Lower picture displays a high resolution 2D line (2006) crossing the interpreted sand wedge horizon.

Based on our interpretations, a new sand wedge model has been developed which is less extensive than older versions (**Figure 9-21**) and lessens the excessive growth of CO_2 toward the west, in order to be more consistent with results from repeat seismic surveys. We have to emphasise that, although the enhanced seismic image could help us to better track the pinch outs, limits to the seismic resolution and exact location of pinch out remain uncertain and hinder further precise history-matching by simulation of the movement of the stored CO_2.

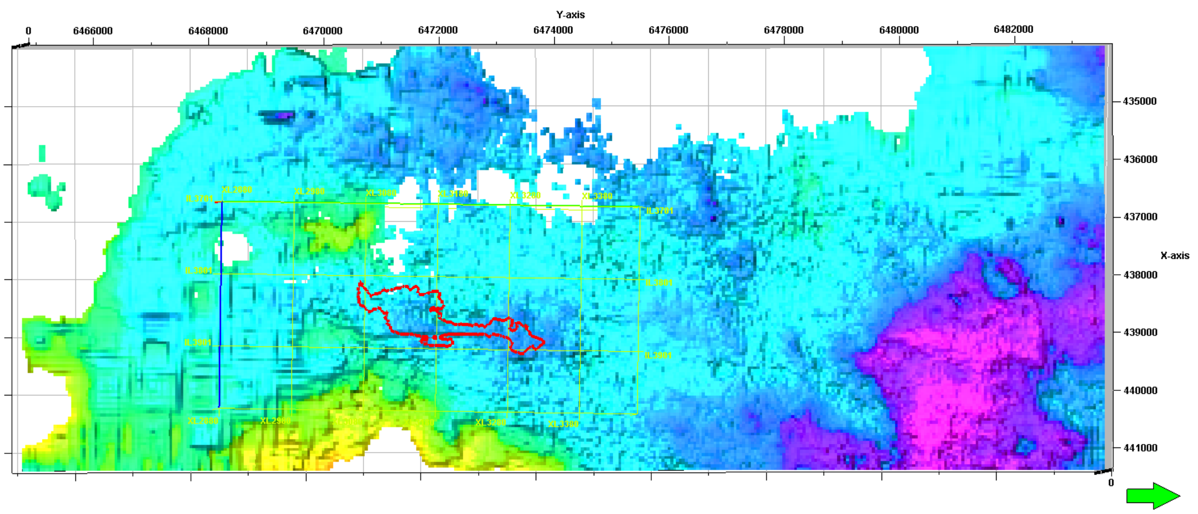


Figure 9-21- Sand wedge layer model

Flux into the sand wedge

As mentioned earlier, the CO_2 thickness per layer can be estimated using reflection amplitude data, as long as the CO_2 thickness is less than tuning thickness. To convert the thickness to volume and consequently to flux, estimates of CO_2 saturation are required. The saturation and density of the CO_2 in the reservoir are poorly constrained variables. CO_2 density is very dependent on the reservoir temperature (Cavanagh et al. 2014) and saturation estimation is limited to capillary pressure measurements in lab (Chadwick et al. 2009), or alternatively at best can be constrained to velocity push-down measurements on repeat seismic data. Chadwick et al. (2009) have reported an estimation of the CO_2 flux into the sand wedge based on reflection amplitude and saturation determined by balancing buoyancy forces against a laboratory determined pressure-saturation curve for the Utsira Sand. Singh et al. (2010) reported CO_2 flux at sand wedge based on injected volumes and plume growth rates observed from the seismic data and assuming 80% saturated pore volume. For this study, we have estimated the CO_2 flux based on the tuning amplitude-thickness relationship and time pushdown observations, and assuming constant saturation along the CO_2 column.

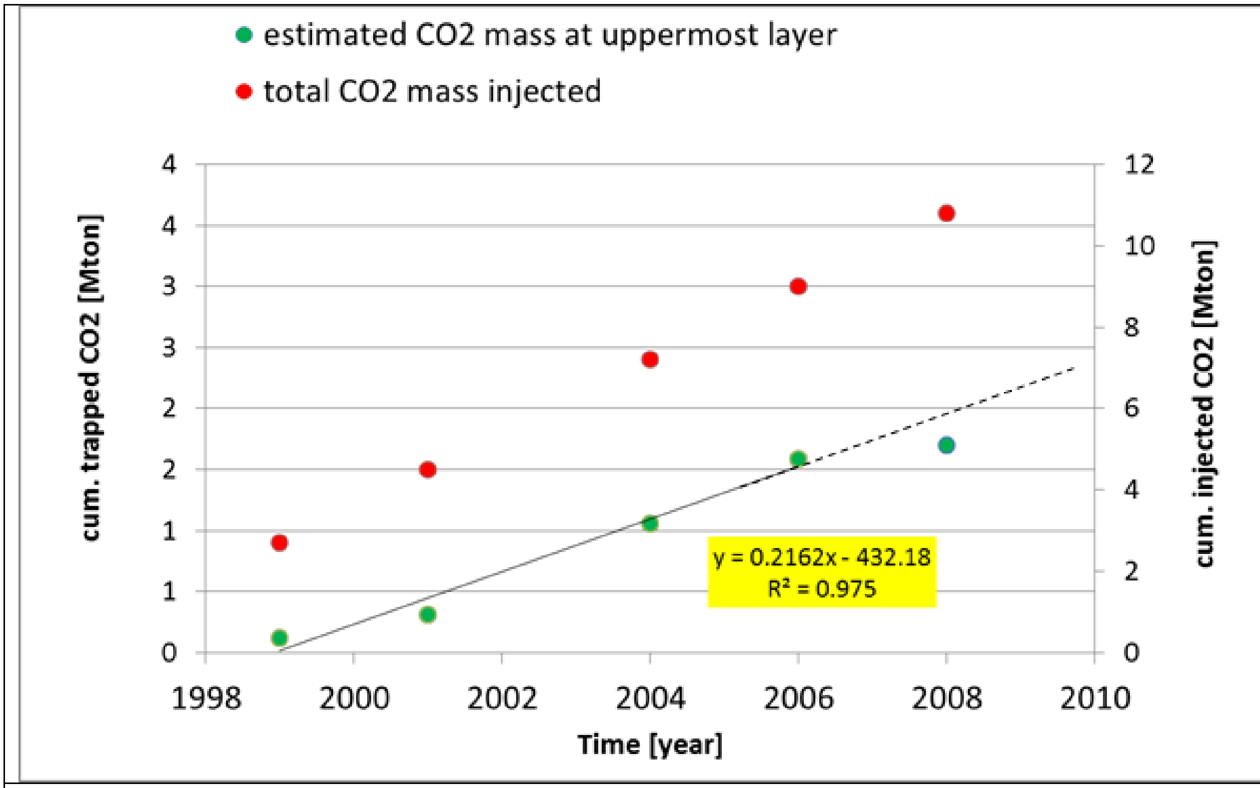


Figure 9-22. Red points show cumulative injected CO_2 mass into the Sleipner, and green points display estimated CO_2 mass at the uppermost sand wedge. Dashed line shoes extrapolation line.

Our estimations shows higher flux into the top layer compared to the benchmark model. Though these estimates are associated with considerable uncertainty, the simulation results demonstrated better match with seismic observations (**Figure 9-24**). In our simulation study, we have only plugged in the flux estimations prior to 2008. Tracking the amplitude changes over consecutive repeat surveys revealed decaying reflection amplitude around the injection point area in 2008 that is interpreted as thickening CO_2 column beyond the tuning thickness (**Figure 9-23**). Also, in order to forecast the flux into the sand wedge, only 1999 to 2006 data were used. The estimated CO_2 mass shows a linear increase with regression coefficient of 0.97. Using this linear regression, we have extrapolated the uppermost CO_2 mass in 2008, 2010, 2012, 2015, 2030 and 2050 and the corresponding fluxes. Assuming annual injection rate of 0.9 Mt, the flux into the sand wedge would never surpass the total injection, which is not the case in the Sleipner benchmark model. Therefore, we can assume constant flux into the uppermost layer, at least as long as the injection continues.

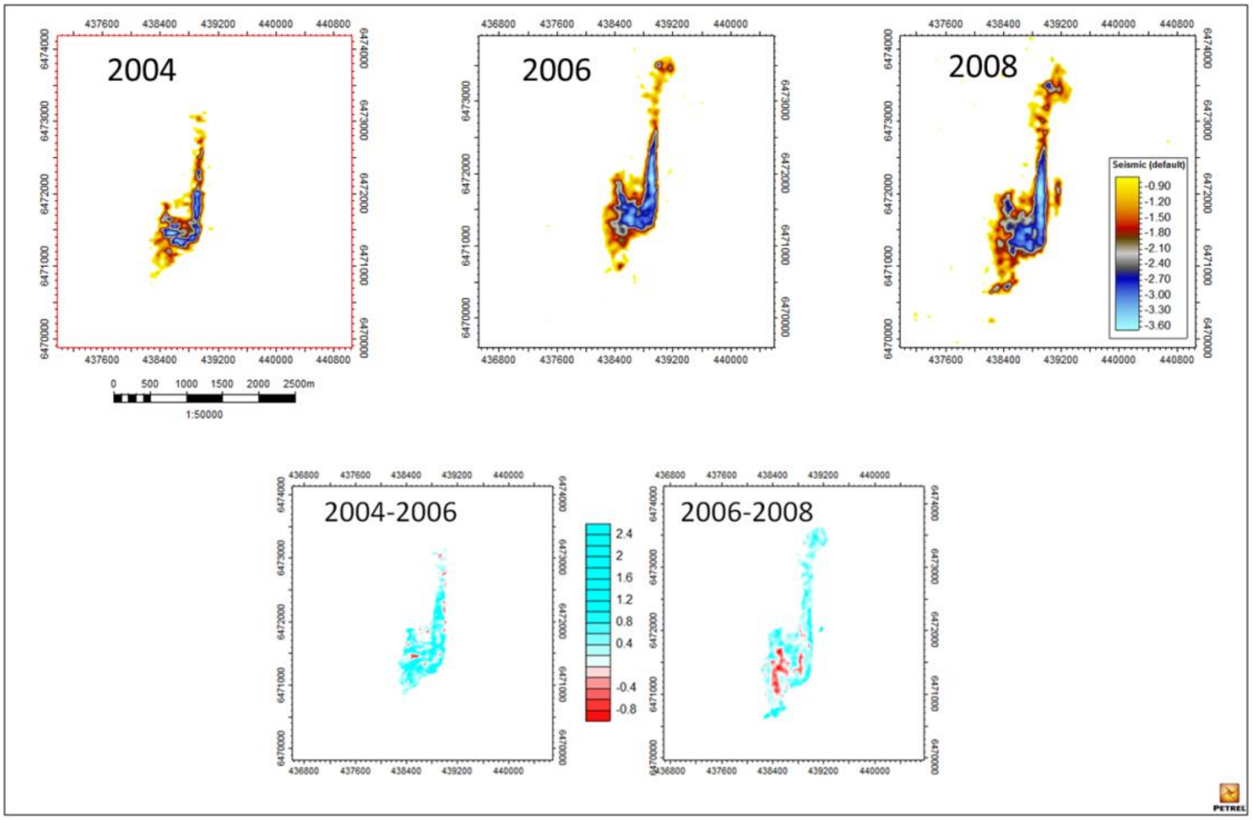


Figure 9-23. Upper row from left to right displays 2004, 2006 and 2008 CO_2 related bright spots respectively and lower row shows the difference between 2008 and 2006 (right) and amplitude difference between 2004 and 2006 (left). The red color corresponds to decrease in the amplitudes.

Reservoir simulation, history matching and forward modelling

Using the estimated (prior to 2008) and linearly extrapolated (2008 till 2050) fluxes into the uppermost sand wedge, a compositional simulation model has been run (using compositional Eclipse) to predict the CO_2 growth pattern. The simulation results are displayed in **Figure 9-24** and **Figure 9-25** for observed CO_2 anomaly (1999 to 2008) and predicted CO_2 anomaly growth (2010, 2012, 2015, 2030 and 2050) respectively. Note that the dissolution of CO_2 is not included in these simulations.

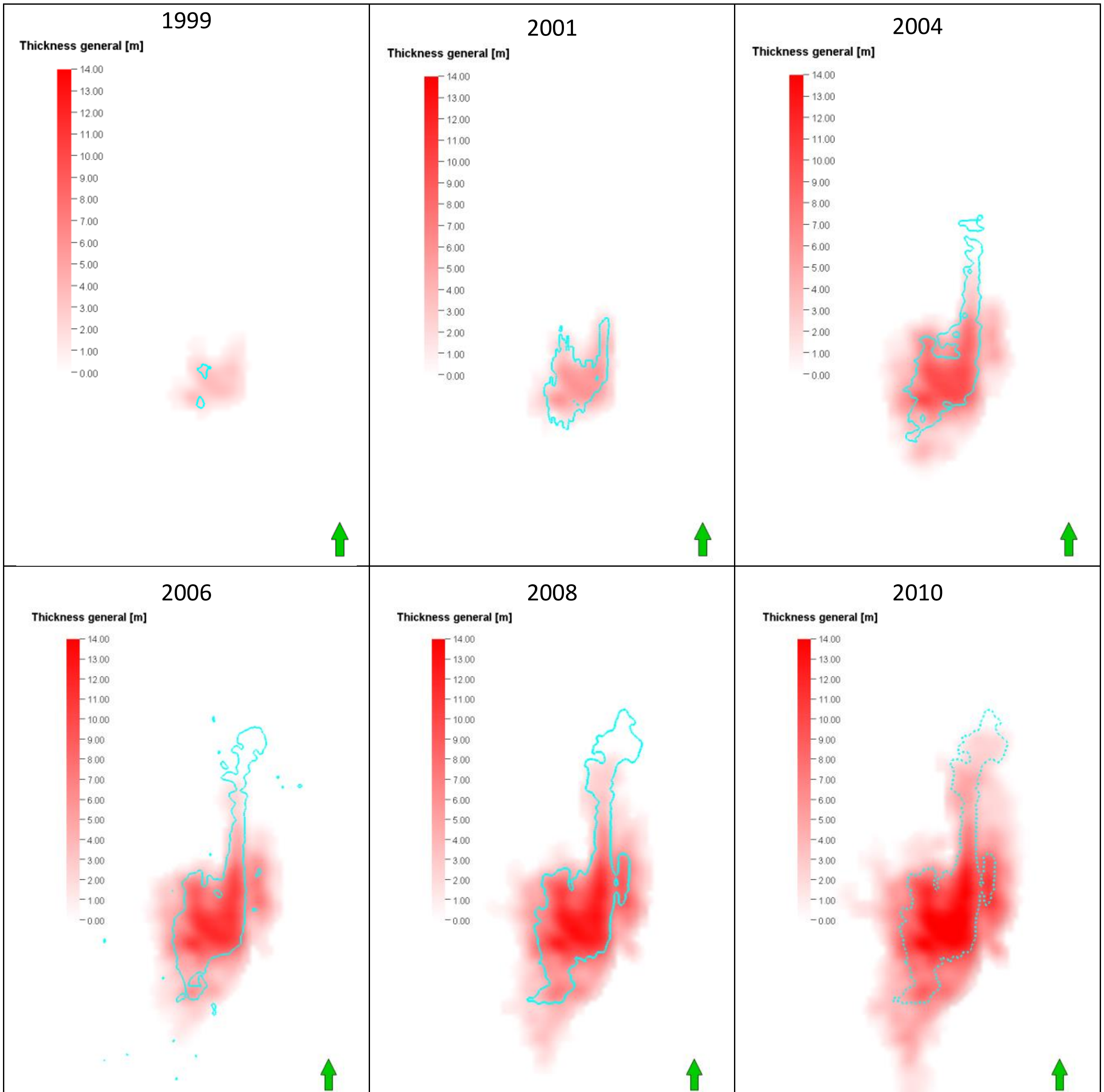


Figure 9-24. Simulation of sand wedge model overlapped by observed CO2 boundary. Note that the observed boundary of CO_2 in 2010 is not available yet and therefore the 2008 outline is shown in dotted lines instead on the bottom right panel.

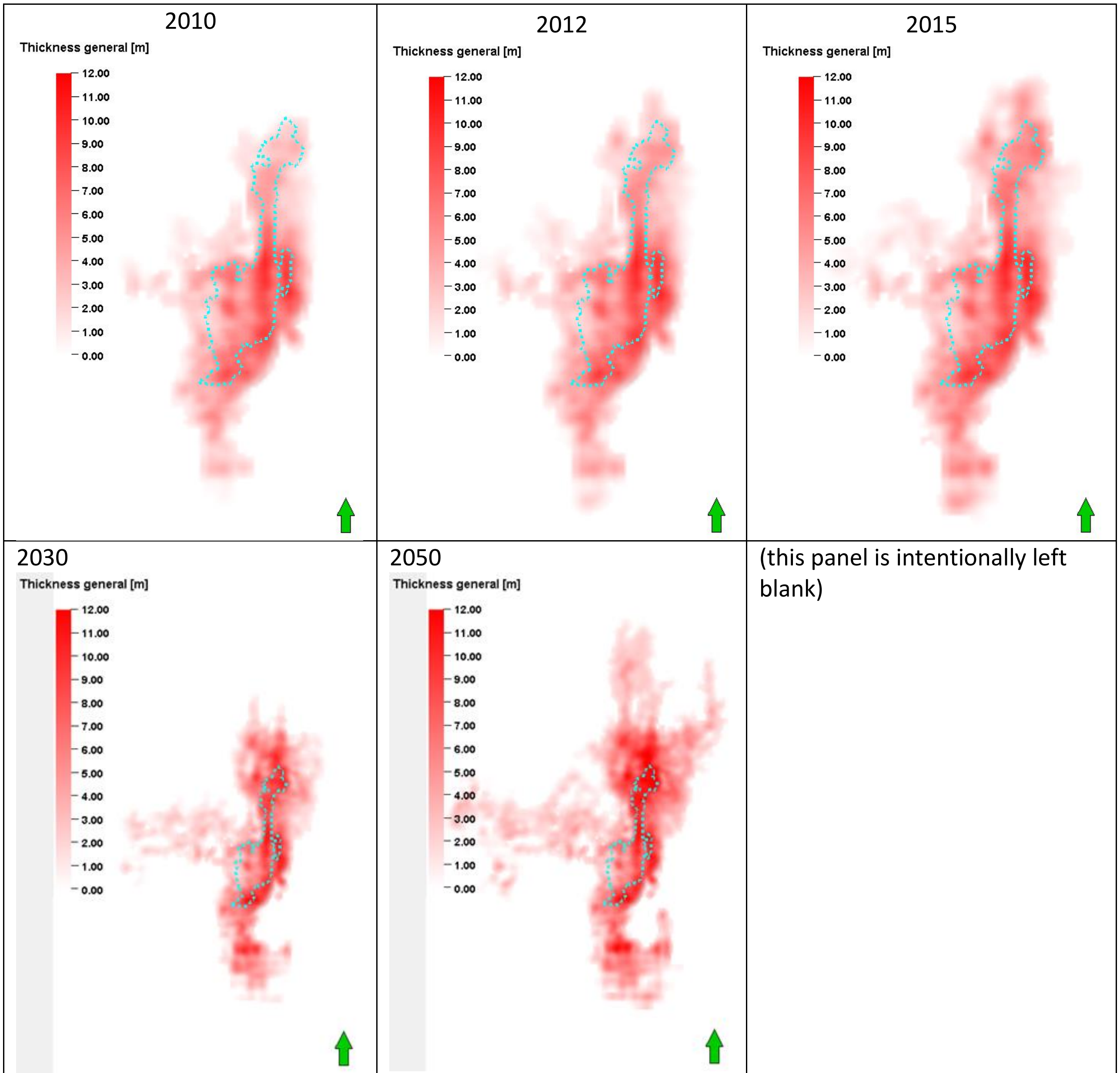


Figure 9-25. Simulated CO_2 thickness map (prediction) at the sand wedge model overlapped by observed CO_2 boundary in 2008 (dashed cyan line). Note the x and y scales are expanded compared to history match snapshots in previous figure. The lightest shades of pink correspond to 1-4 metres of CO2 column thickness, and this is known with high certainty to not generate buoyancy force high enough to exceed the capillary entry pressure of the base Nordland mudstone.

In order to have a better prediction of plausible CO_2 extension at the uppermost layer, we have conducted a simulation study with three main changes compared to the publicly available benchmark model, provided by Statoil.

- Firstly, motivated by the 4D seismic observations, the sand wedge model was modified to be consistent with, at least partly, the observed growth of the CO_2 boundary, in particular at the southwest sector. The modified model is supported by enhanced seismic image and the available 2D high resolution seismic data acquired in 2006.

- Secondly, we had pushed estimation of the uppermost layer CO_2 mass towards its upper limit. This is supported by better match with observed CO_2 boundary on monitoring seismic data.
- Finally, we have used linear regression on estimated uppermost CO_2 mass prior to 2008 data in order to predict the CO_2 flux in our simulation studies. This results in a stabilized flux, that seems to be established by 2006, and will continue at least as long as injection is planned. While, at the benchmark model a 6th order polynomial regression is fitted to differently estimated flux data and implies that the flux is gradually increasing and will reach to annual injection rate by around 2015 (Cavanagh, 2013).

The CO_2 flux into the sand wedge model was simulated using compositional simulator (Eclipse 300) assuming the constant flux that will continue until 2050. Note that in our simulation model, CO_2 dissolution in brine is ignored and flux and timing is selected such that mimics the worst case scenario in terms of CO_2 spread for risk assessment study purposes. The simulation results showed a reasonable match with 4D seismic data. Simulation results also revealed that the receiving CO_2 at the uppermost layer will mostly flow towards north and as soon as gets a chance it will partly flow towards the west. Details of this flow will depend on accuracy of the simulation model and flux estimations.

10. BN Model Main Features

The BN model for propensity to leak (PTL) from CO_2 geological storage sites is structured in a two-level hierarchy consisting of a set of sub-models that represent discrete leakage pathway features that provide data to a top-level aggregation main BN model.

The physical processes and equations representing the event of exceeding the local capillary entry pressure were described in detail in section 9. The Bayesian net representing this is described in this section.

The feature of a seismic chimney representing a potential leak path and the associated process of a specific chimney being contacted by stored CO_2 and a subsequent leakage out of the target storage formation and to the seabed are also captured in a BN model described here.

BN sub-model of estimating the propensity to leak of a chimney

Figure 10-1 and **Figure 10-2** show the BN graphical model and a schematic of the sources of data for individual nodes.

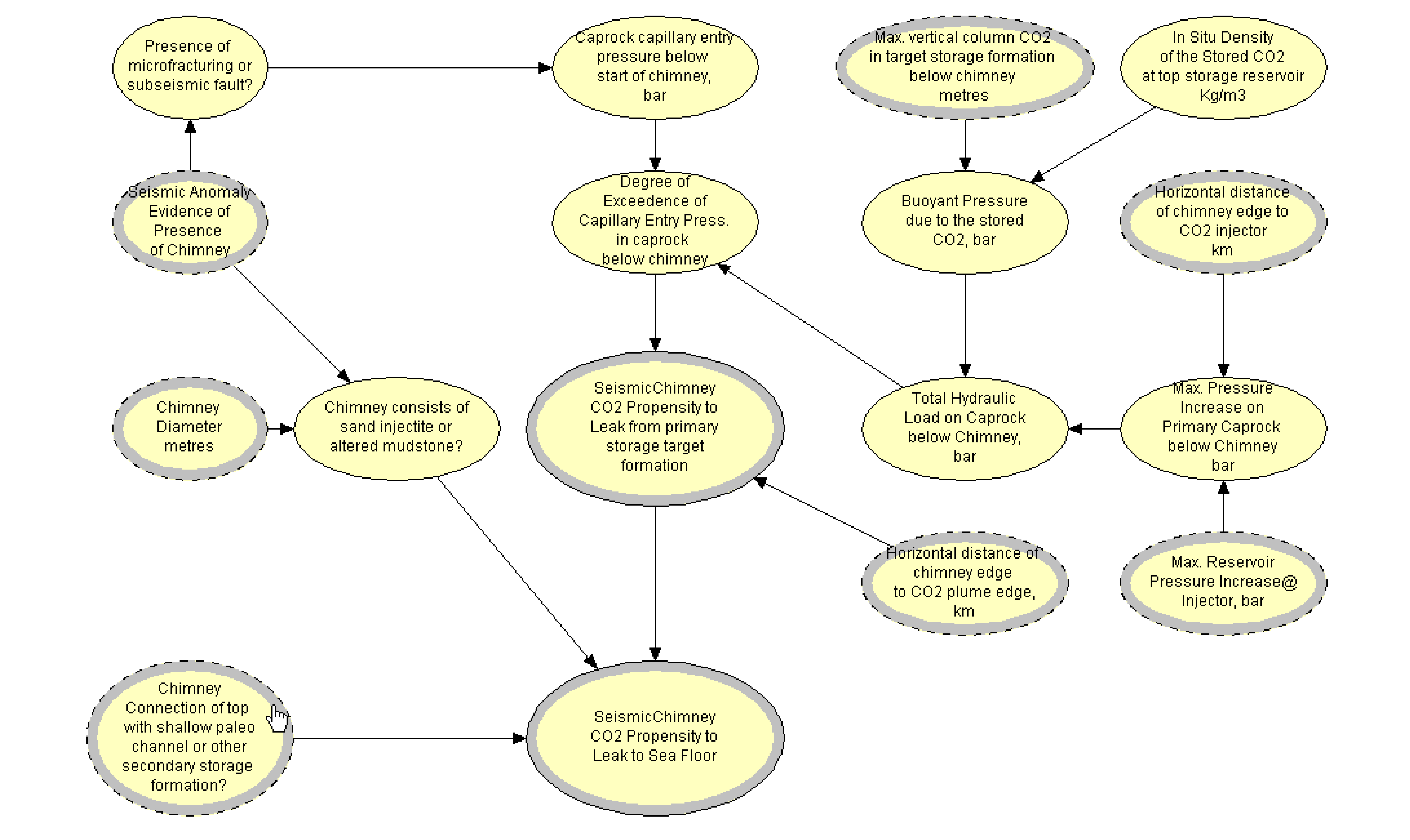


Figure 10-1. BN Sub-model representing propensity to leak along an identified chimney in the seismic data (seismic anomaly). Note some overlap in functionality with that in figure 6. This was done to ensure that local parameter estimates specific to identified chimney are entered locally for each chimney included. More detailed description of where data is sourced for input nodes is shown on figure .

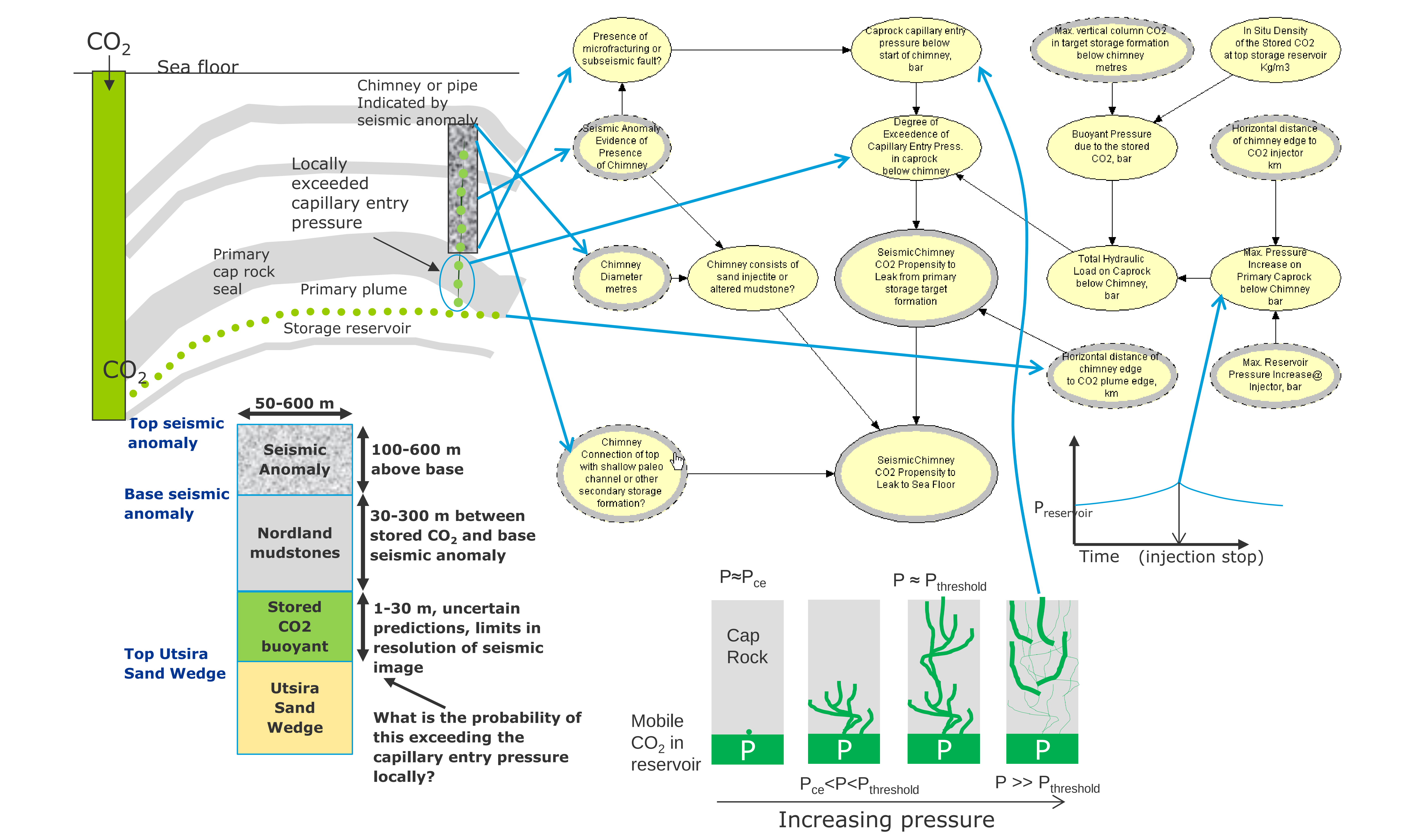
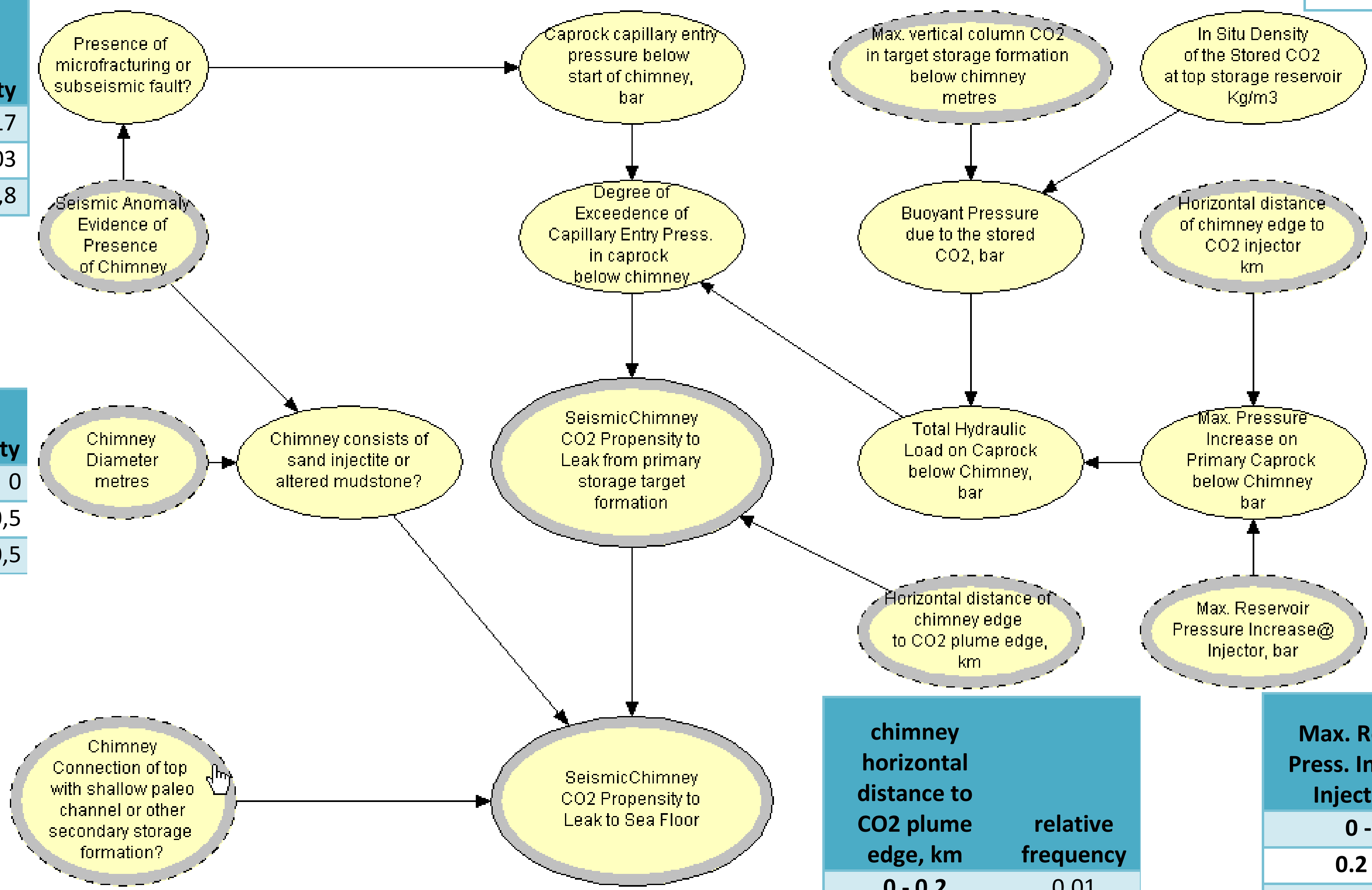


Figure 10-2. BN sub-model for propensity to leak along an identified seismic anomaly labeled as a "chimney" in the context of the overall storage site

Chimney max. CO2 Column below, m	probability
-inf - 0	0,28
0 - 2	0,28
2 - 6	0,28
6 - 12	0,14
12 - 20	0,01
20 - 40	0

In situ density of stored CO2 kg/m3	relative frequency
200 - 300	0
300 - 450	1
450 - 600	2
600 - 750	1
750 - 900	0
900 - 1050	0

Chimney seismic anomaly evidence	probability
type A	0,17
type B	0,03
type C	0,8



chimney horizontal distance to CO2 injector, km	value
0 - 0.2	0
0.2 - 0.5	0
0.5 - 1	0
1 - 3	0
3 - inf	1

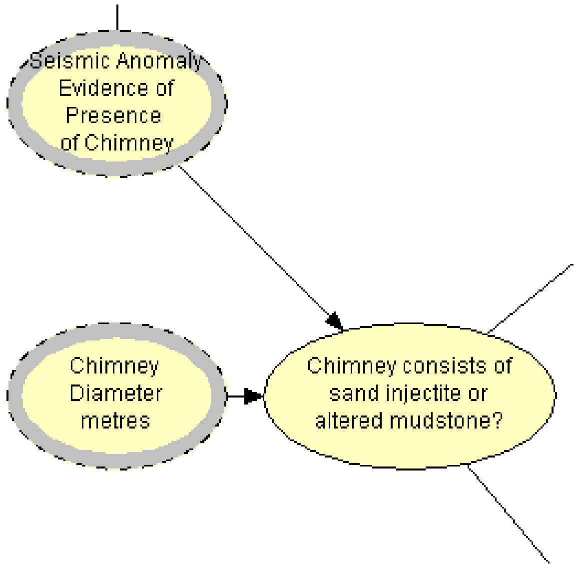
Chimney diameter, m	probability
50 - 150	0
150 - 500	0,5
500 - 1000	0,5

chimney horizontal distance to CO2 plume edge, km	relative frequency
0 - 0.2	0,01
0.2 - 0.5	1
0.5 - 1	0,5
1 - 3	0,01
3 - inf	0

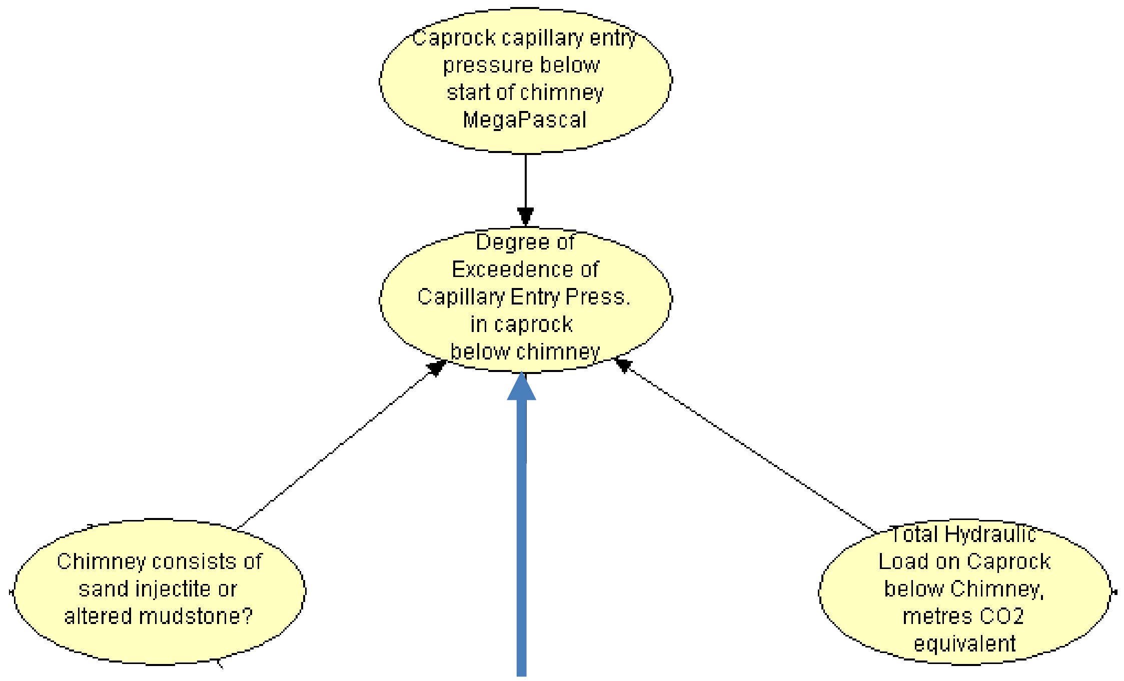
Max. Reservoir Press. Increase@ Injector, bar	relative frequency
0 - 0.2	5
0.2 - 0.5	1
0.5 - 1	0,1
1 - 1.5	0,01
1.5 - 3	0,001
3 - inf	0,0001

chimney connection of top	relative frequency
No conn'xn identified above SCAH	0,1
No conn'xn identified above SCAH	1
Possible conn'xn with shallow paleo sands	0,1

Figure 10-3. Summary input tables for all independent (input) data nodes for Chimney 77. Nodes downstream of these have correlation tables structured according to their immediate upstream nodes. Note that tables can be absolute probability (0-1) or relative probability or frequency. These are normalized internally by the software.



Chimney consists of s and injectite or altered mudstone?									
Chimney Diameter metres	50 - 150			150 - 500			500 -1000		
Seismic Anomaly Evidence of Presence of Chimney	Type A	Type B	Type C	Type A	Type B	Type C	Type A	Type B	Type C
Re-worked mudstone	0.1	0.1	0.2	0.1	0.1	0.8	0.2	0.2	0.85
Microcracks in mudstone	0.1	0.1	0.2	0.8	0.1	0.1	0.7	0.3	0.099
Sand injectite in background of mudstone	0.1	0.1	0.5	0.05	0.1	0.05	0.09	0.4	0.05



if total_hydraulic_load ≤ $P_{cap.entry}$, $then\ degree\ of\ exceedence\ is\ 'very\ unlikely'$

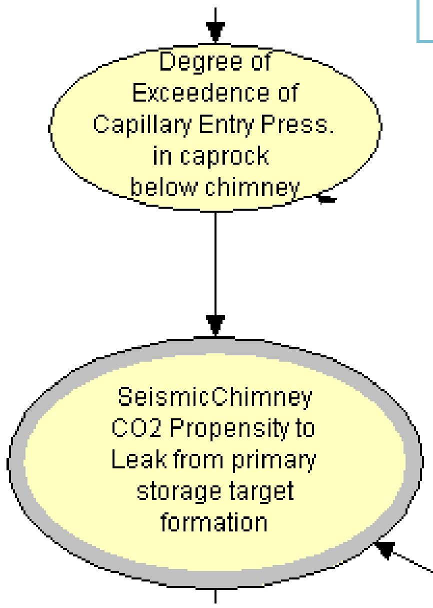
if $P_{cap.entry}$ ≤ total_hydraulic_load ≤ 1.3*$P_{cap.entry}$, $then\ degree\ of\ exceedence\ is\ 'possibly\ exceeded'$

if 1.3*$P_{cap.entry}$, ≤ total_hydraulic_load ≤ 1.8*$P_{cap.entry}$, $then\ degree\ of\ exceedence\ is\ 'significantly\ exceeded'$

if total_hydraulic_load ≥ 1.8*$P_{cap.entry}$, $then\ degree\ of\ exceedence\ is\ 'significantly\ exceeded'$

Figure 10-4. Correlation table for 'Chimney consists of sand injectite or altered mudstone' and equations for the node ' Degree of Exceedance of Capillary Entry Press (Pcap.entry) in caprock below chimney'

Horizontal distance of chimney edge to CO2 plume edge, km	0 - 0.2				0.2 - 0.5				0.5 - 1			
Degree of Exceedance of Pcap.e, in caprock below chimney	Unlikely Exceeded	Possibly Exceeded	Significantly Exceeded	Very Significantly Exceeded	Unlikely Exceeded	Possibly Exceeded	Significantly Exceeded	Very Significantly Exceeded	Unlikely Exceeded	Possibly Exceeded	Significantly Exceeded	Very Significantl y Exceeded
Negligible	0.53	0.15	0.05	0.04	0.44	0.43	0.41	0.39	0.560538	0.45	0.38	0.08
Low	0.26	0.25	0.1	0.07	0.31	0.17	0.23	0.17	0.336323	0.3	0.29	0.12
Medium	0.13	0.25	0.15	0.22	0.15	0.23	0.13	0.15	0.0134529	0.15	0.24	0.16
High	0.05	0.35	0.4	0.31	0.08	0.13	0.14	0.16	0.0784753	0.08	0.07	0.24
Very High	0.03	0.05	0.3	0.36	0.02	0.04	0.09	0.13	0.0112108	0.02	0.02	0.4



Horizontal distance of chimney edge to CO2 plume edge, km	1 - 3				3 - inf			
Degree of Exceedance of Pcap.e, in caprock below chimney	Unlikely Exceeded	Possibly Exceeded	Significantly Exceeded	Very Significantly Exceeded	Unlikely Exceeded	Possibly Exceeded	Significantly Exceeded	Very Significantly Exceeded
Negligible	0.62	0.6	0.43	0.3	0.97	92.0	0.8	0.6
Low	0.21	0.14	0.1	0.1	0.02	0.04	0.15	0.2
Medium	0.11	0.15	0.3	0.4	0.01	0.03	0.02	0.1
High	0.06	0.07	0.1	0.1	0.0	0.0010	0.02	0.06
Very High	1.0E-4	0.03	0.07	0.1	0.0	1.0E-5	0.01	0.04

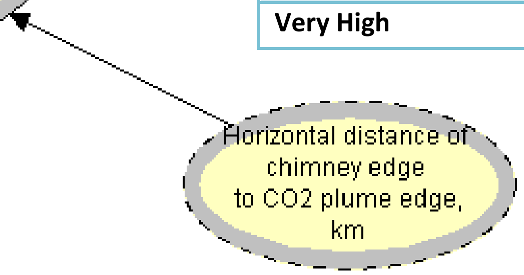
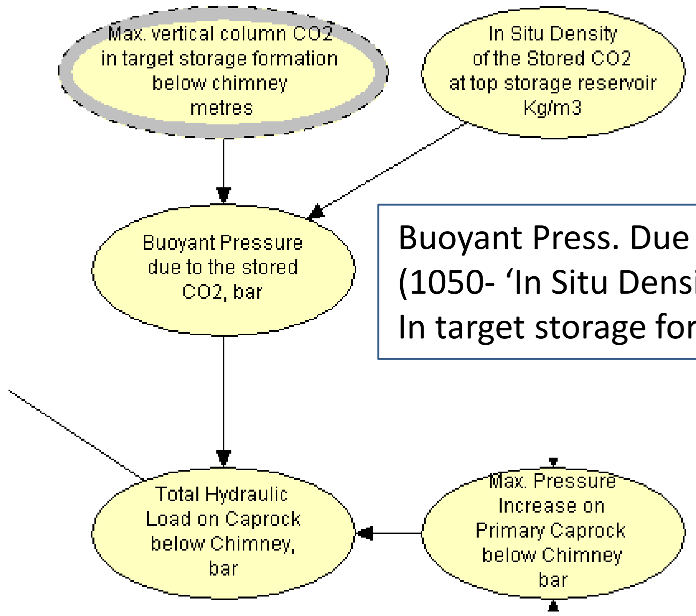


Figure 10-5. Focus on the correlation tables that link input nodes to the intermediate node 'SeismicChimney CO2 Propensity to Leka from primary storage target formation'.

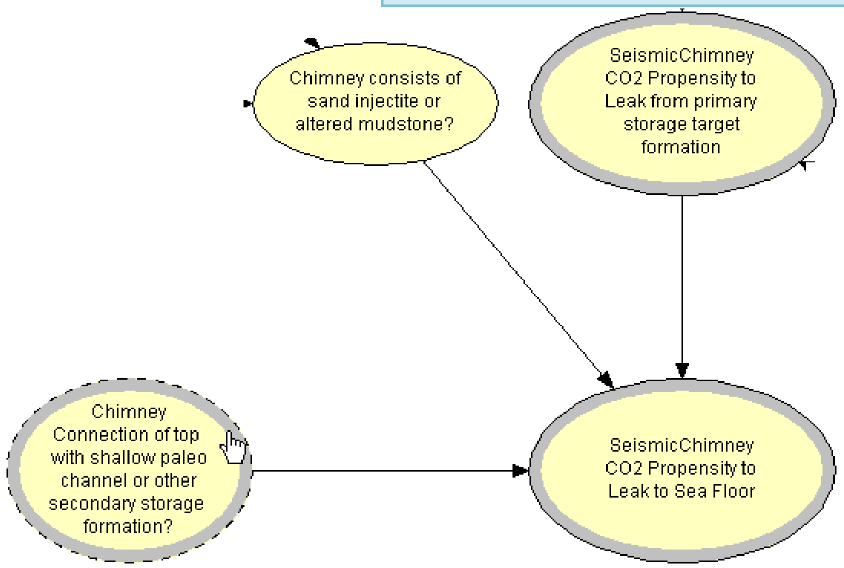


Buoyant Press. Due to the stored CO2, bar =
(1050- 'In Situ Density of the Stored CO_2 at top storage reservoir, kg/m^{3}')*(9.8*10^{-5} *'Max. Vertical column CO_2
In target storage formation below chimney, metres')

Total Hydraulic Load on Caprock below Chimney, bar =
'Buoyant Press. Due to the stored CO_2, bar' + 'Max. Press. Increase on Primary Caprock below Chimney, bar'

Figure 10-6. Focus on the node inputs to 'Buoyant Pressure due to the stored CO2,bar', and node inputs to 'Total Hydraulic Load on Caprock below Chimney, bar'

Chimney Connection of top with shallow paleo channel or other secondary storage formation?	No connexn identified above SCAH														
Chimney consists of sand injectitie or altered mudstone?	Re-worked mudstone					Microcracks in mudstone					Sand injectite in background of mudstone				
SeismicChimney CO2 Propensity to Leak from primary storage target formation	Negligible	Low	Medium	High	Very High	Neg.	Low	Med.	High	V.High	Neg.	Low	Med.	High	V.High
Very Unlikely	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	3.0
Possible	0.0	0.0	1.0	1.0	1.0	0.0	1.0	1.0	1.0	1.0	0.0	1.0	1.0	1.0	2.0
Very Unlikely	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0



Chimney Connection of top with shallow paleo channel or other secondary storage formation?	No connexn identified above FTP														
Chimney consists of sand injectitie or altered mudstone?	Re-worked mudstone					Microcracks in mudstone					Sand injectite in background of mudstone				
SeismicChimney CO2 Propensity to Leak from primary storage target formation	Neg.	Low	Med.	High	V.High	Neg.	Low	Med.	High	V.High	Neg.	Low	Med.	High	V.High
Very Unlikely	1.0	1.0	0.0	1.0	2.0	1.0	1.0	0.0	1.0	3.0	1.0	0.0	0.0	3.0	2.0
Possible	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0	1.0	2.0	1.0
Very Unlikely	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0	1.0

Chimney Connection of top with shallow paleo channel or other secondary storage formation?	Possible connexn with shallow paleo sands														
Chimney consists of sand injectitie or altered mudstone?	Re-worked mudstone					Microcracks in mudstone					Sand injectite in background of mudstone				
SeismicChimney CO2 Propensity to Leak from primary storage target formation	Neg.	Low	Med.	High	V.High	Neg.	Low	Med.	High	V.High	Neg.	Low	Med.	High	V.High
Very Unlikely	1.0	1.0	1.0	2.0	2.0	1.0	1.0	1.0	2.0	1.0	1.0	0.0	0.0	0.0	0.0
Possible	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Very Unlikely	0.0	0.0	1.0	1.0	1.0	0.0	1.0	1.0	1.0	1.0	0.0	1.0	1.0	1.0	1.0

Figure 10-7. Node correlation tables for the node 'Seismic Chimney CO2 Propensity to Leak to Sea Floor'

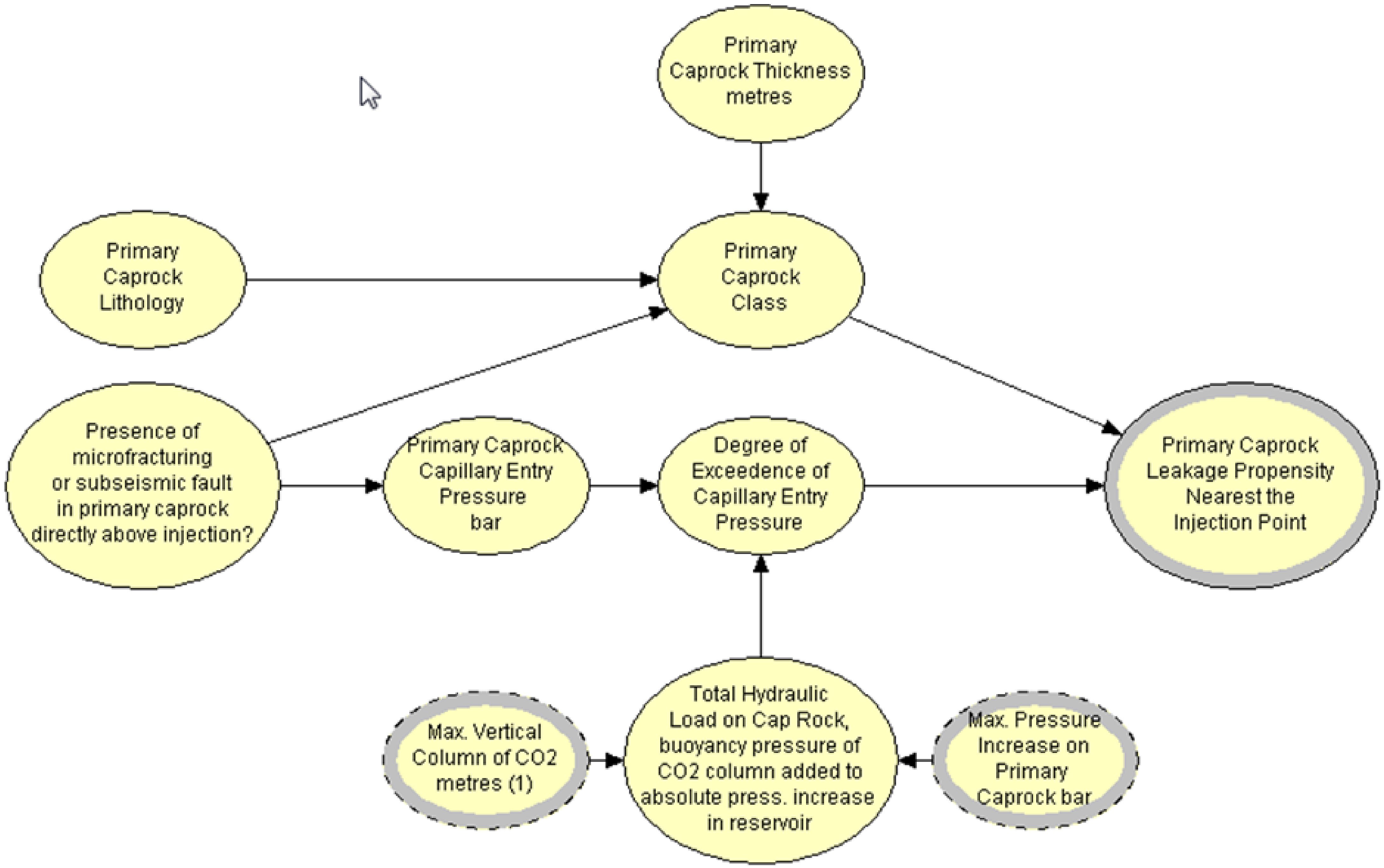


Figure 10-8. Bayesian Net sub-model representing the degree of exceedance of capillary entry pressure at a specific location which may become a path for accelerated vertical flow from the target storage formation to a shallow formation or seabed. Sources of input data for each input node are shown in

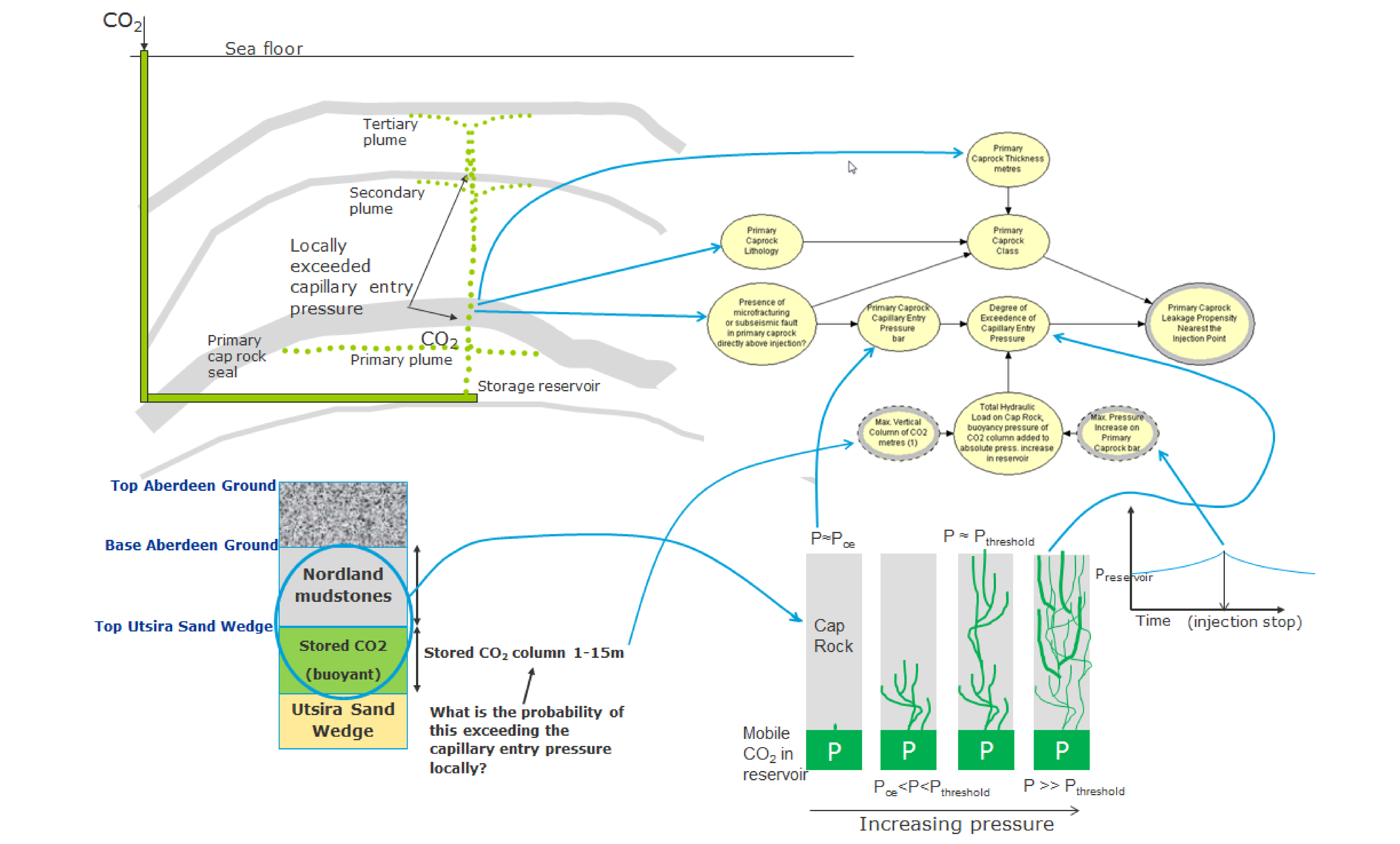


Figure 10-9. Illustration of leakage pathway concept for exceeding capillary entry pressure at a location directly above the injection point (no seismic anomaly or chimney above) and the Bayesian Net sub-model representing it.

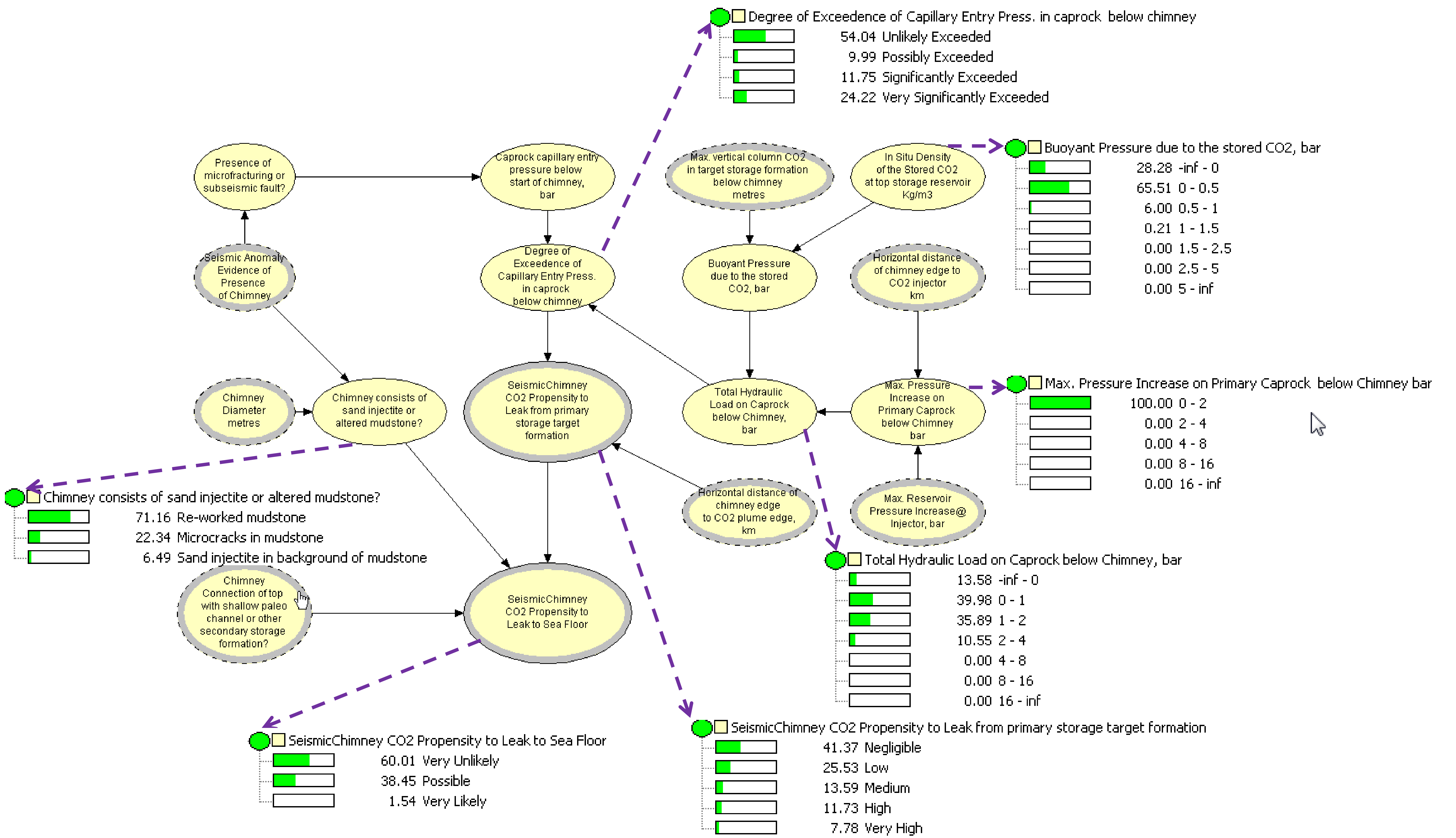


Figure 10-10. Outputs and intermediate results of the BN model for the chimney 77 dataset. The final output for the ERA is 'Seismic Chimney CO2 Propensity to Leak to Sea Floor'. The frequency bars and associated probabilities are directly extracted from the Hugin BN software tool.

Discussion of Bayesian Net PTL results for Chimney 77

The main outputs and intermediate results for chimney 77 are shown on Figure 10-10. The main output is the node 'SeismicChimney CO2 Propensity to Leak to Sea Floor'. The secondary output is the node 'SeismicChimney CO2 Propensity to Leak from primary storage target formation'.

'SeismicChimney CO2 Propensity to Leak to Sea Floor'

The results are repeated in the table below.

Chimney 77	Bayesian net estimate of propensity to leak to sea floor
Very Unlikely	60.1%
Possible	38.5%
Very Likely	1.5%

Aggregating these to a single PTL value gives 22%, which is within the category 'possible'.

The 1.5% estimate that propensity is 'Very Likely' for leakage to the sea floor through chimney 77 is a result that chimney 77 has

- a 6.5% probability of a sand injectite morphology
- about 9% probability of a connection to a shallow paleo-channel and
- about 0.7% probability that the edge of the stored CO2 plume within the target formation will contact the chimney
- in addition to a non-zero propensity to leak from the target storage formation (next section)

Note that the final result is not based on a simple pi product of independent probabilities representing barriers in series. The Bayesian inference mathematics includes and represents a wider range of evidence qualities that may not be entirely indicative but can be counter-indicative.

'SeismicChimney CO2 Propensity to Leak from primary storage target formation'

The results for this intermediate node output are repeated below.

	Bayesian net estimate of propensity to leak from target storage formation
Negligible	41.4%
Low	25.5%
Medium	13.6%
High	11.7%
Very High	7.8%

The factors leading to the 7.8% propensity to leak from the target storage formation are

- About 0.7% probability that the edge of the CO2 plume within the target storage formation will contact chimney 77.
- (11.8% + 24.2%) probability of 'significantly' or 'very significantly' exceeded capillary entry pressure at the base of chimney 77 and

Other Bayesian Net feature models

As shown on **Figure 10-8** and **Figure 10-9**, the process of breaching the cap rock sealing formation above the target storage formation, directly above the injection point, was also represented in this study. Judging from the cumulative evidence of seven time-lapse repeat seismic surveys over the stored CO_2 since 1996, no sign can be identified of any breach of the base Nordland mudstone caprock directly above the injection point. It was decided therefore to not include this in the BN model dataset. The potential leakage scenario which the repeat seismic survey evidence strongly indicates has not and will not be realized is described in **Figure 10-11**.

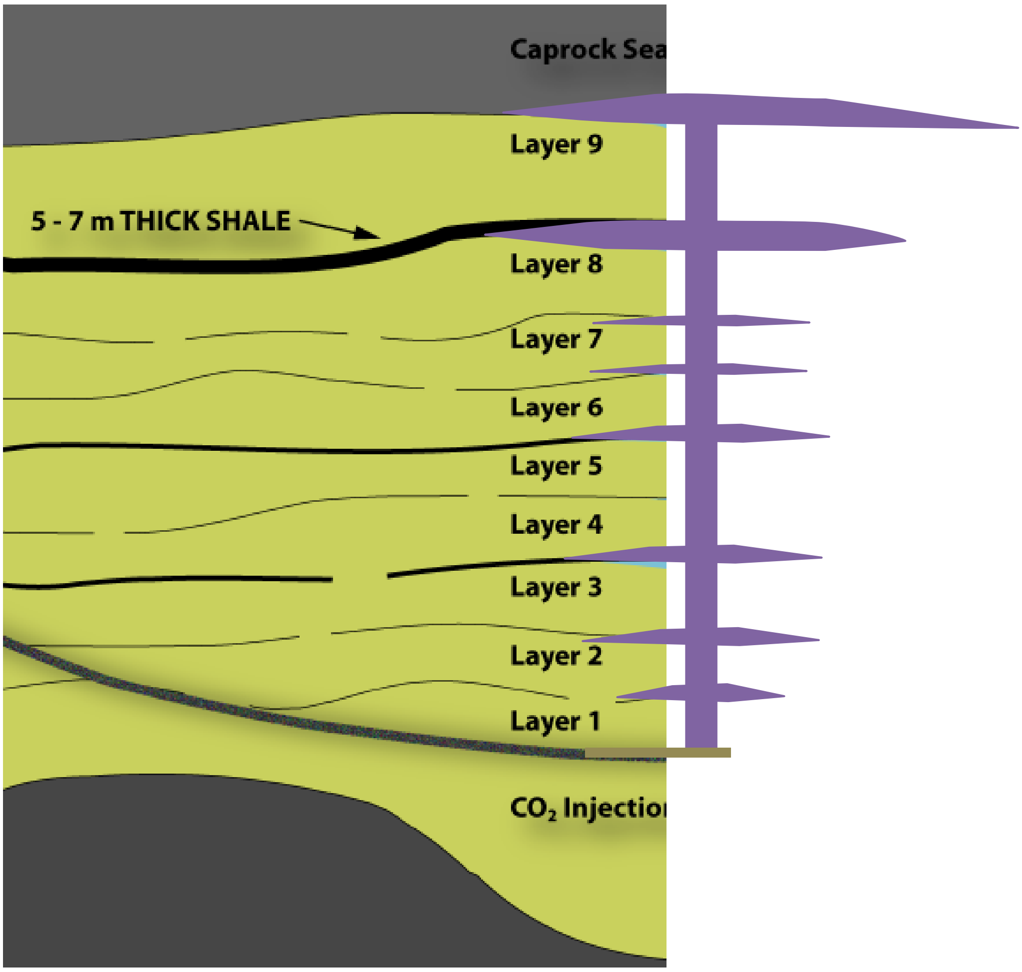


Figure 10-11. Worst case scenario for height of a stored CO_2 column when considering propensity to exceed local capillary entry pressure directly above the CO_2 injection point.

11. Environmental Risk Assessment, Combining Consequence and Propensity to Leak

Risk is commonly defined as the combination of

- a potential, specific consequence (or impact) of a process/event and
- the probability (alternatively frequency, likelihood, or in this case propensity) of the consequence being realized, as described in the ISO standard for risk assessment (ISO 31000).

Assessment of consequence: In the assessment of consequence it was identified that a change in pH concentration from leakage points may influence the bivalves *Tellimya tenella* and *Arctica islandica* on an individual level. On a population level only a very small fraction may be influenced. The other benthic species identified as valuable are only registered with a few specimens far from the Sleipner field.

The data are compiled in a consequence matrix (see below). The results from the consequence matrix will be a direct input to the risk matrix for the given EBSA. The consequence is **"Incidental"** for both species.

Consequence matrix for valuable components at Sleipner.

Degree \ Value		Environmental value		
		Low	**Medium**	**High**
Degree of impact	**Small**	*Arctica islandica*	*Tellimya tenella*	
	Moderate			
	Large			

The results of the Propensity to Leak assessment are repeated in the table below.

Chimney 77	Bayesian net estimate of propensity to leak to sea floor
Very Unlikely	60.1%
Possible	38.5%
Very Likely	1.5%

Aggregating these to a single PTL value gives 22%, which is within the category 'possible'.

The final ERA risk matrix is shown below.

The overall risk is assessed to the lowest category; Negligible (small, negative, the green matrix cells) for both Arctica islandica and Tellimya tenella.

Severity measured in Environmental Value / **Propensity to Leak**	**Severity of environmental impact**			
	Incidental	**Moderate**	**Major**	**Critical**
Unlikely				
Possible	*Arctica_islandica*$_{Chim77}$ *Tellimya_tenella*$_{Chim77}$			
Very Likely				

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13. Appendix A

This appendix contains a brief description of some of the wide range of applications for Bayesian networks that have been registered. Applications include:

1. Offshore jacket inspection: tool for cost-optimal inspection planning of offshore jacket structure with respect to fatigue cracks.
2. Petroleum exploration: evaluation of drilling prospects
3. Pipeline risk assessment: DNV "MARV" project - aiming to provide real-time risk assessment of pipelines based on pipeline condition as monitored in the field, with consequences of mitigation updated in real time. The BN model accounts for internal corrosion (accounting for pipe inclination, water entrainment, and observations of pipeline condition), and third party damage (e.g. farming incident, road traffic, waterways, construction, unauthorised activity). A related EU project COCATE has also developed a safety risk model based on BN. DNV led the BN model development and testing.
4. Marine pipelines upheaval buckling: reliability model for upheaval buckling of trenched marine pipelines, including maintenance costs and use of sonar measurements
5. Oil & gas explosion risk management: evaluation of explosion risk, and risk reduction options on a large North Sea installation.
6. Offshore decommissioning: tool being used to evaluate risks in raising Brent field concrete gravity based installation. Tool also applied to Frigg decommissioning decision support.
7. Drilling decision support: operational decision support system based on real-time sensor readings. Modelled scenario is drilling close to the transition to a high-pressure formation, a gas influx is observed. The drilling team needs to decide whether to circulate, increase the mud weight, plug back, set a casing, etc. (CODIO project on Collaborative Decision support for Integrated Operations)
8. Safety in ship operation / climate change: study of extreme weather conditions as a serious natural hazard to ship operations and possible changes in the statistics of extreme weather conditions.
9. Passenger ship navigation: risk modelling of passenger ship navigation. Models for grounding and collision including nodes to represent management factors (training, planning etc.), working conditions (responsibilities, weather etc.) and personal factors (tiredness etc.)
10. Ship grounding and collision analysis: software package for grounding and collision analysis developed at the Technical University of Denmark within the project: Information technology for increased safety and efficiency in ship design and operation.
11. Marine diesel engines: detection system for misfire and exhaust valve leaks in marine diesel engines.
12. Road tunnels: model for probabilistic assessment of excavation performance of tunnel projects which considers the quality of the design and construction process. Case study deals with the excavation of a road tunnel.
13. Rock fall onto roads: general framework for natural hazards risk assessment - applied to rating systems for assessing rock-fall hazard risks on roads

14. Appendix B

The starting point of a forward-looking or a diagnostic analysis and conclusion often starts with raw data that consists of imperfect/ambiguous proxies that are used to produce a “diagnosis” or “verdict”, which is generalized here with the term “hypothesis”. Statistical data for frequency of occurrence may be lacking. Several different types and sources of evidence and subjective interpretation may give ambiguous or inconsistent indications on the hypothesis. In its purest and simplest form, the Bayesian method presents four possible outcomes on our judgement on the hypothesis.

	Null hypothesis Is actually TRUE	Null hypothesis Is actually FALSE
Analysis outcome: Reject the null hypothesis	False Positive (type I error)	**Correct Outcome (true positive)**
Analysis outcome: Accept the Null hypothesis	**Correct Outcome (true negative)**	False Negative (type II error)

Type I Error: “Convicting an Innocent Person” or “Diagnostic test says you have disease X but in fact you are healthy (disease-free)”.

Type II Error: “Letting a guilty person go free” or “In fact you have disease X but the diagnostic test says you are healthy”.

Thomas Bayes established a simple mathematical relationship (1740s) between various uncertainties for a given proposition and the probability that the proposition is true. A simple illustration of this is given as an example here.

Suppose that a medical test has 95% reliability for a true positive for testing for a specific condition in a population in which the general frequency of occurrence for this condition is 0.5%. Is this a good test? We apply the simple Bayes formula:

$$P(A_j \mid B) = \frac{P(A_j)\,P(B \mid A_j)}{\sum_{i=1}^{n} P(A_i)\,P(B \mid A_i)}$$

$$\frac{0.005 \times 0.95}{(1 - 0.95)\,(1 - 0.005) + 0.005 \times 0.95}$$

This gives a probability value that the medical test gives a “true positive” of someone having the condition of 0.087, 8.7%. In other words, it is 91.3% probable that the medical test gave a “false positive”.