UNIVERSITY OF TROMSØ UIT

FACULTY OF SCIENCE AND TECHNOLOGY
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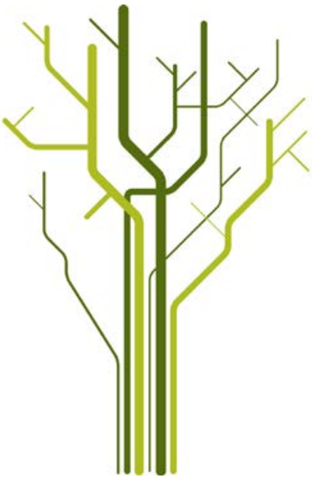
Fluid leakage assessment of the overburden structure at the Sleipner CO$_2$ storage site

Ida Bruun Lydersen

EOM-3901 Master's Thesis in Energy, Climate and Environment

July 2013



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Abstract

Carbon capture and storage (CCS) has been proposed as one of the alternatives for climate mitigation. CCS is a process where CO_2 is trapped from large point sources, transported to a storage location and injected into storage reservoirs. One of the alternatives for CO_2-storage is underground geological storage. Characterizing such an underground reservoir is crucial for safe storage, where leakage from the reservoir is considered the biggest hazard. Mapping both the reservoir and the surrounding area is therefore important. Knowledge of the geology and in particular the flow of fluids in the area is of special interest, as they give an impression of how the system acts and can give information enabling reservoir simulations of future flow.

The Sleipner field is located in the North Sea, and was the first underground geological CO_2-storage facility in Norway. In this thesis, it is in the overburden of the Sleipner field, that vertical curvilinear structures have been observed, mapped and described. The origin of these features has also been of interest and interpreted.

The vertical features are interpreted to be fluid flows, found across the data set (ST98M11) interpreted in this thesis. The fluid flows in the data set have similar characteristics, both in size and the seismic amplitude anomalies seen in connection to them. Concerning the distribution of these fluid flows, they seem to have the highest occurrence rate in the southwestern corner of the data set, which might be seen in context with the seal defined for the Sleipner reservoir thinning out to the south west. The origin of the fluid flows seem to be connected with the underlying layer of polygonal faulting and mud diapirism, as well as being influenced by an intermediate layer of glacial inheritance.

Acknowledgements

5 years of fulfilling my own dream; complete an education which can contribute to a better understanding of how we can continue sustainable growth on this planet – is completed. Since I started out in the Blekkulf-club as a 6 year old I cannot feel anything less than pride of myself for following a goal for so many years. I want to thank all the people who have inspired me to follow my dream, my family and especially my mother and father for always being there for me when I've needed support and help. And especially driving me to and from the university whenever I've asked for it… ☺ You have been an inspiration to me throughout my life, making my path easier to walk and easier to find.

I'd like to thank my supervisor Stefan Bünz for introducing me to 3D seismic interpretation early on in my education, and arranging everything for me in my study plan so I could follow my wish to learn more and write my thesis on CO_2-storage. Without this I would not have been where I am today. I'd also like to thank my co-supervisor Alexandros Tasianos for his excellent inputs and inspiration on the subject, and his great companionship during our stay at Svalbard!

I especially want to thank everyone who's been in my class (EKM '08) for their help and support in subjects, as well as everyone who has been a part of my education. I'll never forget the laughs, the struggles, the mountaineering trips or the quizzes.

An acknowledgement is pointless without mentioning my best friend, Maria, who's also been a vital support for me these years. Thank you for every silly shopping spree we've been on to take my mind off the stress. A very special thank you to my dear Cato is needed as well. Thank you for surviving through phone calls and for travelling with me to reset my brain – without you this thesis wouldn't have been! What is better than travelling to Iceland to get geological inspiration? ☺

Last but not least: thank you my beloved dog Luna, who came into my life parallel with the start of my education. Since I started at UiT in August 2008 you've been there for me every single day of my education, turning any mood into a good one.

Ida Bruun Lydersen
Tromsø, July 2013

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1. INTRODUCTION

1.1 Objective

The main objective of this master thesis is

- Identifying and mapping the distribution of fluid-leakage structures in the overburden above the CO_2-storage reservoir at Sleipner in the North-Sea.

The secondary objective of this master thesis include

- Assessing the origin of these fluid-leakage structures

1.2 Motivation

An ever growing population inhabits our planet, pushing the need for energy higher and higher as time progress. Together with this rising demand for energy, the question of climate change has brought concern. Production of energy leads to the emission of a variety of natural occurring gases which have an undesirable side-effect. They are said to increase the greenhouse-effect and thereby changing the climate faster than what it would naturally. This is a matter of great debate, and recent studies have shown a remarkable robustness of nature to fluctuations in temperature (Otto, et al. 2013).

Nevertheless, to cover the need for energy, while tackling the theme of climate change, a considerable amount of research has been put into possible climate mitigation technologies. The overall goal is to stabilize the emissions of greenhouse gases, at a level which prevents dangerous anthropogenic interference with the climate system (Kyoto protocol, 1997). There are many ways of categorizing the proposed solutions for climate mitigations, the works of Freund and Kaarstad (2007) has been used as an inspiration in the following list. Freund and Kaarstad say there are four main ways of "accessing energy without damaging the climate";

<u>Reduce</u>
Reducing the demand for energy involves both cutting actual usage of energy, improving current and future technology with a more efficient energy usage and reducing the overall need for energy, such as turning the lights off each time you leave a room. Rather than helping, this can actually contribute to increase the net energy usage. Reduction also demands big social campaigns to make people change their regular behavior.

<u>Recycle</u>
Recycling involves more than just recycling the plastic bottles and metal boxes in your home. Recycling energy also includes using excess energy. In the industry heat recovery can make a gas turbine more effective my utilizing the steam which is too hot for turbine 1 in another turbine, creating a "turbo" effect and almost doubling its overall efficiency. This energy is mostly let out into the atmosphere as steam as of today. Recycling energy must be made more profitable before a big implementation will be done.

<u>Substitute</u>
Substituting energy is one of the most "classical" ways of climate mitigation - another known name for this is renewable energy. Instead of using the classical hydrocarbon

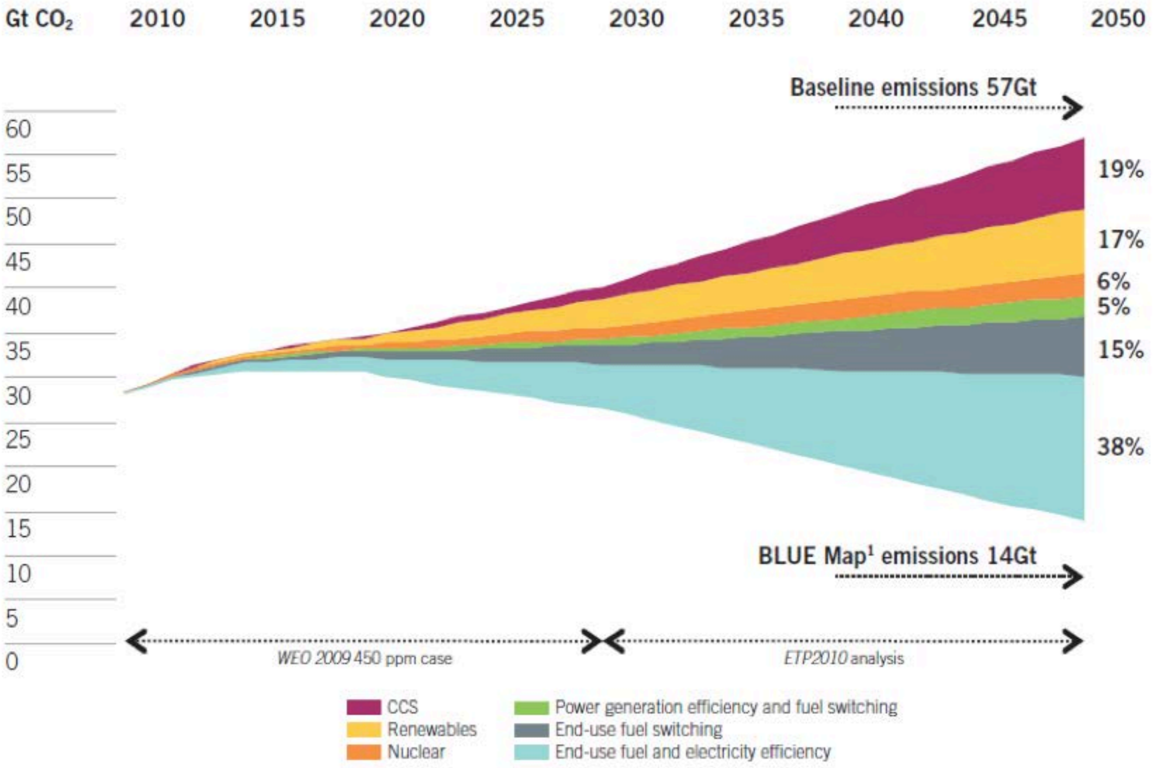
sources for energy, the coal, oil and gas is substituted with nuclear energy, wind energy, wave energy, tidal wave energy, biofuels, biomass, solar energy, water energy, geothermic energy and energy from waste - as well as new technologies emerging as more and more research is put into this. Substituting coal energy with gas energy is another way of greatly reducing the greenhouse gas emissions, as gas energy is much cleaner. Sadly these renewable energy sources are often expensive and very invasive on ecosystems.

Dispose

Sequestering CO_2 occurs naturally, as both trees and the ocean draw CO_2 from the atmosphere in natural processes leading CO_2 to be stored for thousands of years. But trees have only a finite lifespan, releasing the stored CO_2 back into the atmosphere when they die, and the ocean have only a certain fraction it can absorb before it is saturated. Obviously a more long term and reliable way of sequestering CO_2 is needed, which is why geological CO_2 sequestration has become a central part of the proposed "solution" towards stabilizing the anthropogenic effect of greenhouse gas emissions (CICERO, 2007). Sequestering the CO_2 from the atmosphere requires capturing the CO_2 from combustion, which only can be acquired from large point sources such as factories, power plants and refineries.

These large point sources sum up to about 56% of all emissions globally (Eiken, 2011). Norway, represented by Statoil ASA, has been one of the first countries in the world to implement large scale carbon capture and storage. Today we have two active injection wells on Norwegian territory; one of them is in the Snøhvit field, located in the Barents Sea, and the second one is located in the Sleipner field, located in the North Sea.
With an implementation of carbon capture and storage, a report from IPCC in 2005 (IPPC, 2005) states that 80-90% of the net emission from a power plant can be captured and stored. A desired effect without doubt, but also an expensive one. The same report suggests that required energy needed to capture the CO_2 is in the range of 10-40%, depending on which fuel the power plant is using. One of the main problems with CCS is making the process from capturing to storing the CO_2 less expensive, which requires further technological research.

Figure 3 Global CO_2 emissions and GHG emissions reductions



[1] Blue Map scenario reduces all global energy related emissions to half their current levels by 2050 (IEA 2008).

Illustration 1.1 – The "baseline emissions" is the amount of CO_2*-emissions which will be globally if no climate change mitigation techniques are put to action. The "BLUE Map" scenario shows which level of* CO_2*-emissions we will reach if we implement the various types of climate mitigation techniques mentioned in the figure. In the BLUE map scenario from IEA (2008) we see that CCS is almost 20% of the total cuts, and has a solid increasing tendency of importance. Picture from IEA, 2008.*

1.3 What is carbon dioxide-storage?

IPCC defines: "*Carbon dioxide* (CO_2) *capture and storage (CCS) is a process consisting of the separation of* CO_2 *from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere*" (IPPC, 2005). It is this long-term isolation, or storage, which is of focus in this project. There are three main types of storing the CO_2:

*Mineral carbonation which is the chemical process of which carbon and a given mineral is made to react with each other, creating a new mineral (carbonates) and effectively capturing the CO_2 within a new molecule.
*Ocean storage involves injection of CO_2 in a fluid state into very deep areas of the ocean. At such depths the pressure is high, and the long term reaction will be dissolution of the CO_2 into the ocean - joining the global carbon cycle.
*Geological storage is the one that is most studied and most used for CCS-projects per today. Any kind of porous rock formation that can, or presently, holds fluids can be used for CO_2-storage.
(All info from Fridtojf Riis, 2011)

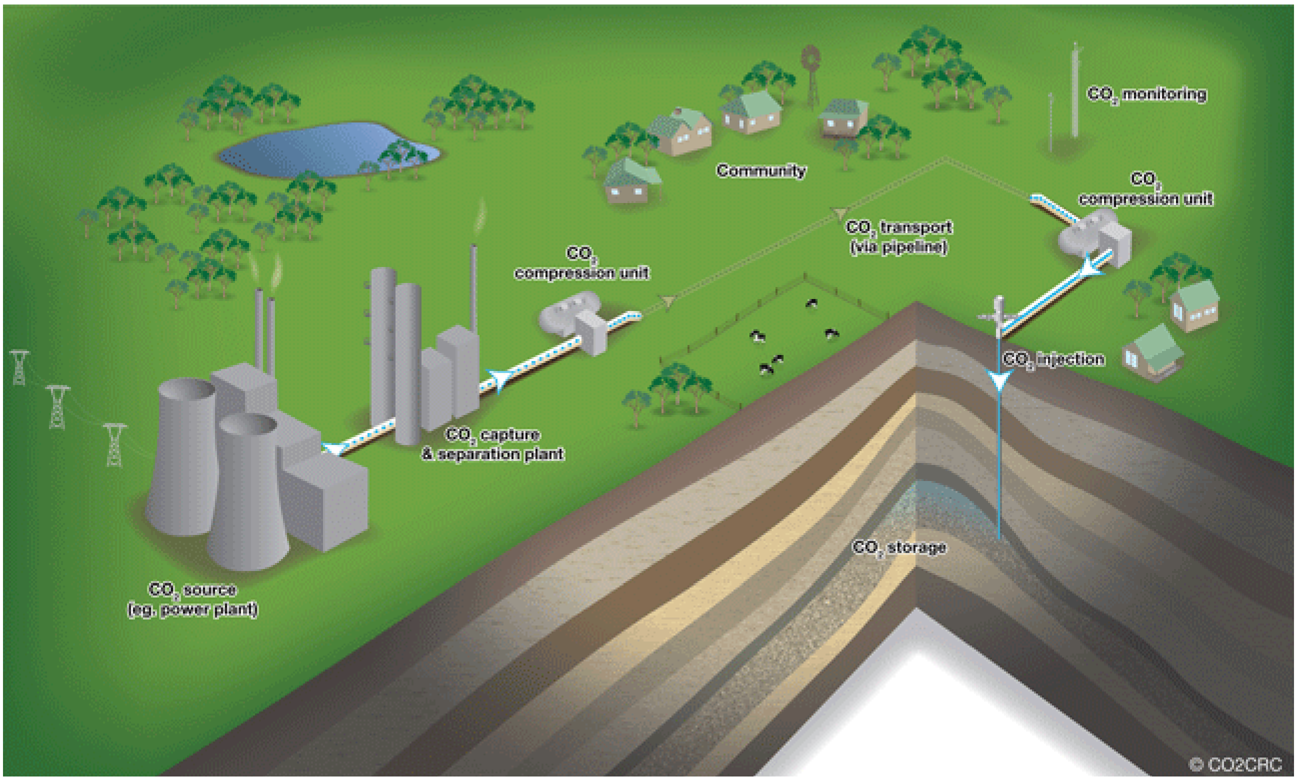


Illustration 1.2 – The whole process from capture via transportation to storage of CO_2*. Image courtesy* CO_2*CRC – (http://www.*CO_2*crc.com.au/aboutccs/)*

1.3.1 Types of geological storage

To safely store CO_2 in the sub-surface, you need a geological formation known as a reservoir, and a cap rock which keeps the CO_2 in the reservoir. The demands for a good CO_2-storage site can be correlated with the demands for a good petroleum reservoir. You need porosity, permeability, volume and a tight seal on top.

It is therefore not surprising that the most widespread type of reservoir for CO_2 storage per today is the saline aquifer. The saline aquifer is characterized with generally good porosities, permeability, good volumes and a form of seal. Other good alternatives are depleted gas -and oilfield, as well as currently active oilfields where the injection of CO_2 can increase pressure and enhance the oil recovery (EOR). This can potentially be a good way of mitigating the effect of increased energy needs due to injection.

Other options for CO_2-storage which can create energy are un-mineable coal seams. These lie to deep in the earth's crust to be exploitable by conventional mining, but by injecting CO_2 into the seams the CO_2 reacts with the coal chemically, creating methane.
(Whole text: Eiken, 2011)

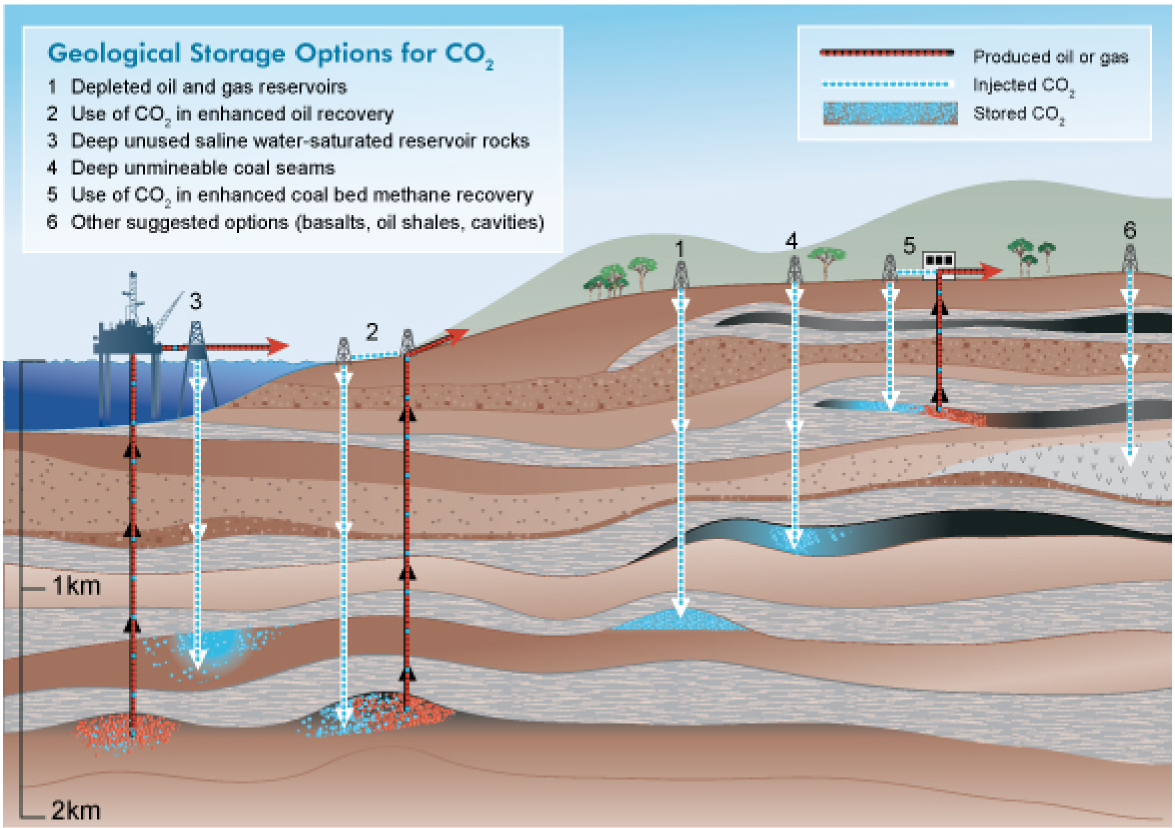


Illustration 1.3 – The various types of geological storage options available today. Image courtesy CO_2CRC (http://www.CO_2crc.com.au/aboutccs/storage.html)

1.3.1.1 Entrapment of the CO_2 within the reservoir

Within the reservoir, the actual CO_2 entrapment is a four stage process. These four stages can be treated as variables of time, and it should be noted that they don't necessarily always occur in the given order which follows.

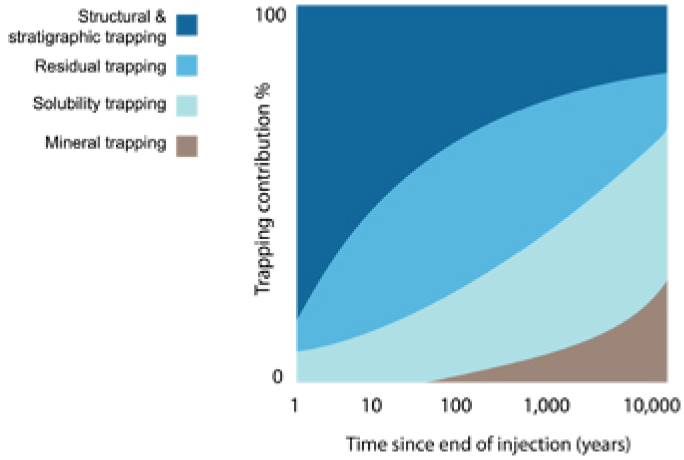


Illustration 1.4 – An example of mixed entrapment methods given as variables of time and amount of entrapment per stage. Image courtesy CO_2CRC (http://www.CO_2crc.com.au/aboutccs/stor_trapping.html)

The first stage of entrapment is the structural/stratigraphic trapping. The injected CO_2-brine will in most cases be more buoyant than the reservoir fluids, making it rise upwards until it reaches a seal. Often completely similar to what we know from the petroleum industry, structural entrapment consists of a structure such as an anticline or a fault-plane. The shape of the reservoir makes for a four way closure and the seal on top more or less stops the content from seeping out. It is important to keep the pressure within the reservoir low, so the seal does not break.

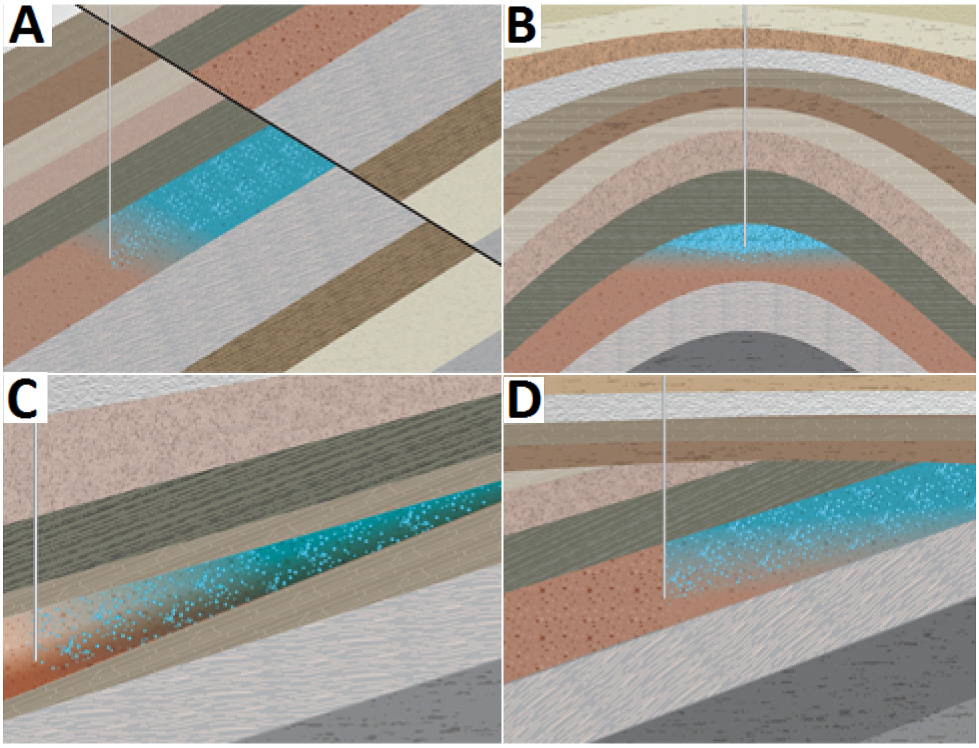


Illustration 1.5 – 4 different types of structural trapping of CO_2. A: Fault plane B: anticlinal structure C: pinch-out D:stratigraphical trap Image courtesy CO_2CRC (http://www.CO_2crc.com.au/aboutccs/stor_trapping.html)

The second phase of entrapment is residual trapping. As the CO_2 starts to stabilize and move horizontally and vertically through the pore space in the reservoir, the pore space acts like a sponge and traps the CO_2 in the pore spaces. This happens when the throat connection in the pore space between cuts "continuous CO_2-bubble-body" into half. The result of this process is several isolated drops of the injected CO_2-brine spread across the pore space of the reservoir. This is a stable phase of which CO_2 can be stored for millions of years in the reservoir.

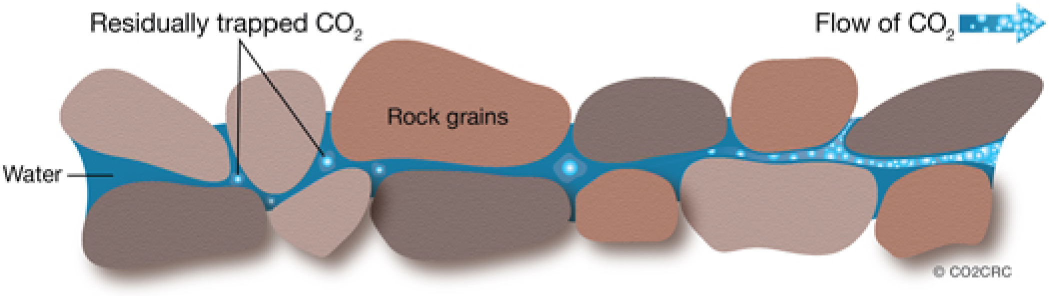


Illustration 1.6 – Residually trapped CO_2 appear as isolated bubbles in the reservoir fluid (in this case, water). Image courtesy CO_2CRC (http://www.CO_2crc.com.au/aboutccs/stor_trapping.html)

The third phase is solution-entrapment. The CO_2 will react with its surroundings and be trapped. In all reservoirs there are a certain amount of water and other reservoir fluids, which is called formation water. The CO_2 and formation water will after a time of interaction start to produce a weak acid. This solution is more stable than the freestanding CO_2-brine which was injected, but is also heavier than the brine and the new fluid (acid) will start to sink towards the bottom of the reservoir.

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2H^+$$

Formula: CO_2 and water will react together to make carbonic acid.

As the CO_2 has dissolved into a weak acid, it can react with certain minerals. This brings us to the final type of entrapment: mineral trapping. When the weak acid reacts with the formation minerals they can create new - solid - minerals called carbonate minerals. This is the most stable and safest state the CO_2 can be stored, since is it chemically bonded to the rock. By this point, we've successfully put CO_2 into the earth permanently. In some cases you skip some steps and go straight to mineral trapping, in other cases this is a slow process that takes millions of years. This depends upon the formation fluids and minerals on site.

$$\underset{\text{anorthite}}{CaAl_2Si_2O_8} + H_2O + CO_2 \rightarrow \underset{\text{calcite}}{CaCO_3} + \underset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4}$$

Formula: Calcite can be produced by reactions between reservoir minerals and the CO_2-brine.

(All text: Riis, 2011)

1.3.2 Monitoring storage sites

As we can understand by now, sequestering CO_2 in the subsurface involves both methods and technology which have been developed for the petroleum industry. This is a big advantage for the CO_2-storage solution, as old infrastructure from previous offshore installations can be used to some degree in the CO_2-storage process.

It is crucial to do proper processing of a site before choosing where to inject and store the CO_2, which in many cases will be stored at the location for billions of years (Riis, 2011). Again we can use site characterization and performance predictions from techniques familiar to the petroleum industry. One of these techniques is of main focus in this project: seismic imaging. This is the most used assessment and monitoring method for offshore CO_2 storage (Riis, 2011). 4D seismic is a collection of similar 3D surveys taken at different years. This can give you a clear image of how the CO_2-bubble acts within the reservoir. Such an example can be seen in illustration 1.7.

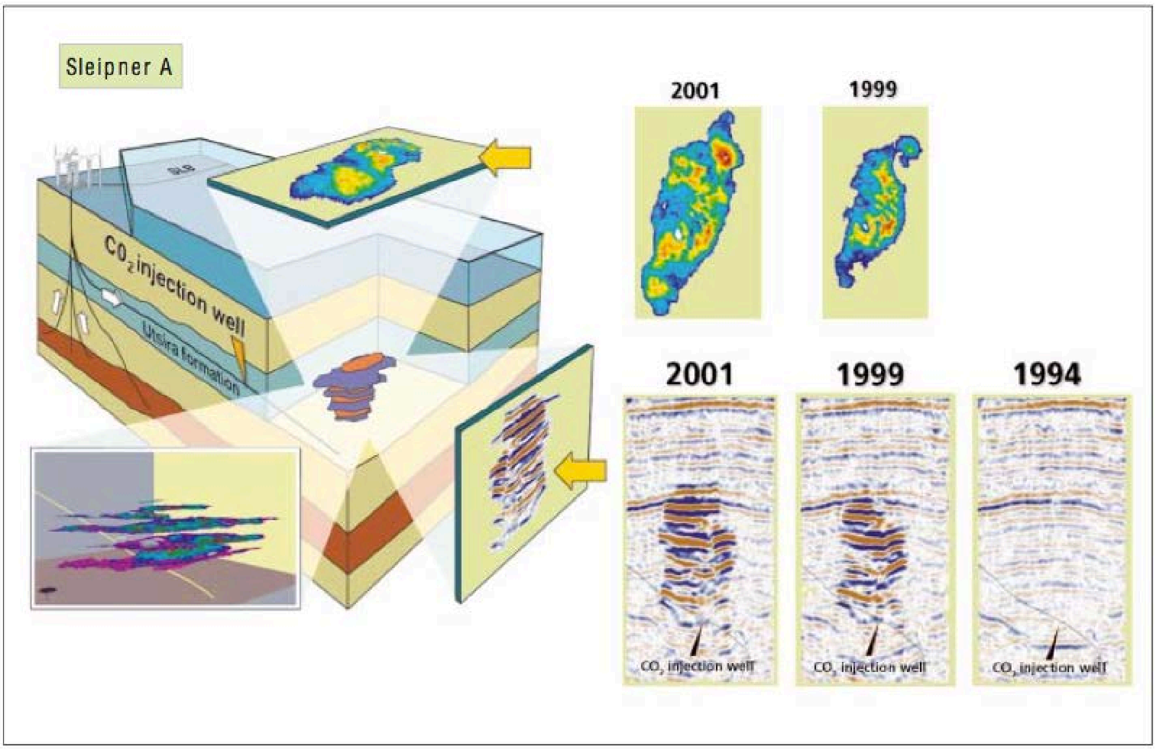


Illustration 1.7 – Lower right: time-lapse seismic sections showing how the CO_2-bubble has evolved since pre-injection (1994) to 2001. Upper right: Amplitude attribute maps showing the horizontal view of how the CO_2-bubble has expanded since injection. (Image courtesy: Statoil)

For land based storage projects it is more common to monitor already injected CO_2-reservoirs with satellite radar-measurements of the ground. Looking for changes in the elevation of the ground through time, potential leakages can be detected. More direct ways of monitoring CO_2 leakage, such as actual CO_2-emission sensors can detect leakage quickly (Eiken, 2011). For other monitoring examples, see illustration1.8.

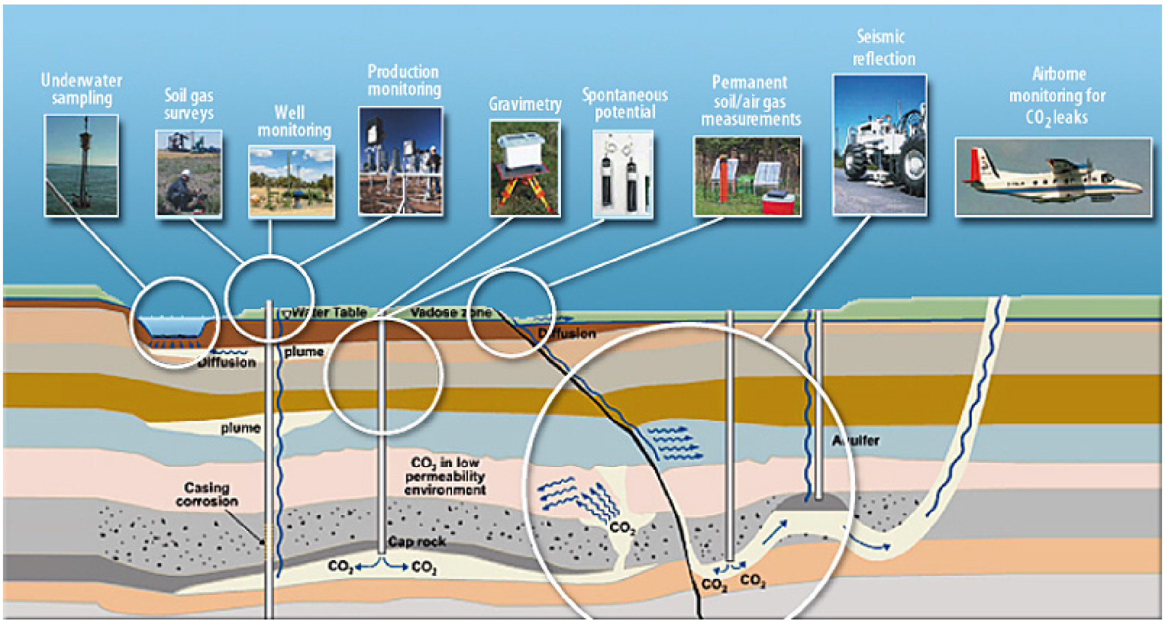


illustration 1.8 – Various kinds of CO_2-storage monitoring to check for leakage. Image courtesy: IEA

1.3.3 Risks

Since the focus of this thesis is on offshore, saline aquifer, CO_2-storage, we will focus on the risks concerning this form of CO_2-storage. The main risk of storage is connected to the properties of the cap rock - the actual seal. Constantly monitoring the pressure regime in the reservoir is crucial so the seal is not overstrained and cracks open. Good knowledge of the surrounding stratigraphy and natural pressure conditions is of high value. Mapping any faults in the area, as well as the horizontal layout of the reservoir for any potential migration routes is also important. Since the storage is meant to last for millions of years, even a slight inclination can cause a leakage pathway up and out of the reservoir. Seismic modeling and reservoir modeling is crucial to minimize this risk.

The other main general risk is the integrity of the human made technology. After the actual injection phase is shut down, a big challenge is to properly cement the well shut. CO_2 will as mentioned dissolve in water creating a weak acid known as carbonic acid (HCO_3^-), which will act as a corrosive agent on the cement plug in the well. Acid-resistant cements are in development (Bennaceur, et al. 2004).

1.4 Introduction to subsurface fluid-flow

Subsurface fluid flows are defined as water, gas or oil moving within a reservoir or in-between subsurface layers. The movement is determined by the fluid potential, defined as:

$$\mathrm{F_p} = P - \rho g h.$$

P = fluid pressure
p = density of fluid
g = acceleration of gravity
h = distance to reference level (for example: sea level)
(Judd, et. al. 2007)

1.4.1 The petroleum system

A petroleum system consists of three basic elements; the source rock, the reservoir rock and the cap rock. The latter two are the same as needed for a CO_2-storage location. The source rock contains organic material which can produce petroleum when high pressure and high temperature is applied to the rock. A good reservoir has porosity and permeability which is high – to ensure a lot of fluid can be contained within the pore space (porosity), and that the fluids can flow through the reservoir (permeability) (Selley, 1998). To contain the petroleum a good cap rock is needed, which has low permeability and preferably creates a type of trap. An active petroleum system involves an active source rock, migration of petroleum from the source rock to the reservoir and entrapment of the petroleum by a structural, stratigraphical, diapiric or hydrodynamic trap. A combination of all can also occur. (Bjørlykke et al. 2006)

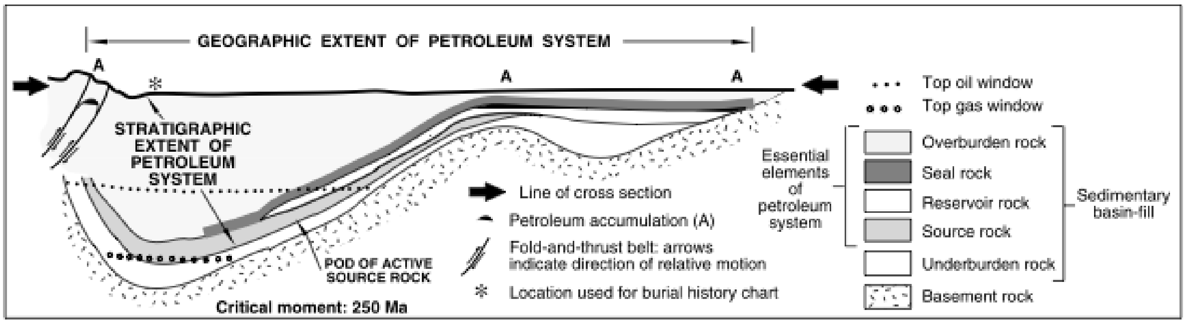


Illustration 1.9 – Conceptual model of the petroleum system. Image courtesy: AAPG.

1.4.2 Fluid migration

Fluid migration can be divided into two main modes; primary and secondary (Selley, 1998). The primary migration is the one where petroleum from the source rock moves into permeable carrier beds. Secondary migration is movement of the hydrocarbons from the carrier beds into the reservoir and entrapment (Selley, 1998). A third type of migration, tertiary movement, has been defined by Minescu et al, 2010. This is the movement of hydrocarbons from the reservoir and into the surrounding layers, which also can be called leakage. Features such as gas chimneys, pockmarks, mud-diapirs and other hydrocarbon seepages are said to be the result of tertiary migration.

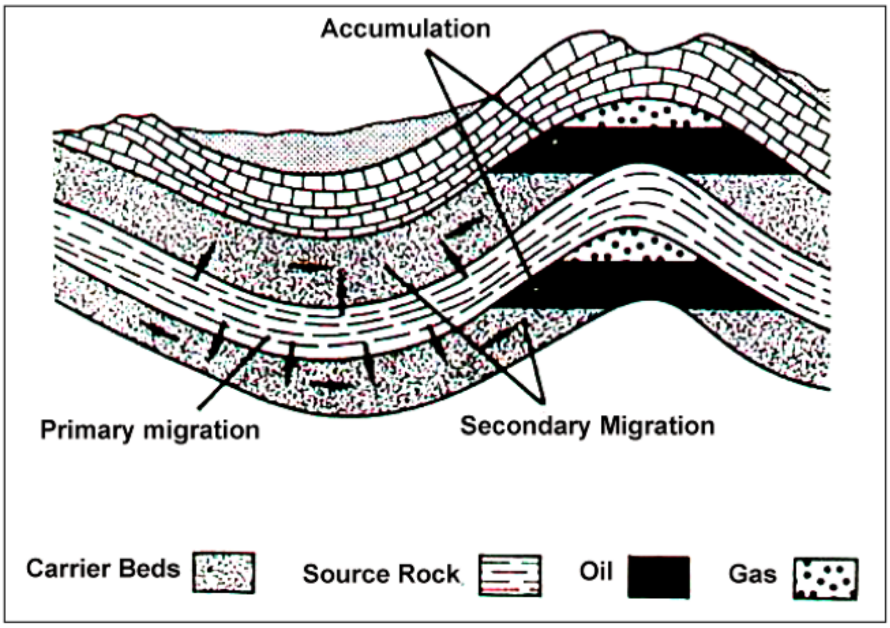


Illustration 1.10 – Conceptual model of primary and secondary migration, from Tissot & Welte, 1984.

1.4.3 Fluid-flow in sedimentary basins

Fluid flow can be caused by meteoric flow, driven by thermal convection, driven by compaction and is greatly affected by faulting. Meteoric flow is driven by rainfall or other kinds of fluvial addition from a source outside of the basin. The flow is determined by the elevation of the groundwater table and the density of the fluid – providing a drive down into the basin. This water is often fresh-water. (Bjørlykke, et al. 2006)

Compaction-driven pore water flow is driven by the fact that sediments that become compacted lose their porosity and therefore the pore water within the pores needs to be expelled. The loss of porosity is said to be a function of effective stress, temperature, time and lithology. (Bjørlykke, et al. 2006)

When water gets heated, a thermal expansion of the water will drive thermal convection. With increased temperature the density of the fluid is reduced, creating a density inversion. In this way we will get a self-recharged “circular” fluid-flow which is not dependent on external supply of pore water. (Bjørlykke, et al. 2006).

Faults serve as conduits for the fluid flows through barriers such as dense shale, faults can cause pressure drops and thereby bringing a shortcut for any fluid flows and they might be caused themselves by extreme pressure caused by fluid flows gathering at a trap. (Bjørlykke, et. al. 2006).

1.4.4 Mud diapirs

A mud diapir is a fluid-flow structure. It is a focused area which acts as a conduit which has expulsion of water, slam, gas and oil wandering up through the underground towards the sea-floor or land surface. A mud diapir is a positive topographic structure which behaves similarly to a mini volcano. It can have eruptions which expel both solid material (such as blocks of rocks) as well as fluid. There are two main theories on mud diapirs;

One is suggested by Cartwright et al 2007: “The key requirements for mud diapirism is inflation, in-situ over pressuring and external triggers (such as earthquakes).” This is supported by Gregersen et al 1997, which states that mud diapirs can occur with the following requirements: under compacted clay masses, high pore-water pressure and compaction from above. Cartwright and Gregersen seems to emphasize compaction driven fluid-flow as the reason for mud diapirism.

Another proposed model suggested by Martin Hovland is a relatively new concept incorporating supercritical water in the process. In other words, Hovland thinks thermal expansion is one of the main reasons for mud diapirism. The model is explained as follows: super critical water in the subsurface escapes from a basin through a weakness in the reservoir, and starts its journey upwards. Supercritical water is very reactive and breaks material down very easily, which can explain the flow through layers and its composition. On its way upwards it gets cooled, but still very reactive. (Hovland, 2011)

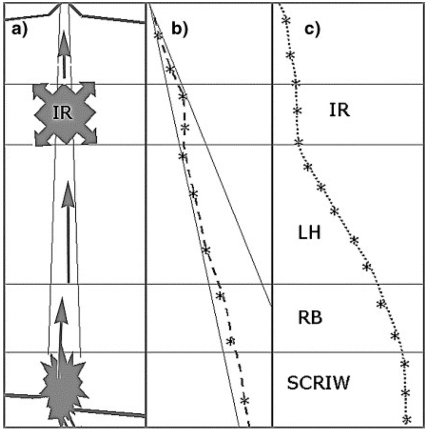


Illustration 1.11 – a) a conceptualized mud volcano which is rooted in a super critical water zone (SCRIW). As the water passes through an intermediate reservoir of gas (or similar), the pressure increases. b) pressure profile within the conduit of the mud volcano. c) Temperature profile within the conduit of the mud volcano. From Hovland, et al 2006.

1.4.5 Focused fluid flows

A main subject in this thesis is focused fluid flow pathways. They are recognized by vertical curvilinear pathways when observed on seismic, and depending on their characteristics we can divide them into different types. Gas chimneys, fault zones, and acoustic pipes are defined by K. Andreassen (2009) as typical fluid flow pathways. Mud diapirs can be added, as Løseth et al. 2008 mentions, which is of interest in this thesis.

These fluid flow pathways are best mapped with high resolution 3D data. On such data they appear as curvilinear vertical features of wiped, disturbed and/or chaotic reflections. Acoustic masking is one of the most typical features of a gas chimney and any kind of fluid flow, and is the first thing an interpreter would look after. Acoustic masking is the result of high fluid content in the sediments, which reflect back an image of highly disturbed strata (Sherrif, et al 1995). Such acoustic masking can be several kilometers to a few meters wide, as well as varying in depth similarly, all depending on the size of the actual fluid flow (Andreassen, 2009). In addition the actual resolution of seismic data will affect what we can observe, as well as the accosting masking itself making it difficult to determine from which depth it originates from (Løseth, et al. 2008). A short introduction to resolution of seismic data will be given in chapter 3.3.

In addition to their typical seismic image, fluid flows are often accompanied by a variety of seismic indications. Andreassen 2009 mentioned some of these;

Amplitude anomalies – bright spot // dim spot.
Flat spot – base gas reflection if the gas column is thick enough
Polarity reversal – troughs become peaks and vice versa, typical for bright spots
Velocity effects – pull-downs created by the change in acoustic impedance.
Other effects – Loss of high frequencies and diffraction.
See illustration 1.12 and 1.13 for actual seismic examples of these.

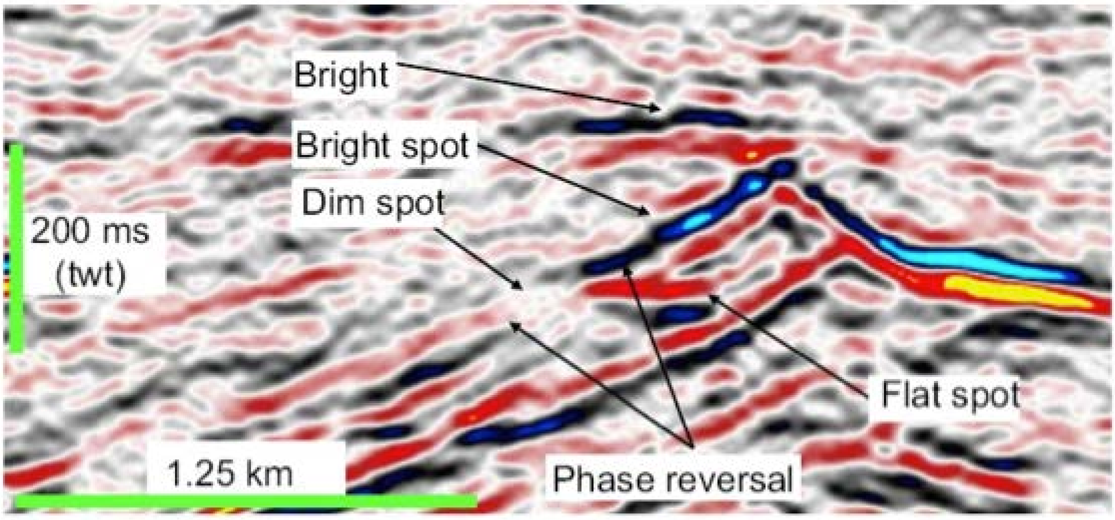


Illustration 1.12 – Brightspot, dim spot, flat spot and phase reversal as it can be viewed on a seismic section. From Løseth et al.2008

Areas where the cap rock has been hydro-fractured, areas where the cap rock is thinner, areas where the cap rock has higher permeability or areas where the cap rock has been the subject of tectonic activity and faulting can cause leakage of hydrocarbons. Gas chimneys or gas clouds can indicate such areas (Løseth et al. 2008), with variations in shape and size. They can be broad diffuse shadows or narrow zones of well-defined wipe out / deteriorated seismic signal. Since these gas chimneys are correlated with areas of gas flow, pull down effects can be seen within the chimneys. They often end up in bright spots or dim spots, indicating gas accumulation and the fact that the gas chimney has hit a more permeable rock (Løseth et al. 2008).

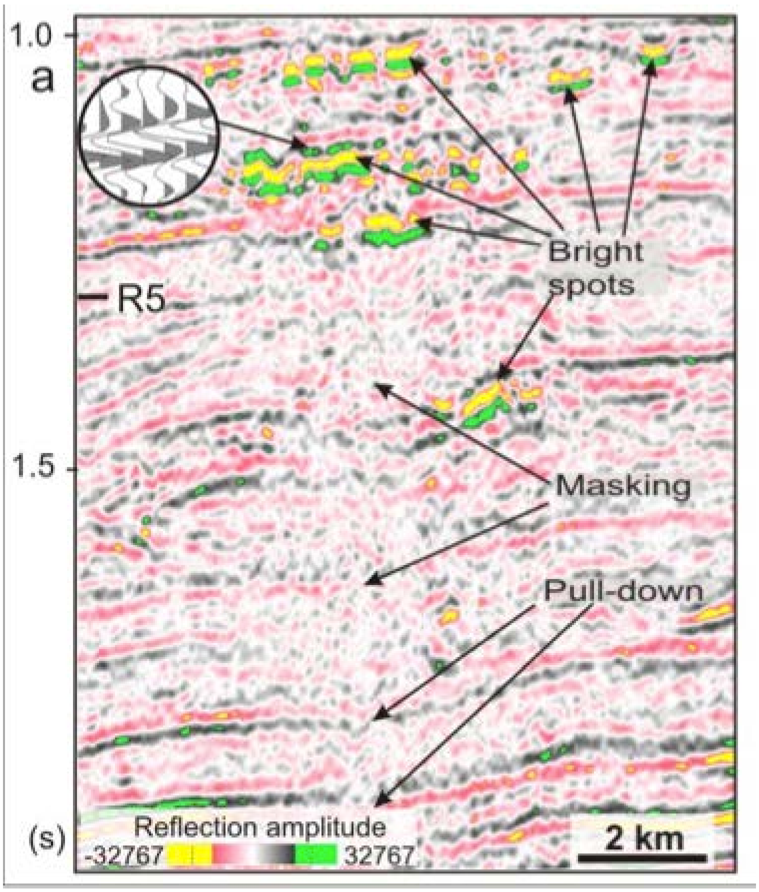
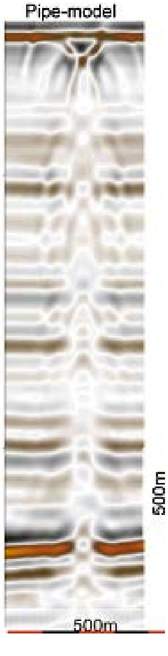


Illustration 1.13 – acoustic masking with pull-down effects and bright spots. From Andreassen et. al. 2007.



Acoustic pipes are an even narrower version of the gas pipe, where the seismic isn't just distorted seismic signals, but almost vertical and narrow structures with a clear disruption in the seismic. They cover quite long vertical areas, with a diameter less than 200m (Løseth et al 2008). Løseth et al. 2008 states that the acoustic pipes could be related to zones of fractures in impermeable sediments which were clay rich, and represent vertical pathways for fluid flow.

Illustration 1.14 – Seismic section showing an example of a typical acoustic pipe. From Løseth et al. 2011.

Mud diapirs can be recognized by areas of chaotic reflection patterns under topographic positive features, areas of no reflection and deformations around the feeder pipes (Løseth et. al., 2009). Typically the reflection free zones are the areas where the sediments are completely stirred and have no internal structure. The areas close to the mud volcano might seem deformed, due to the overpressure and altering of the sediments (Løseth et al, 2009). Mud volcanoes can often be seen in relation with faults due to the deformation caused by overpressure (Løseth et al, 2009). Inside or directly beneath the mud diapir, bright spots can be observed which indicate sediment injections or alterings, possibly due to chemical reactions or the actual physical altering of the sediments when active (Løseth et al, 2009).

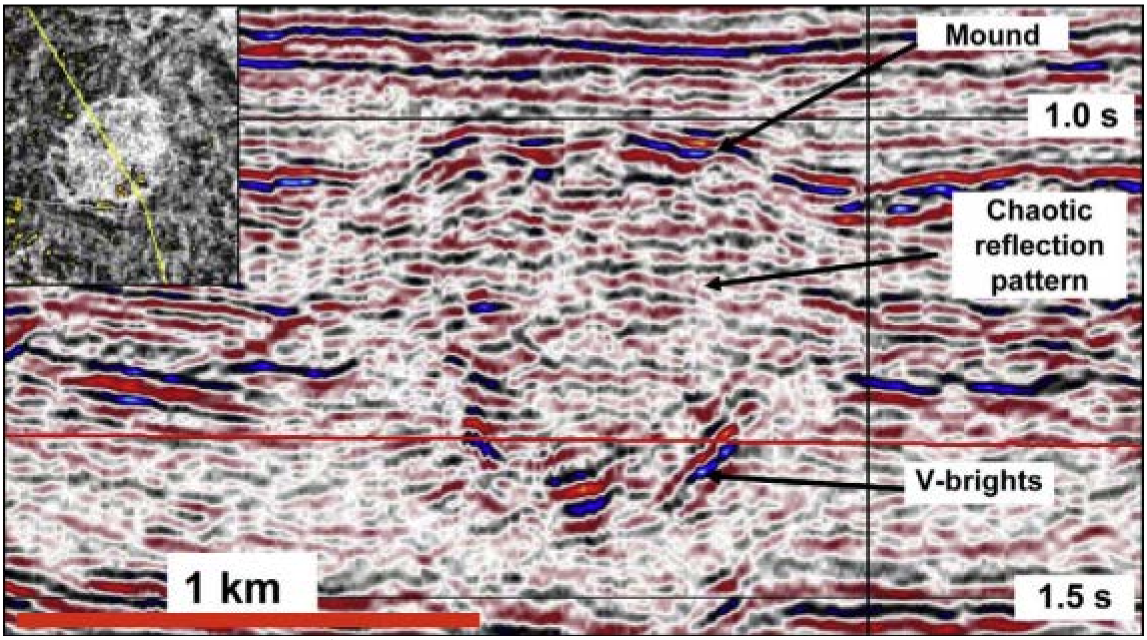


Illustration 1.14: An example of a mud diaper as pictured in Løseth et al. 2009. It is a positive mound shape with a chaotic internal reflection pattern.

2. Description of the study area

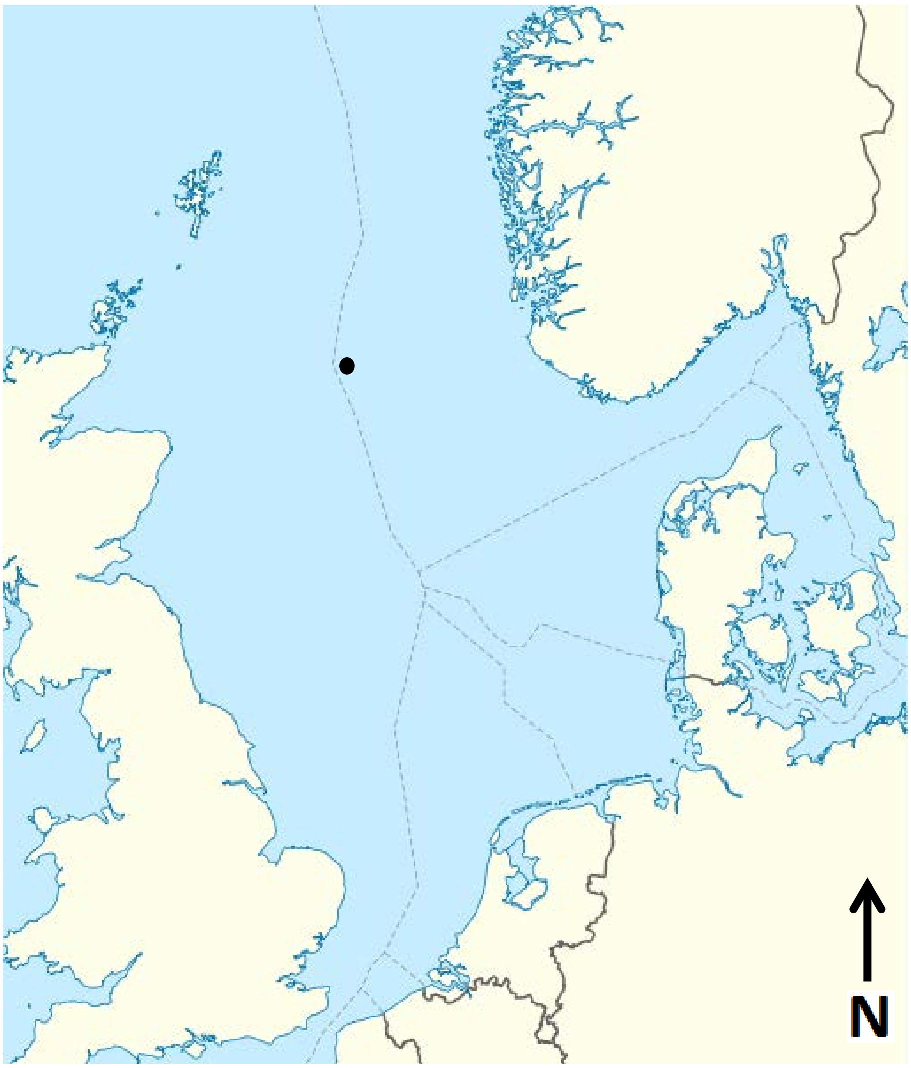


Illustration 2.1 – Location of the Sleipner field is marked with a black dot, with the border between Norway and the UK defined as a grey dotted line. Map courtesy creative commons, edited by the author of this thesis.

2.1 Tectonic evolution, sedimentary environment and stratigraphy.

Our study area is located in the westernmost part of the Norwegian sector, close to the border of United Kingdom. The study area is situated on the eastern part of the Viking graben, called "Utsirahøgda". The Viking graben is a result of extensional tectonic activity stretching from the Permian throughout the Mesozoic era (Gregersen et. al. 1997) The Viking graben has a slight NNW-SSE direction and more or less follows the border between the Norwegian and UK. During cretaceous the Viking graben experienced thermal subsidence due to the rift system warming up the crust, which caused the north sea to experience subscidence compared to the Shetland area which experienced uplift (Head, et al. 2004). The subsidence caused infill from the regional topographic highs, and the area has since been dominated by deltaic, shore zone, shelf, slope and basin depositional systems (Gregersen et. al. 1997).

During the Oligocene the sea level decreased, probably due to uplift (Gregersen, et. al. 1997). This caused the deposition of a thick shale unit across large parts of the northern North Sea. The silt and clay had low density and could be described as a thick soup-like fluid (Ramberg et. al. 2006, Halland et al. 2011).

In Miocene the main sedimentary deposition came from the east, the Shetland platform, which created a massive delta feeding the Viking graben (Halland et al. 2011). The sands which were deposited were affected by the oceanic currents of the graben structure, tidal wave currents and a general southward sedimentary transport along the ocean floor was especially apparent in the area of the Utsira reservoir due to a narrow part called the Viking strait at the location (Ramberg et al. 2006).

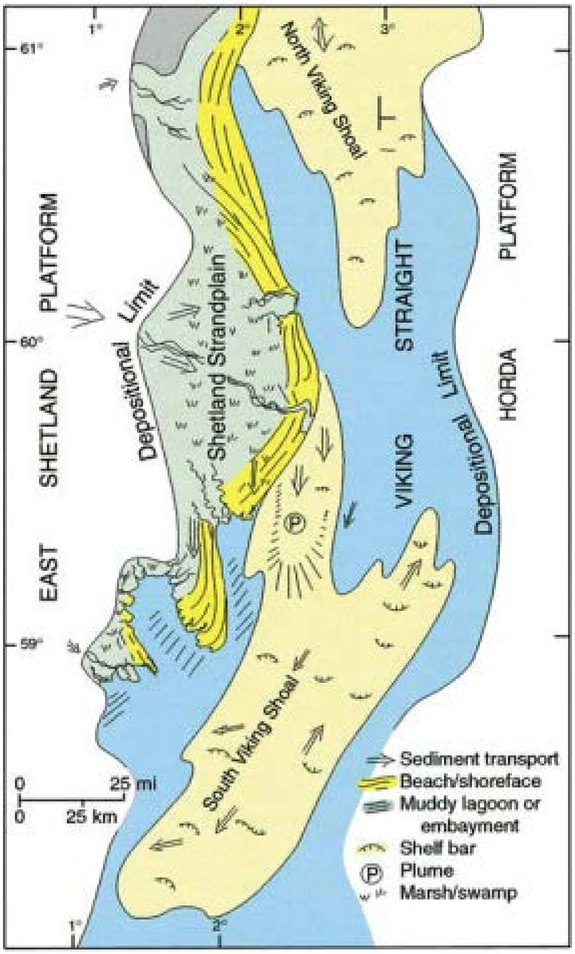


Illustration 2.1 – Depositional environment during the Miocene. Progradational delta into the viking strait. Tidal currents are indicated. From Galloway, et al. 2001.

During the Pliocene the uplift of Scandinavia caused a change from an eastwards depositional regime, to a westwards progradational deposition (Gregersen, et al. 1997). The shale drape is at some areas of the study area interfingering with the Utsira sand, which is believed to indicate the transition from sand-dominated deposition to mud-dominated deposition (Head et. al. 2004). Later into late Pliocene- early Pleistocene into Holocene glaciation occurred, which created glacial till deposits and erosional surfaces. Progradation from the west continued with quarternary deposits overlying the Pleistocene unit (Chadwick et.al. 2000a).

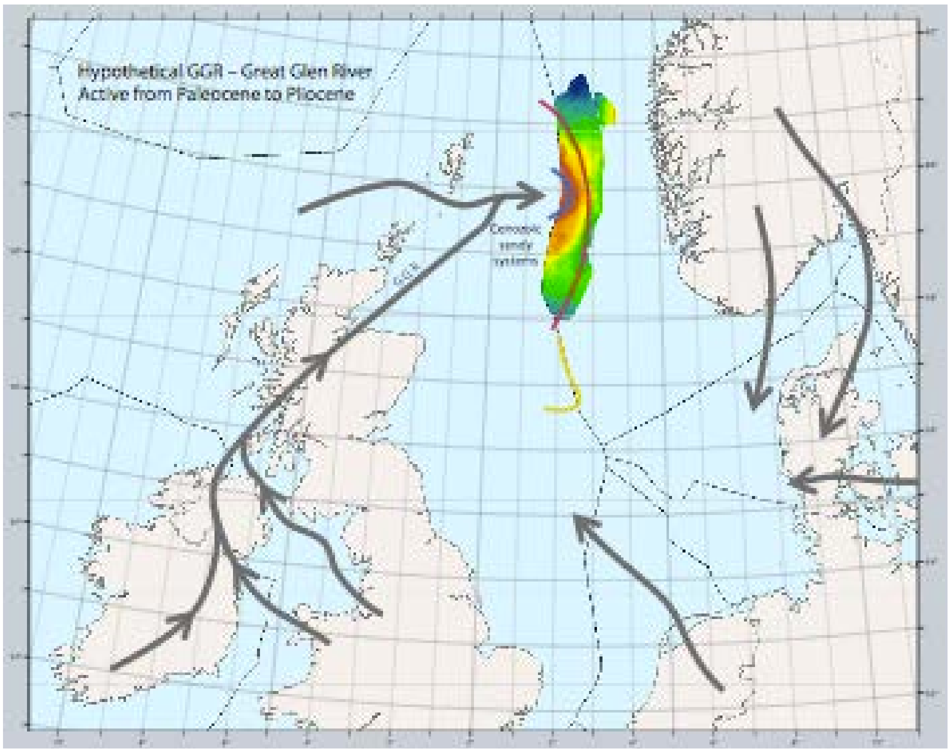


Illustration 2.2 – Paleocene – Pliocene sedimentary movement. Image from Halland et al. 2011

2.2 Description of the Utsira formation

The Utsira Formation is located in the North Sea, slightly east of the Viking Graben. The Utsira aquifer is of Miocene-Pliocene age, and consists of marine sandstone deposits which are basinally restricted. The reservoir sand makes out two distinct basins, which are thought to have little or no hydraulic contact (Chadwick et. al 2000a). Wire-line logs suggests thin layers of shale exists within the Utsira reservoir, but these only cause irregularities in the way the CO_2 migrates within the reservoir and has nothing to do with the capacity of the seal or the storage efficiency (Zweigel et al, 2000). The entire Utsira sand reservoir stretches out 450km from north to south and around 40-90km from west to east. The Sleipner injection facility is located in the southernmost basin, which also is the biggest basin of the two, see figure.

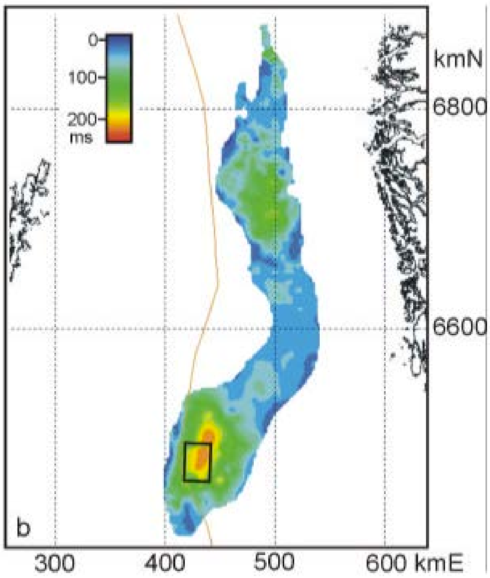


Illustration 2.3 – Seismic survey ST98M11 as located on the Utsira Reservoir. The Utsira reservoir is pictured as an isochore two-way-time map. From Zweigel, et al 2004.

The Utsira sand is easy to distinguish on both seismic data and on geophysical logs, with distinct reflectors and low gamma-ray values in logs (Chadwick et. al., 2000a). The direct overlying unit is a shale drape, part of a bigger formation named “the Nordland formation”. The overburden consists of thick prograding wedges believed to be of Pliocene age (Chadwick et. al., 2000a), dipping from both east and west onto the basin. These prograding wedges vary regionally in the area, but above and around Sleipner they tend to coarsen upwards, with succeeding shale-sandy layers which are again overlain by sandy quarternary layers of several hundred meters thickness (Zweigel et. al., 2004). It is suggested that the Nordland shales are distal remnants of the prograding deltas from the western and eastern basin margins (Zweigel et. al., 2004).

The shale drape itself varies from 50-100 meters thick (Chadwick et. al., 2000a), and is thought to be mainly shaly directly above the Sleipner injection area (Holloway et. al., 2000). Further up in the package the clinoforms is suggested to be possible sandy elements, degrading the seal potential (Holloway et. al., 2000).

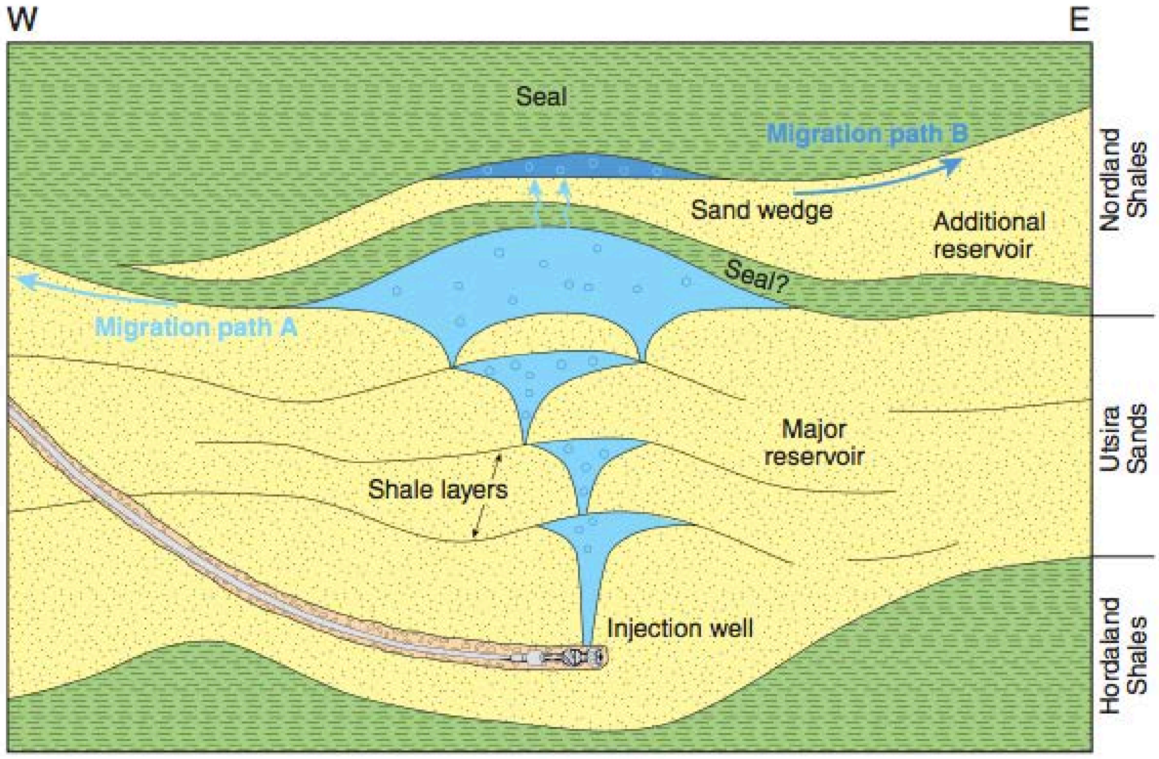


Illustration 2.4 – A conceptualized drawing of the Utsira Reservoir with the injection well in place. The drawing is not to scale. From Zweigel, et al. 2000.

At the base of the Utsira sand, a previous project has revealed dome like structures. These are interpreted as possible mud diapirs which seem to have been active during the deposition of the Utsira sand. Above these mounds, we can see depressions in the Utsira sand and overlying formations, indicating compaction and/or internal collapse which created subsidence. This interpretation is supported by several articles (Holloway et. al., 2000), and are also seen in connection with clear fluid flows and amplitude anomalies within the Utsira reservoir, as well as inside the cap rock. The irregularities in the structure of the Utsira reservoir created due to these collapses form domal and anticlinal structures that can potentially act as traps and/or migration pathways during CO_2 migration within the reservoir. Below the mud diapirs, a layer of polynomial faulting underlies the entire study area. This layer corresponds with an Oligocene age and is classical for the clays deposited at that time (Ramberg, et. al. 2006).

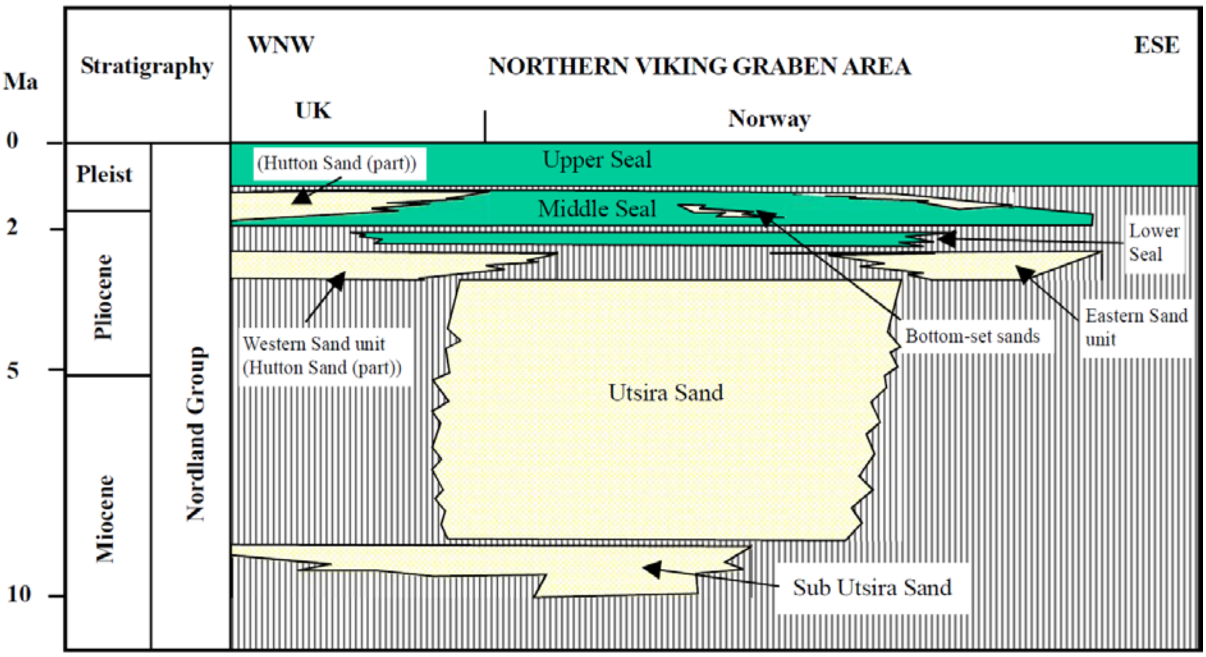


Illustration 2.5 – Stratigraphy of the area, from Holloway et. al 2000.

2.3 Petrophysical properties of the Utsira reservoir

The Utsira reservoir is overall a highly permeable and porous reservoir with a high content of fine grained sand, which is homogenous. It has a normal (hydrostatic) pressure and is water filled.

Pressure: 80-110 bar
Temperature: 37 degrees Celcius
Permeability: 1-8 Darcy
Porosity: 35-40%
Net sand content: 80-100%

These are very desireable, as other CO_2-storage locations have less permeability and porosity, as well as high reservoir pressure which can cause trouble. All data from Eiken et. al., 2011.

2.4 The Sleipner CO_2-storage facility today

Statoil and their partners have injected CO_2 into the Utsira reservoir since 1996. In total 16 Million tonnes has been injected to date, with a number of around 1 million tonnes per year injected into the subsurface (Global CCS institute, 2013). To monitor the injection, a set of six repeated seismic surveys have been acquired (Eiken et al. 2011). This gives potential for the so called "4D seismics" where the changes over time can be visualized. As the CO_2-plume has a distinct high amplitude reflection, revealing volume, aerial distribution and any leakage to the levels above the Utsira formation (Eiken et al. 2011).

From the 4D seismic, it has become apparent that the internal flow of the injected CO_2 inside the reservoir follows the topography very closely. At the location of the injection intra-sand shale layers of only meters thick create separated zones of saturated sand with CO_2-brine. See illustration 2.6. There are no signs of leakage to the overburden in the seismic (Eiken et al. 2011). It is evident that the so called "CO_2-bubble" has stabilized in a small positive topographic domal / trap-feature which is located above the injection site, but is prospected to migrate westerly into a larger domal feature as the small domal feature gets filled beyond its spill-point (Chadwick, et al. 2000a).

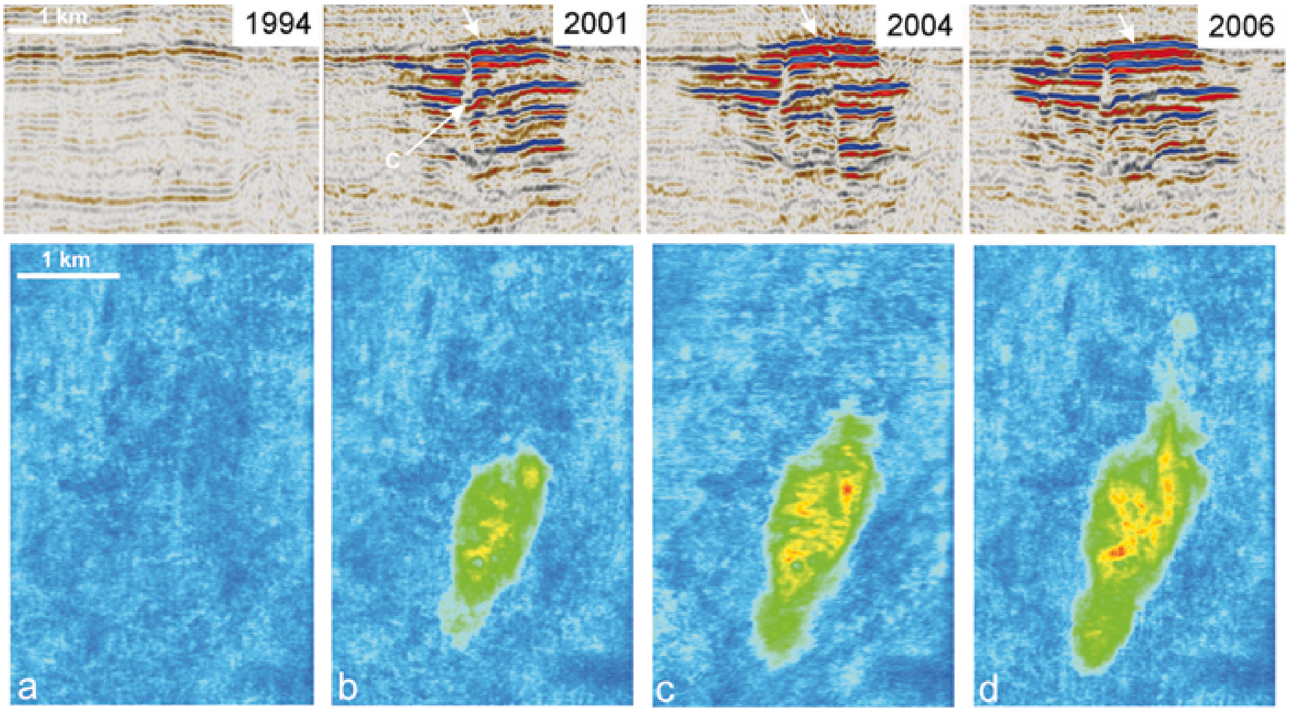


Illustration 2.6 – 4D seismics from Sleipner. 1994 is pre-injection. The bottom images b, c and d are time slices showing the amplitude change over time. This can indicate the extent of the CO_2-bubble, as well as the concentration of CO_2-brine. The red shows high concentration, which corresponds with the injection point. From Eiken, et al 2011.

Seabed gravimetric measurements have been carried out to constrain uncertainties connected to the time lapse seismic surveys. The gravimetric measurements have made modeling of dissolution of CO_2 into the reservoir fluids more reliable, as it is difficult to determine from seismic alone (Arts et al. 2008). The best fit between gravimetric and the seismic was found to be a high temperature model of the reservoir (Arts et al. 2008).

3. Data and methods

3.1 Dataset

For this project, a 3D seismic mega block has been interpreted, ST98M11. In total, the seismic cover an area of 25km (cross line) x 32km (inline), and is close to the UK/Norway median line (see illustration 2.1) (Zweigel, 2000). The cube was downloaded from Petrobank, and was already processed when downloaded. According was shot in 1998, by CGG for Statoil.

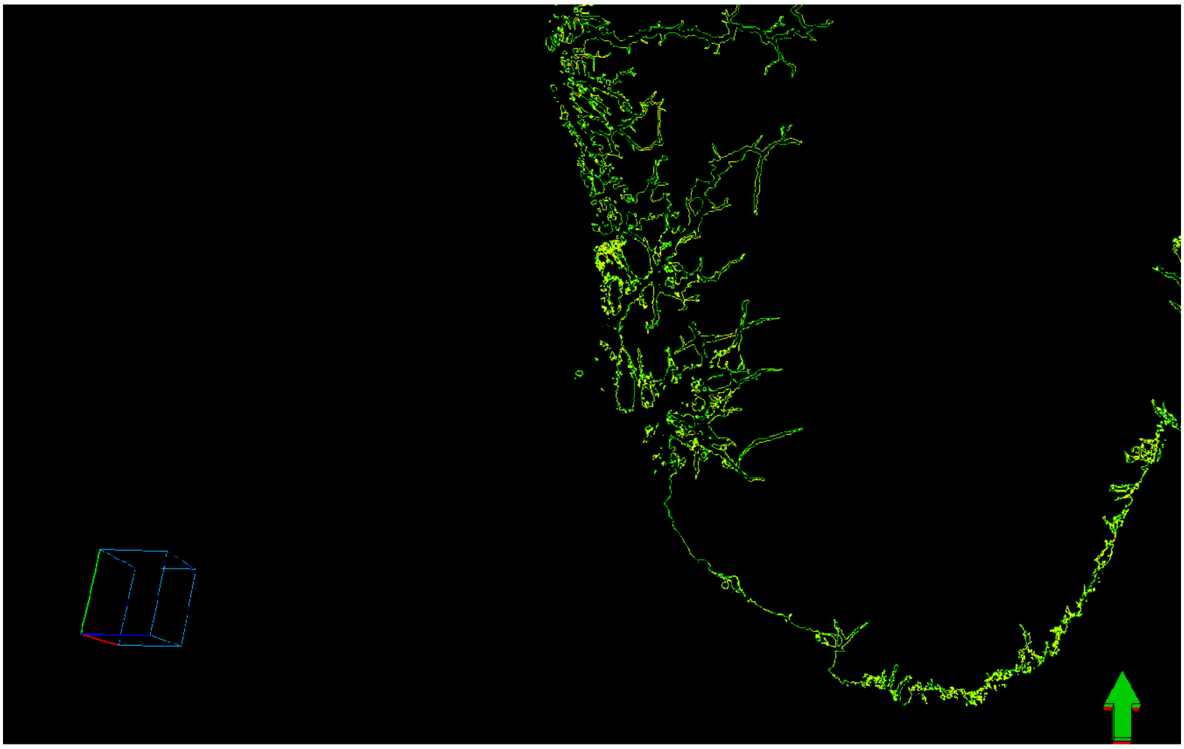


Illustration 3.1 : Seismic cube indicated in relation to the Norwegian coastline. Green arrow indicates north.

3.2 Seismic theory

A seismic line visualizes the underground either onshore or offshore through the use of seismic waves. These waves are created by a source, and they are reflected back to a receiver due to the reflection coefficient in the subsurface. Depending on the type of sediment and its compaction, you have varying levels of seismic velocities in the subsurface, as well as varying density of the sediments both horizontally and vertically. The velocity and the seismic velocity define the acoustic impedance of the rock, and it is the acoustic impedance contrast which is called the reflection coefficient. Gas and fluids typically increases the contrast due to the reduction in seismic velocity.

Seismic data come in 2D and 3D, as well as 4D where you survey the same area over a timespan of for example years to see how things change over time. For this thesis 3D data has been interpreted. 2D seismic is often used in a more regional interpretation - giving the general idea of how the subsurface looks like - while 3D data goes into the details of a specific area, often tens of square kilometers. 3D data is therefore ideal for mapping potential CO_2-storage areas, as we need reliable models to safely store the CO_2. All info in chapter from Olaussen, 2011 and Andreassen, 2009.

3.3 Seismic resolution

Seismic resolution is a way of measuring which size an object needs to be in order to be imaged in the seismic. We can split the resolution into two factors; vertical and horizontal.

The vertical resolution is normally given as: any object less than 1/4 of the width of the wavelength, will not be seen. See figure for definition of wavelength. This means that any anomaly, any layer or any object in the subsurface needs to be bigger than 1/4 of the wavelength, in order to be distinguished on the resulting seismic. Since the wavelength is given as velocity/frequency, knowledge about the subsurface through core samples or logging can be important so to define which velocities the different layers have and therefore their seismic resolution. Depending on the frequency of the seismic wave you get good resolution in deep or shallow areas, but it is hard to get good resolutions across the entire vertical section due to attenuation – the loss of energy the deeper the wave goes.

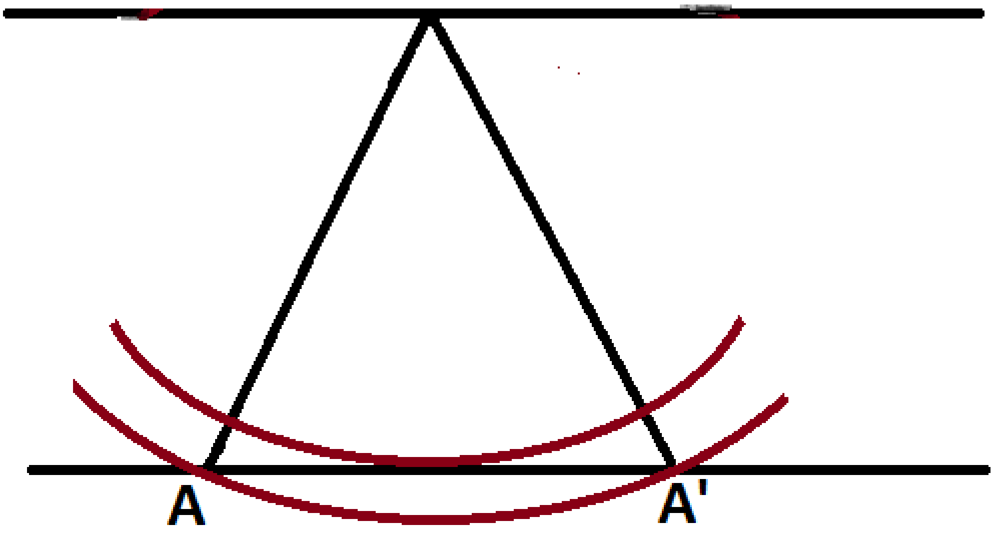


Illustration 3.2 – Fresnel zone, defined as the area between A-A'.

The horizontal resolution is crucial for 3D seismic, and is given by the Fresnel zone. See figure 3.2 for illustration. The Fresnel zone is given as the wave front of the sound wave emitted from the source. This wave front travels with a given frequency, and the zone increases in radius the further it travels. The Fresnel zone can be seen upon as the area of a reflector which is covered by the wave front at a certain depth. If two features appear within the Fresnel zone you cannot distinguish them. The Fresnel zone can of course become very large the further away from your source you come, and to enhance the resolution at high depths migration can be done, both 2D migration and 3D migration (see figure). The Fresnel zone is affected by dipping layers, loss of energy and diffraction due to "point-features", all which are greatly reduced when migrating the data.

3.4 Petrel

All interpretation and visualization has been done on Petrel© 2011 software. Note that on all figures any green arrow represents northwards direction.

Petrel provides an easy interface to interpret, visualize and navigate through 3D seismic. Interpreting as is done is this thesis is done by defining a new seismic horizon under "Interpretation map" in your project. The interpretation will follow a continuous reflector, which has to be defined as a peak, a trough or a zero-crossing. Other parameters are defined as is deemed fitting, before doing the actual interpreting. This can be done either through auto tracking or manual tracking. The choice of tracking depends on reflector continuity and strength, often determined by which type of deposits you have.

After interpreting horizons the interpretations are made into surfaces, which can be put through arithmetic process which enhances a certain parameter of the surface. This is called surface attributes and can be applied to a single surface, in between surfaces or in a given window of time. Similarly, the seismic volumes can be put through "volume attributes" which results in different aspects of the seismic trace to be enhanced in the entire volume. Here availability of the z-axis, the time slice, is of particular interest for interpretation in this thesis. It should be noted that Petrel gives the depth in negative two-way-time (TWT) which increases as we move down the layers. For simplicity this thesis gives all depths in positive TWT, which gives the same results only in positive values.

In this thesis the following surface attributes have been applied:

Isochron map
The variation in time between two horizons is calculated, and is displayed as a contour map (Schlumberger, 2013). This is also known as a thickness map, and features such as differential deposition or erosion can be interpreted (Schlumberger, 2011).

RMS amplitude
Measures the number of instantaneous trace samples over a specified window. This can be utilized to detect high amplitude anomalies. High amplitude anomalies are as previously discussed a possible indication of gas accumulation (Schlumberger, 2011).

$$\sqrt{\frac{\sum_i^n amp^2}{k}}$$

RMS amplitude formula, where k is the number of live samples. From Schlumberger 2010.

The following volume attributes have been applied:

Structural smoothing
Structural smoothing can be done to a whole volume in order to make reflections more continuous, generally making the seismic sections easier to interpret. Details might be lost in the process, but also noise (Schlumberger, 2011).

Chaos

Chaos measures the lack of organization on a horizon, typically from the edge detection method. Chaos is a good attribute to enhance features such as faults, gas migration pathways and channel in-fills. These give a chaotic or discontinuous seismic reflection pattern (Schlumberger, 2011).

Variance

By measuring the amount of variance in the seismic signal, this attribute indicates the lateral continuity of the seismic reflector (Schlumberger, 2011). Discontinuities, especially faults and other features with a high lack of continuity will be easier to point out in a variance cube. Variance is also based on the edge detection method (Schlumberger, 2011).

4. Results

The following results have been drawn from the interpretation of the ST98M3 3D seismic data, with stitched pieces from ST98M3. Horizon interpretation correlated with attribute maps and cubes have visualized the presence of suggested fluid flows and their possible origin. Figure 4.1 shows an outcrop of the seismic cube which will be used as a guide in the following chapter figures.

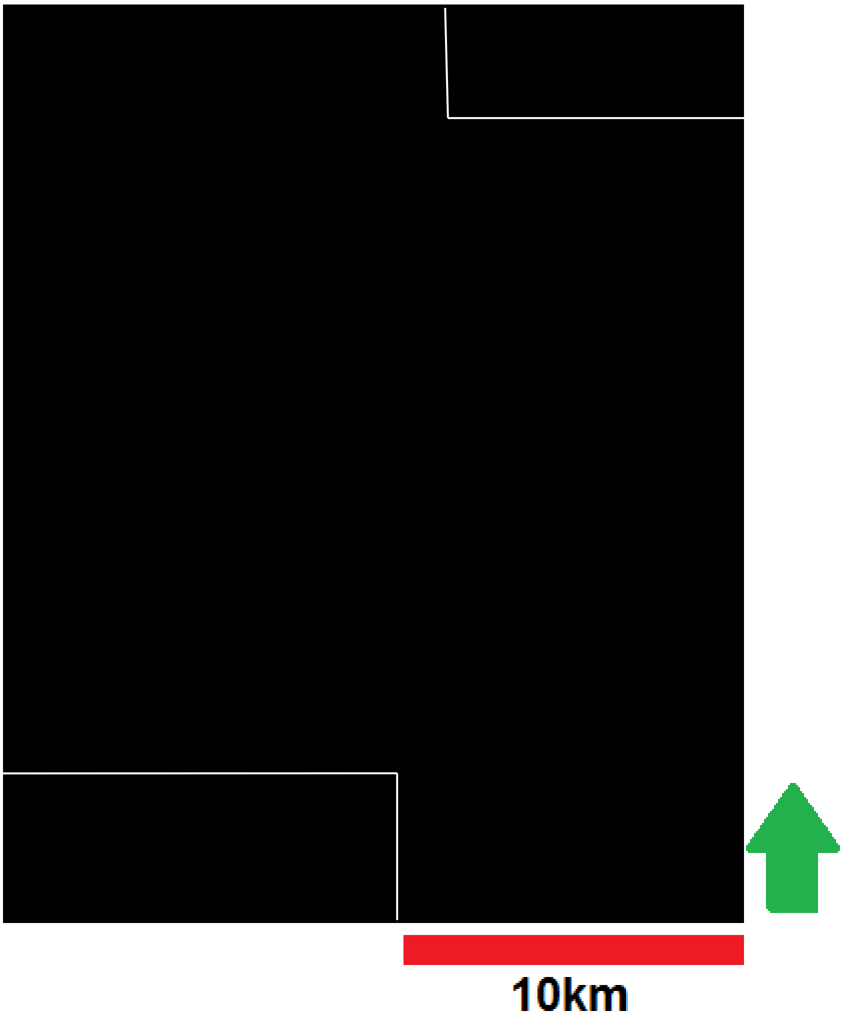


Figure 4.1 – outline of the ST98M3 cube within the white lines, the upper right hand corner and lower left hand corner consists of stitched in seismic cubes (ST98M3).

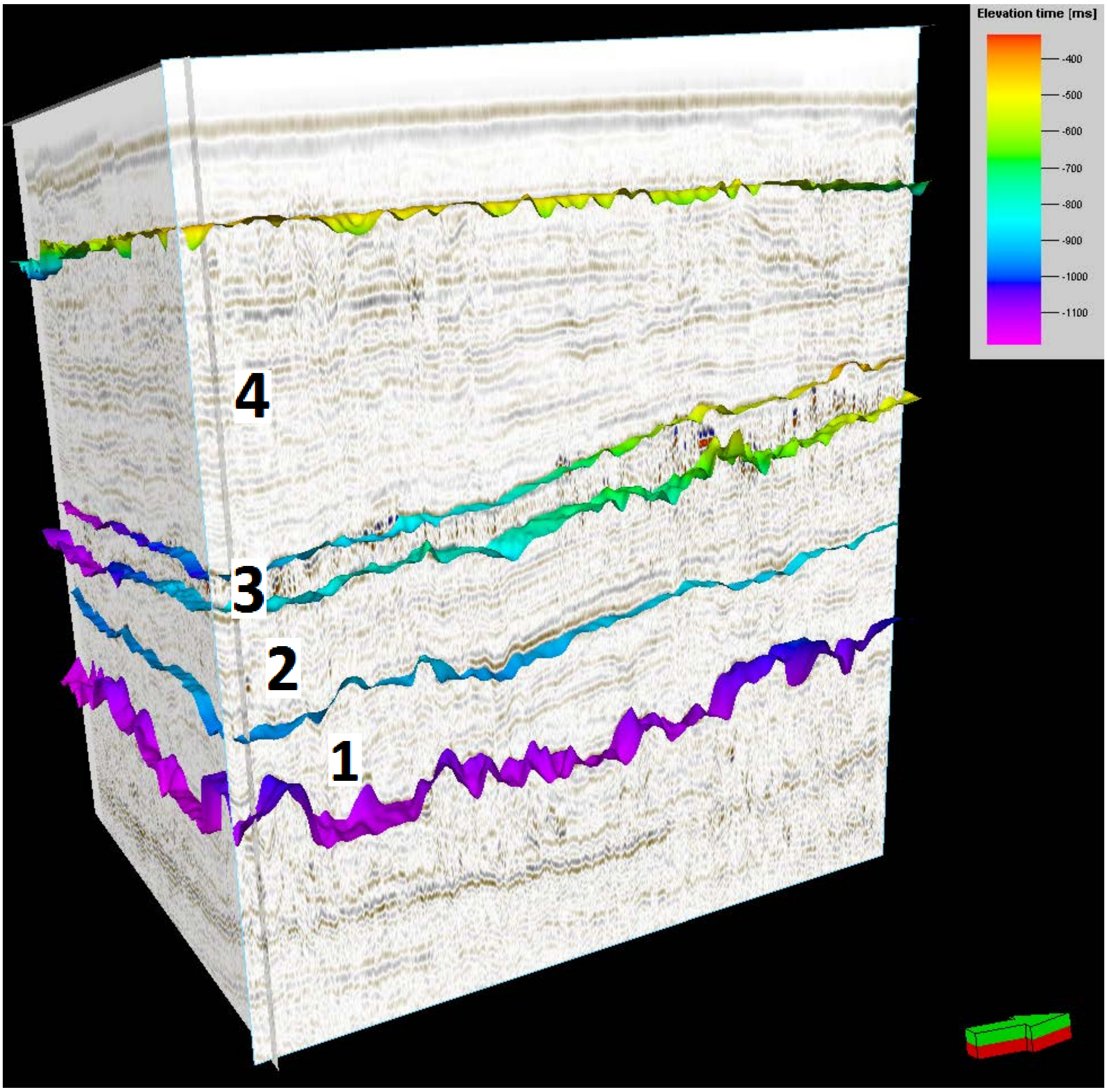


Illustration 4.2 - Main units pointed out, on the cube where crossline 2192 and inline 803123 is visualized. Right side points to the north. ***1****: Utsira* ***2****: Lower Pliocene* ***3****: Upper Pliocene* ***4****: Quarternary*

In the following I will discuss the results of the interpretation, which include the various horizons in the cube, features observed which might pose as contributors to the observed fluid flow structures in the overburden. I will give a description of the characteristics and the possible origins of these fluid flow structures. The overburden is defined as the area from Top Pliocene unit to the seafloor. For the thesis a general seismic velocity of 2000m/s has been used, for simplicity. All depths are approximations.

4.1 Stratigraphy - Horizons interpreted

A total of 5 horizons have been interpreted for this thesis. Based on previous project work on the data set by the author of this thesis, 3 of these were already known and were further processed during this thesis. These are the "base Utsira", "top Utsira" and "top Pliocene" horizons. These were chosen due to their continuity and high amplitude which make them easier to interpret and also point towards them being the defined boundaries between different units (reference). "Intra Quarternary" was chosen due to its relatively high continuity and slightly higher amplitude than the surrounding reflectors. It also defines the highest depth at which we observe fluid flows in the data set (with some exceptions, see chapter 5 Discussion). The "intra Pliocene" horizon was inspired by literature (Galloway et. al., 2000) due to the features that could be mapped in the upper Pliocene unit.

1: Base Utsira
2: Top Utsira
3: Intra Pliocene
4: Top Pliocene
5: Intra Quarternary

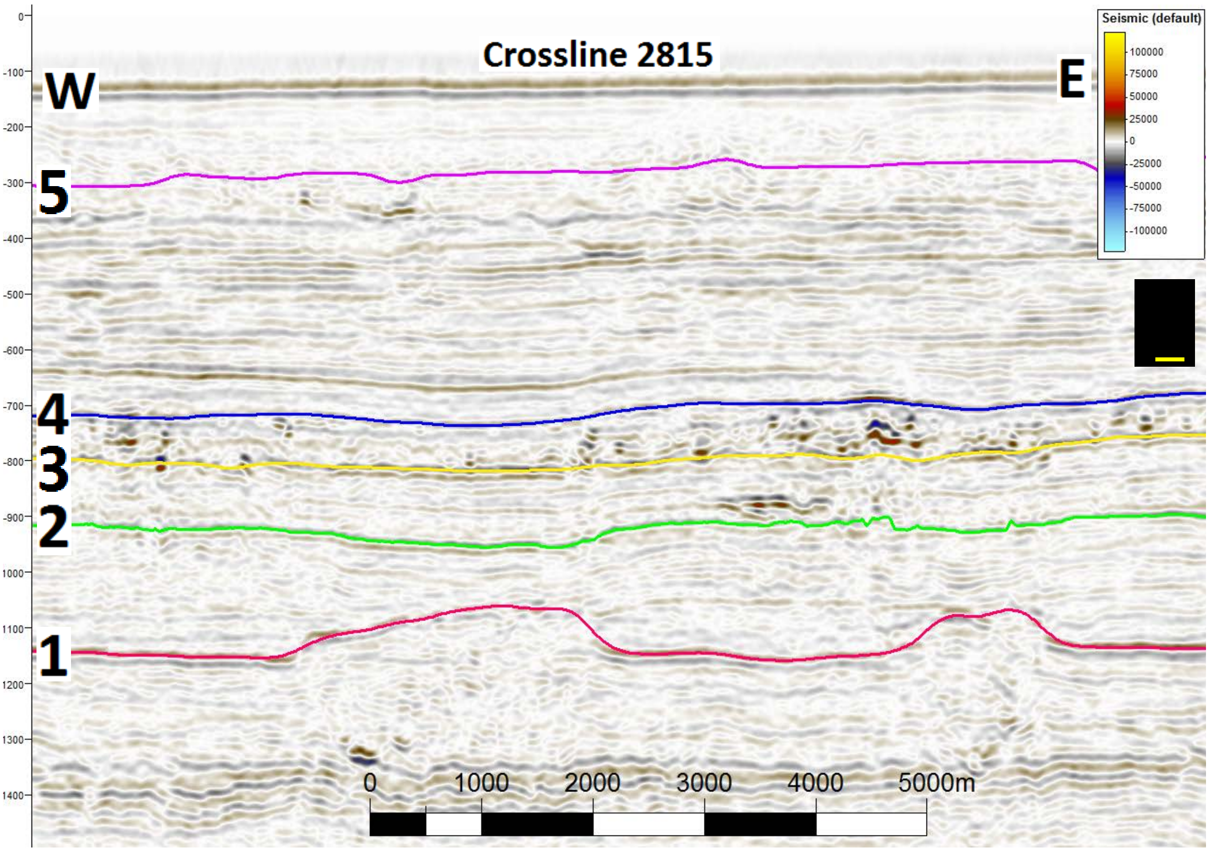


Figure 4.3: Crossline 2815 showing the different interpreted horizons, as numbered in the text above the illustration.

4.2 "Base Utsira"-horizon

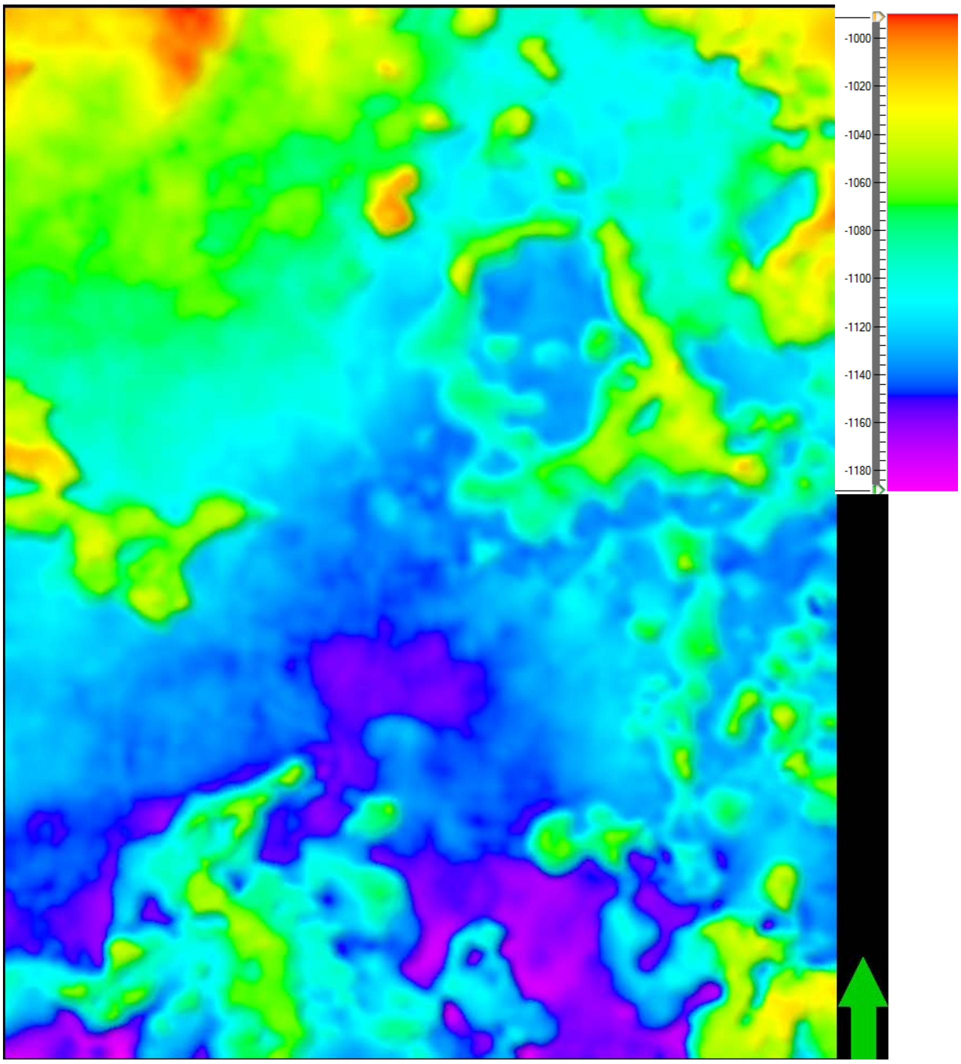


Figure 4.4 – Topographic map of the "Base Utsira"-horizon.

"Base Utsira"-horizon is interpreted as a positive peak reflector ranging from ~1178ms to ~949ms. It has multiple mound-like formations (see structural map, illustration 4.4) scattered across the study area, which are positive reliefs on the horizon.

4.2.1 Mound-like features description

The mound-like features range across the "Base Utsira"-horizon, only an area of the mid-western part of the cube is undisturbed according to the structural map. They have a chaotic internal reflection (see illustration 4.5), and are up to 200m high. Together with the mounds we can see disruptions in the "Base Utsira"-reflector, which can be followed vertically for 50-150meters. Within or slightly below the mound-like features there can be observed high amplitude anomalies (see red circle in illustration 4.5). In the layers above the mud volcanoes, there are tendencies of onlapping onto the mud volcanoes. Below the "Base Utsira"-horizon at circa 1400ms TWT depth, there is an extensive layer of many highly disrupted reflectors with slight vertical shifts at the disruptions. Illustration 4.6 (p37) shows a time-slice of the layer. The feature stretches across the entire cube.

4.2.2 Mound-like features interpretation

The chaotic reflection pattern within these positive mounds, as well as on-lapping reflectors intra-Utsira, points towards these features being interpreted as mud diapirs. This is supported by the works of Løseth, et al. 2009, as mentioned in chapter 1.4.5. The chaotic internal reflection comes from the disturbed and un-sorted nature from the violent nature of a mud diapir, and the onlap might indicate that the feature was there when the overlying sediments got deposited.

The disruptions in the "Base Utsira"-horizon which was seen in correlation with the positive mounds can be interpreted as faults, which are supported by the works of Zweigel et. al., 2004. These faults can be interpreted as a product of the collapse of the mud diapirs, since they only appear in relation to the mound features across the "Base Utsira"-horizon.

The high amplitude anomaly is an indication of an increase in amplitude of the seismic wave, which might be due to chemical altering of the sediments within and/or below the mud diapirs. This can be seen in relation to the high pressure, temperature and flow of fluids through the area, which might have caused a drop in velocity in the area (Løseth, et al. 2009).

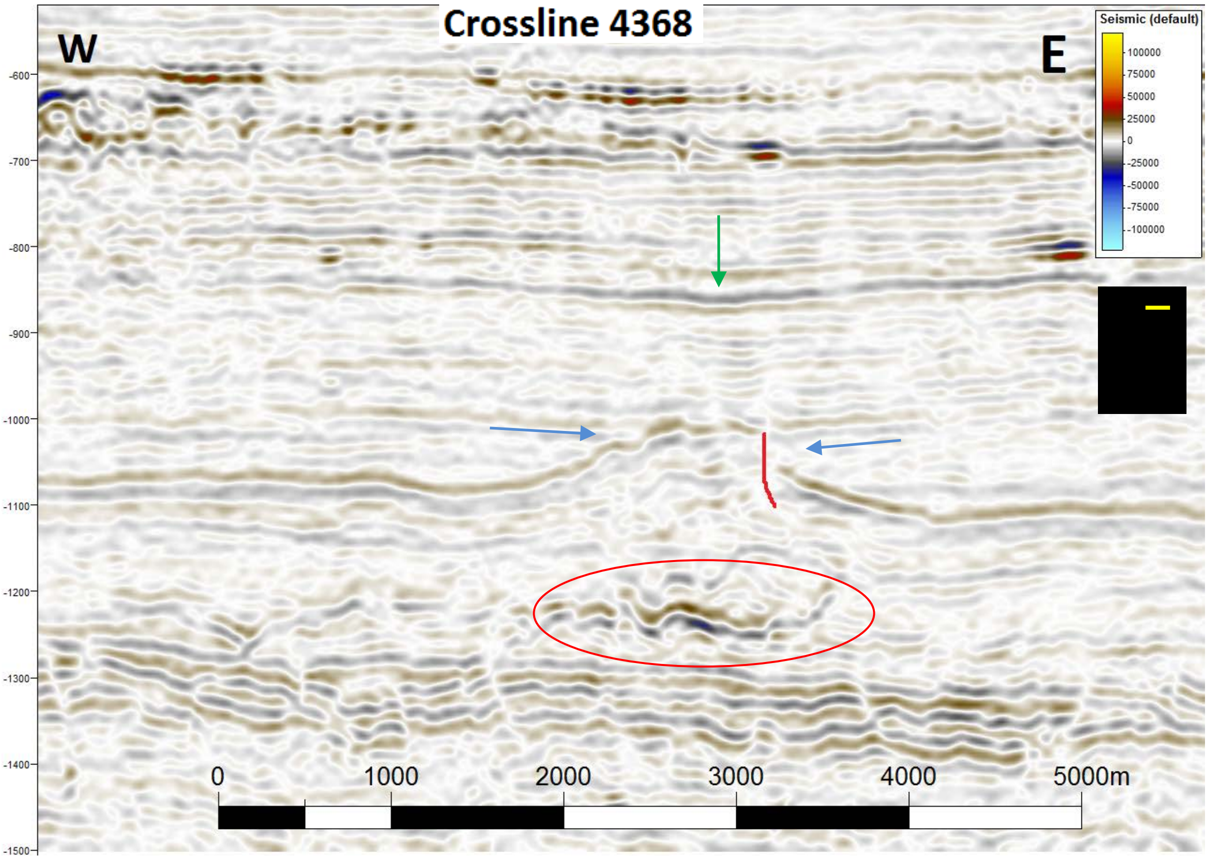


Illustration 4.5 – Mound shape interpreted as a mud diapir. The depression in the "Top Utsira" horizon is marked with a green arrow, blue arrows indicate onlap, red line indicate a fault and the red circle indicate the high amplitude anomalies connected with the mud diapirs (Løseth et al. 2009).

Beneath this layer of mound-like features there's an extensive layer of vertical shifts and disrupted reflectors, interpreted as polygonal faulting. An example is seen in illustration 4.6, of time slice at 1340ms. It can be debated whether or not this poses as a direct contribution to the mud volcanoes, but as previously mentioned in this task mud volcanoes are often activated by tectonic activity and are often seen in correlation with highly faulted areas (Hovland et al, 2007).

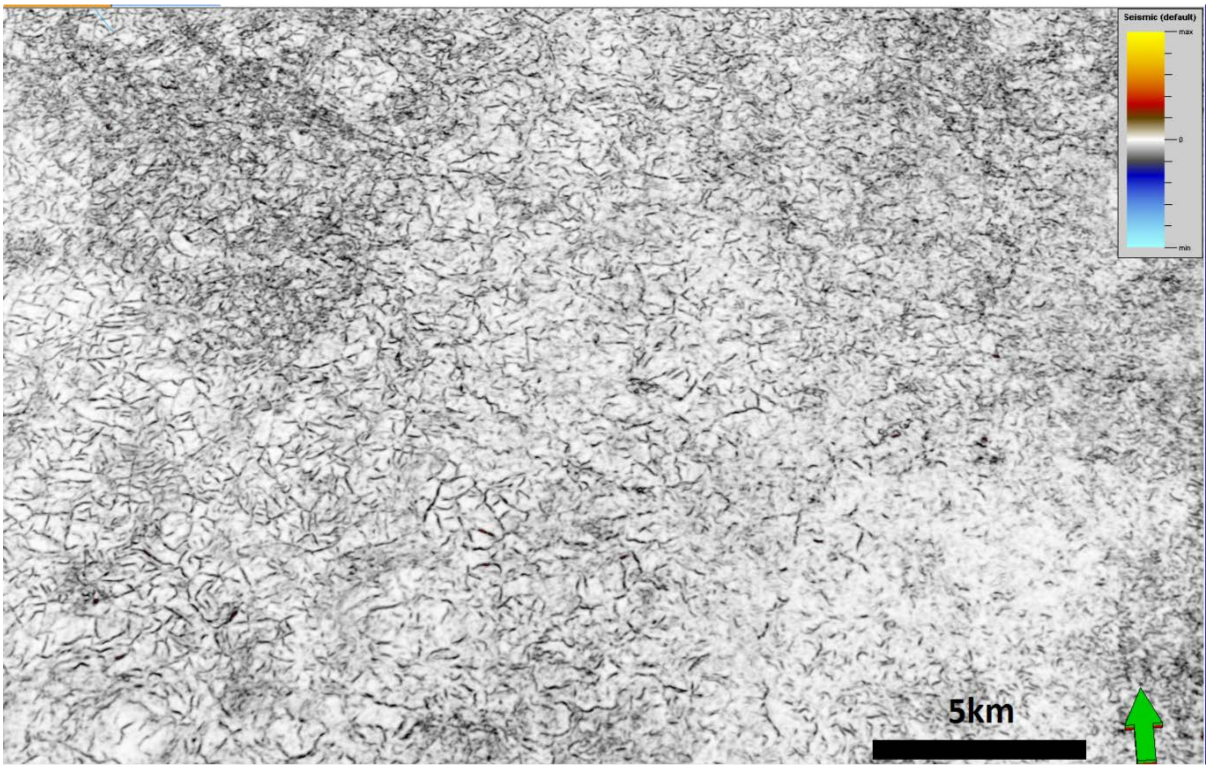


Illustration 4.6. – Chaos attribute map at time-slice 1340ms.

4.3 “Top Utsira”-horizon

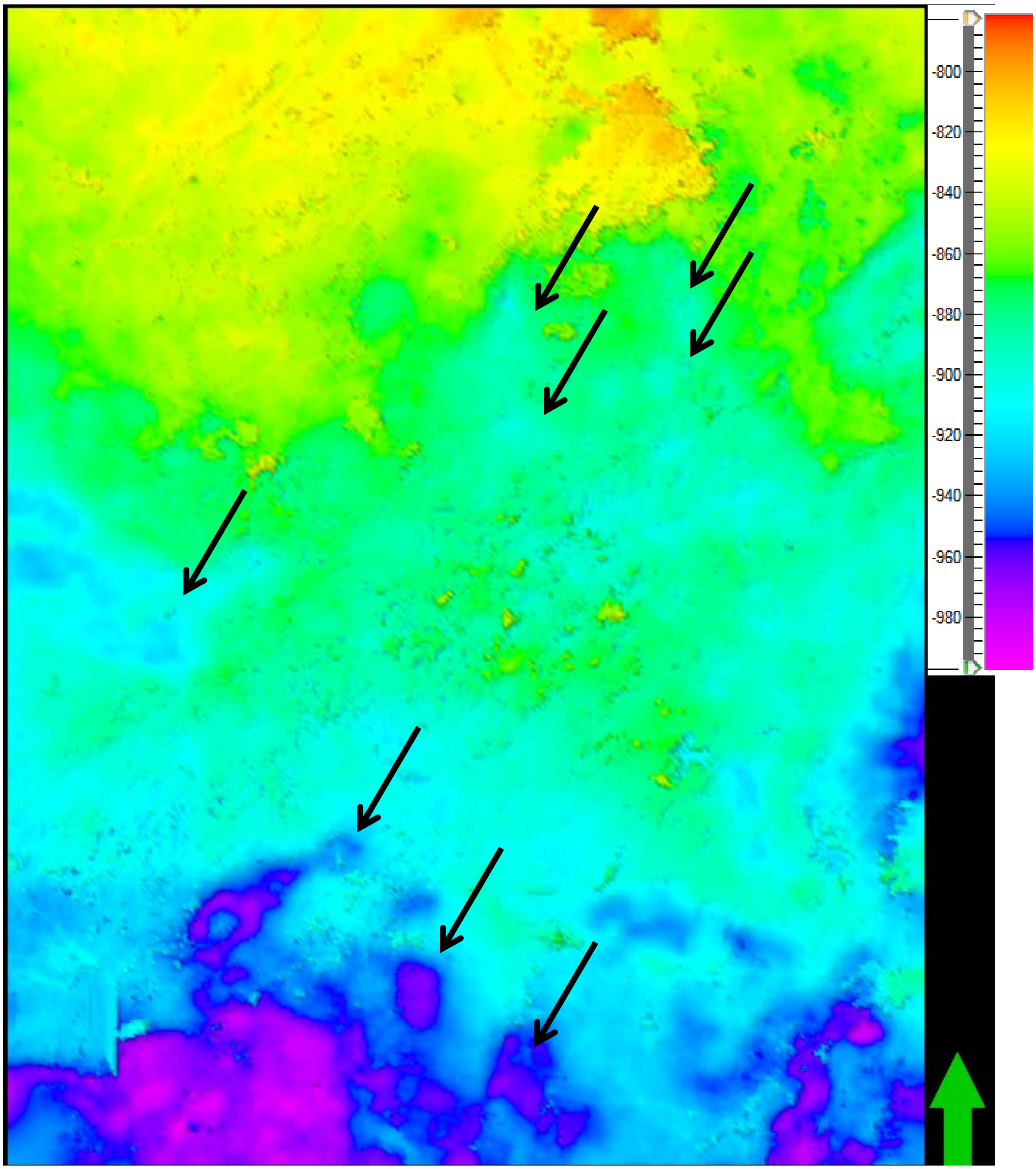


Illustration 4.7 - “Top Utsira”-horizon topographic map, black arrows indicate some of the depressions seen on this horizon.

"Top Utsira" is a negative peak reflector ranging from ~996ms to ~778ms. The horizon has a slight south-southwestern dip and the only distinct features seem to be slight depressions scattered across the horizon.

4.3.1 Description of depression features

Across the “Top Utsira”-horizon, slight depressions can be seen as on illustration 4.7 with black arrows. They are only 10-20 meters deep, and show no apparent trending on the horizon. They are in concordance with the surrounding layers, and the depressions can be followed in the layers below – intra Utsira.

4.3.2 Interpretation of the depression features

Interpretation shows that the depressions in the “Top Utsira”-horizon correspond with the underlying mud volcanoes, indicating a direct connection. It can be seen very clearly on the seismic section, see illustration 4.5. It can be interpreted that the collapse of the mud diapirs caused the overlying layers to sink in, creating the depression features. These depressions cause regional dips and can therefore create potential migration pathways for CO_2 and gas, as well as forming structural traps (Arts et.al. 2000).

4.3.3 The Utsira unit

The Utsira unit is defined as the area between “Base Utsira”-horizon and “Top Utsira”-horizon. It is the reservoir for the Sleipner CO_2-storage site, as defined by Galloway, et. al., 2009. The Utsira reservoir is southwards dipping with continuous horizontal reflectors interpreted as layers of sand. Occasionally anomalously high amplitudes occur within the Utsira unit, as can be seen circled in red on illustration 4.8. These high amplitude anomalies can be interpreted as accumulations of gas. The high amplitude anomalies seem to be unrelated to the underlying mound features, by correlating their location and the location of the mud diapirs. This might be due to the amplitude anomalies being multiples of the overlying high amplitude anomalies, or it is remnants of fluids pre dating the age of the mud diapirs seen. They seem to be located in a specific area of the cube – slightly mid-westernly, perhaps indicating a structural control.

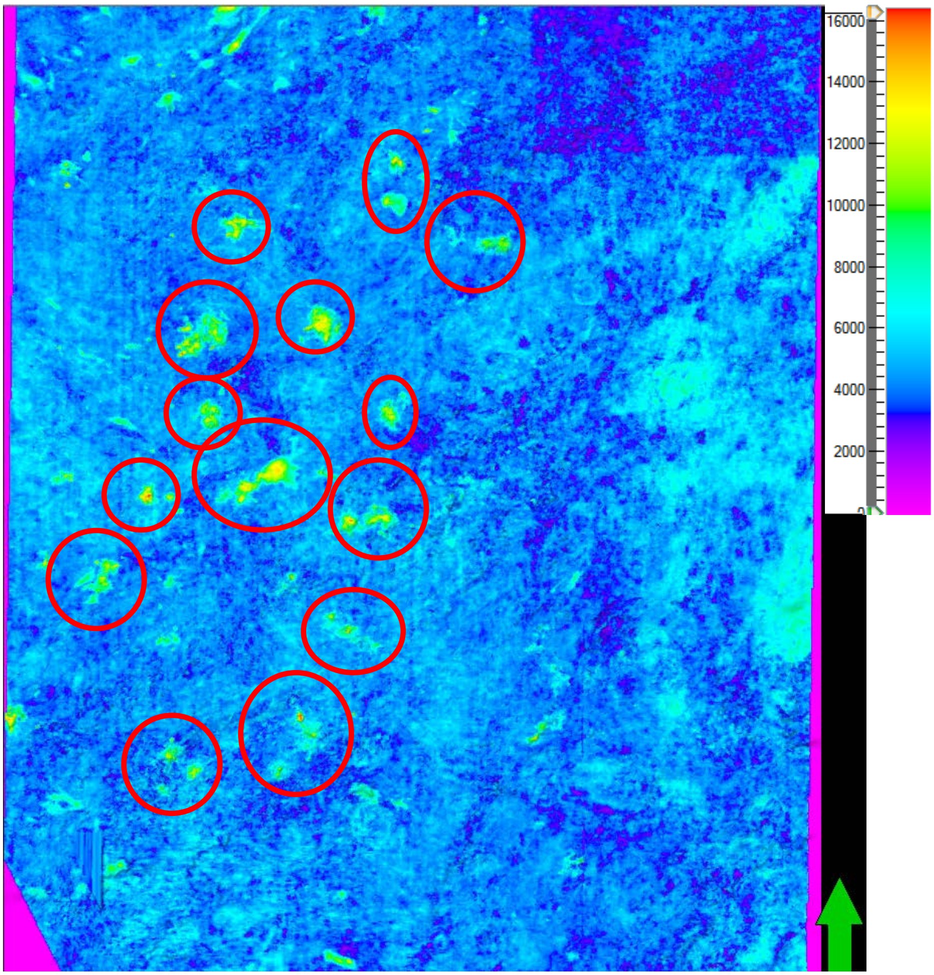


Illustration 4.8– RMS amplitude map between “Base Utsira”-horizon and “Top Utsira”-horizon, red circles indicate high amplitude anomalies.

4.4 "Intra Pliocene"- horizon

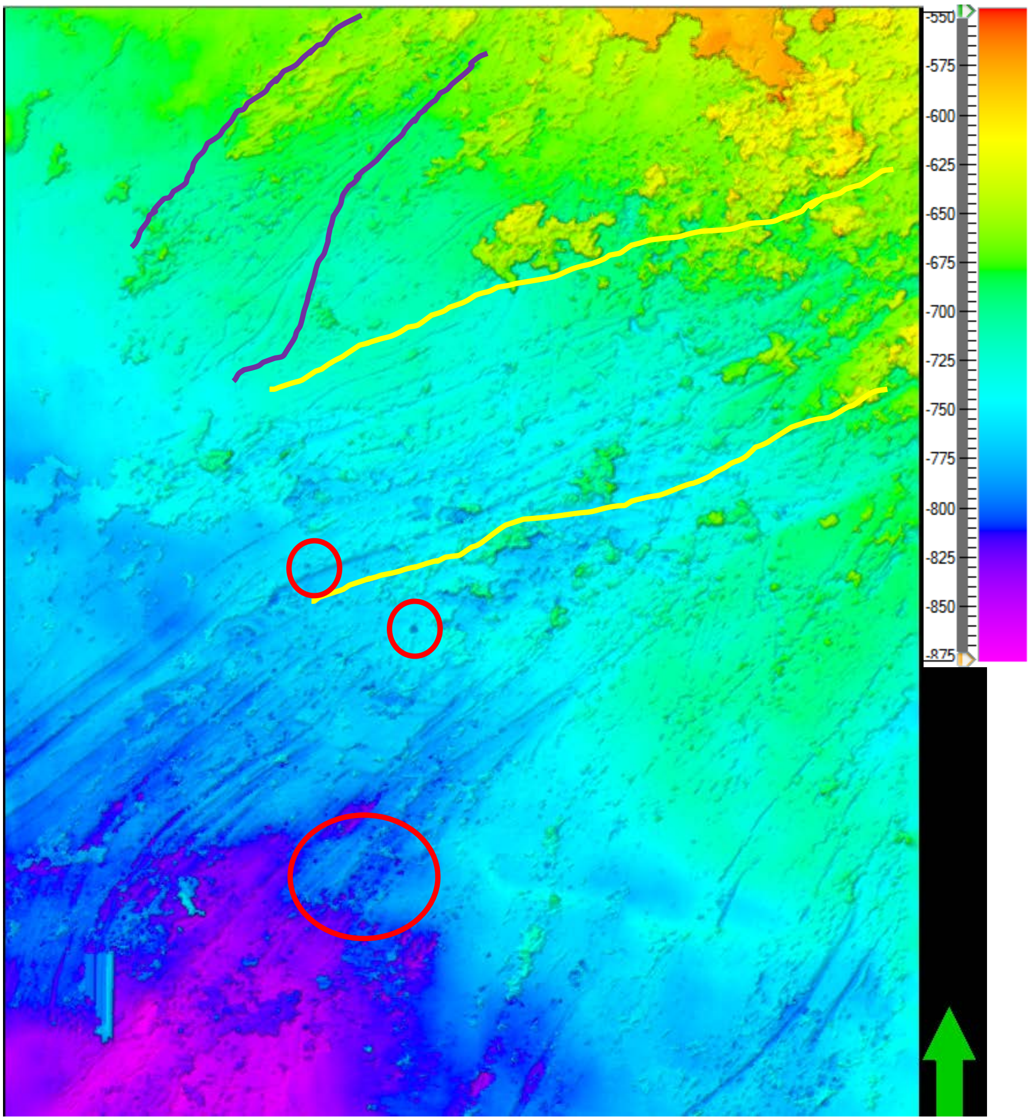


Illustration 4.9 – "Intra Pliocene"-horizon topography map, with two different directions of linear features indicated in yellow and purple. Red circles indicate examples round features.

The "Intra Pliocene"-horizon is clearly dipping in a south western direction, between ~547ms and ~876ms. The most prominent features of this horizon are the curvilinear lines which are prominent in a north-northeastern//south-southwestern direction.

4.5.1 Description of curvilinear features

The curvilinear features seen on illustration 4.9 have a NNE-SSW direction. They range from 50m to 250m depth and are 1km to 10 km long. Their width is generally 50-100m. They have a clear curving nature, accompanied by circular features.

4.5.2 Interpretation of curvilinear features

The curvilinear features as seen on illustration 4.9 are interpreted as glacial plough marks, indicating this was an area of active glaciation at that time. There seems to be two main directions, one which is more south-southwesternly bent than the other which is more southwestern (see color markings on illustration 4.9). The south-southwestern lines seem to be deeper than the southwestern ones, which can indicate that the south-southwestern lines were made first and the southwestern lines came later. The circular features might be pockmarks, as pointed out with red circles on the figure and can be seen on illustration 4.10. Pockmarks are a feature often accompanying glacial activity (Andreassen, et al 2007b) due to the scouring of the seafloor and the subsequent release of trapped gas from below.

There are two areas of seismic noise on this horizon, which corresponds to the areas where the seismic cube has been stitched together with other seismic cubes (see markings on illustration 4.1).

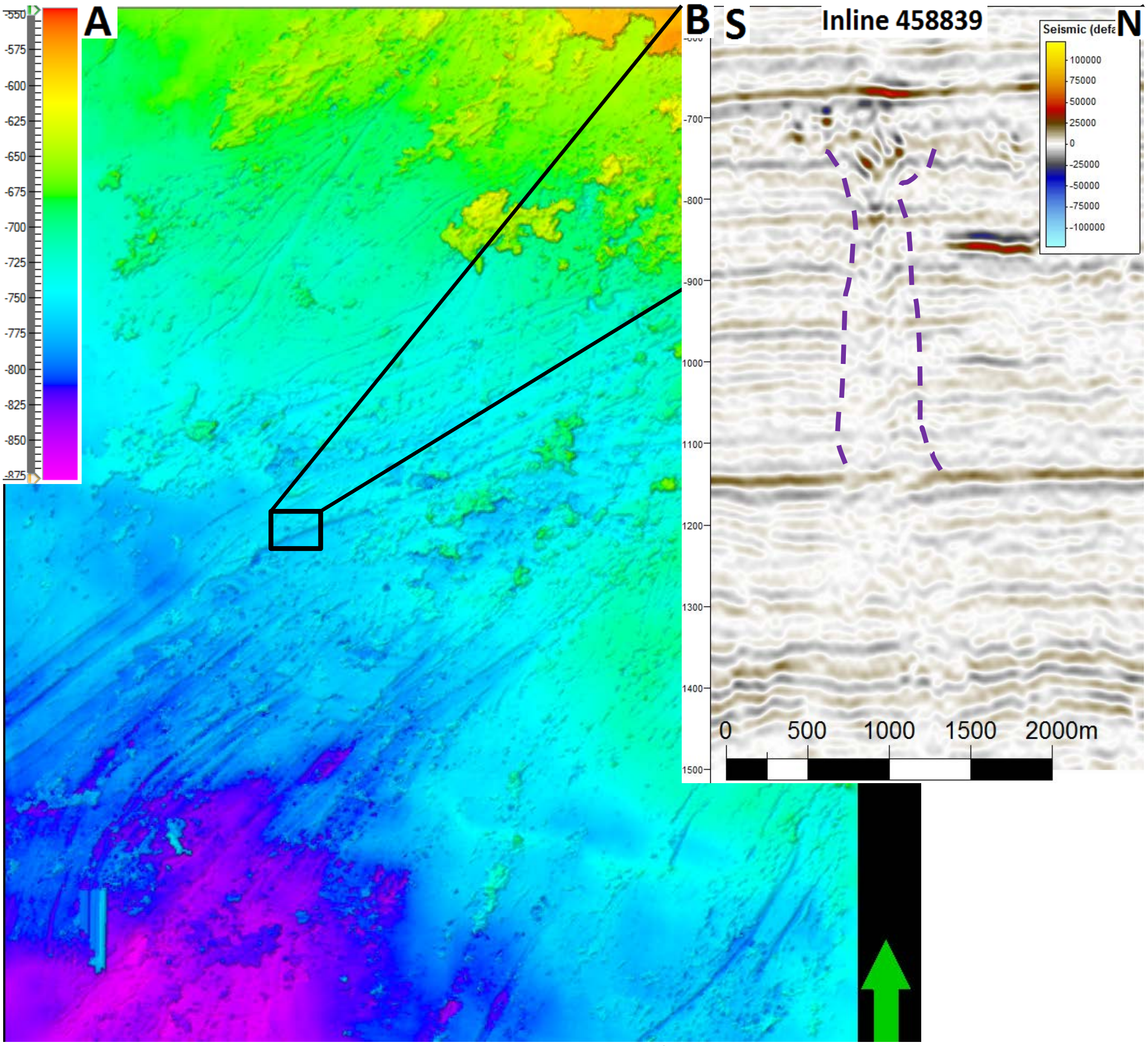


Illustration 4.10 –A: A possible pockmark on the topographic map of "Intra Pliocene"-horizo enlarged on seismic line 458839 (B): purple dashed line show possible outline of the feeder pipe and chimney.

4.5 “Top Pliocene”-horizon

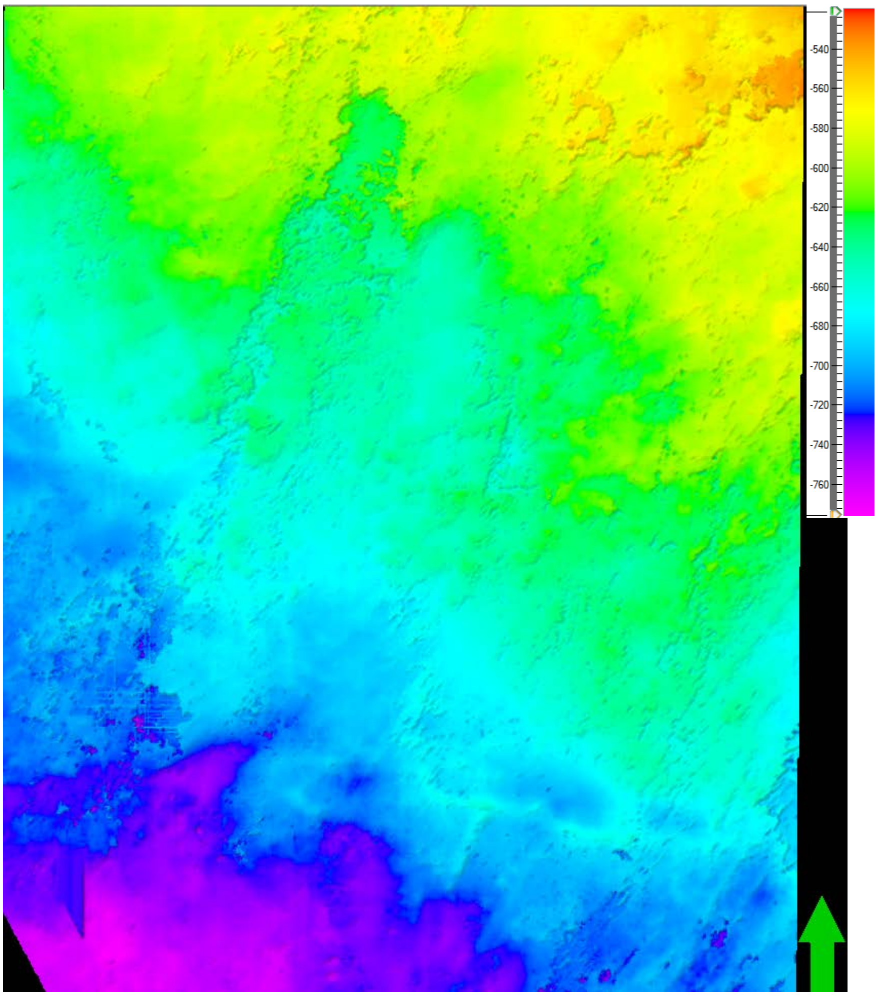


Illustration 4.11 – “Top Pliocene”-horizon topography map.

The “Top Pliocene”-horizon is defined between ~547ms and ~775ms, seen on illustration 4.11. It has a south western dip such as the previous horizons, and is dominated by a slight north-northeastern//south-southwestern linear feature which might be correlated to the “Intra Pliocene”-horizon glaciation.

There are again clear signs of seismic noise, which is due to the stitching of the seismic. See figure.

4.6 Pliocene unit

The Pliocene unit is defined as the cap rock of the Sleipner CO_2-storage project (Galloway, and is located from ~782ms (“Top Utsira”-horizon) to ~547ms (“Top Pliocene”-horizon). On an RMS amplitude map of the unit, seen on illustration 4.11, we can see two distinct amplitude anomalies. These are also seen on chaos and variance attribute cubes, see examples on illustration 4.17 (p40). The amplitude anomalies can be divided into the following descriptions.
*NW-SE trending linear shapes
*high amplitude anomalies

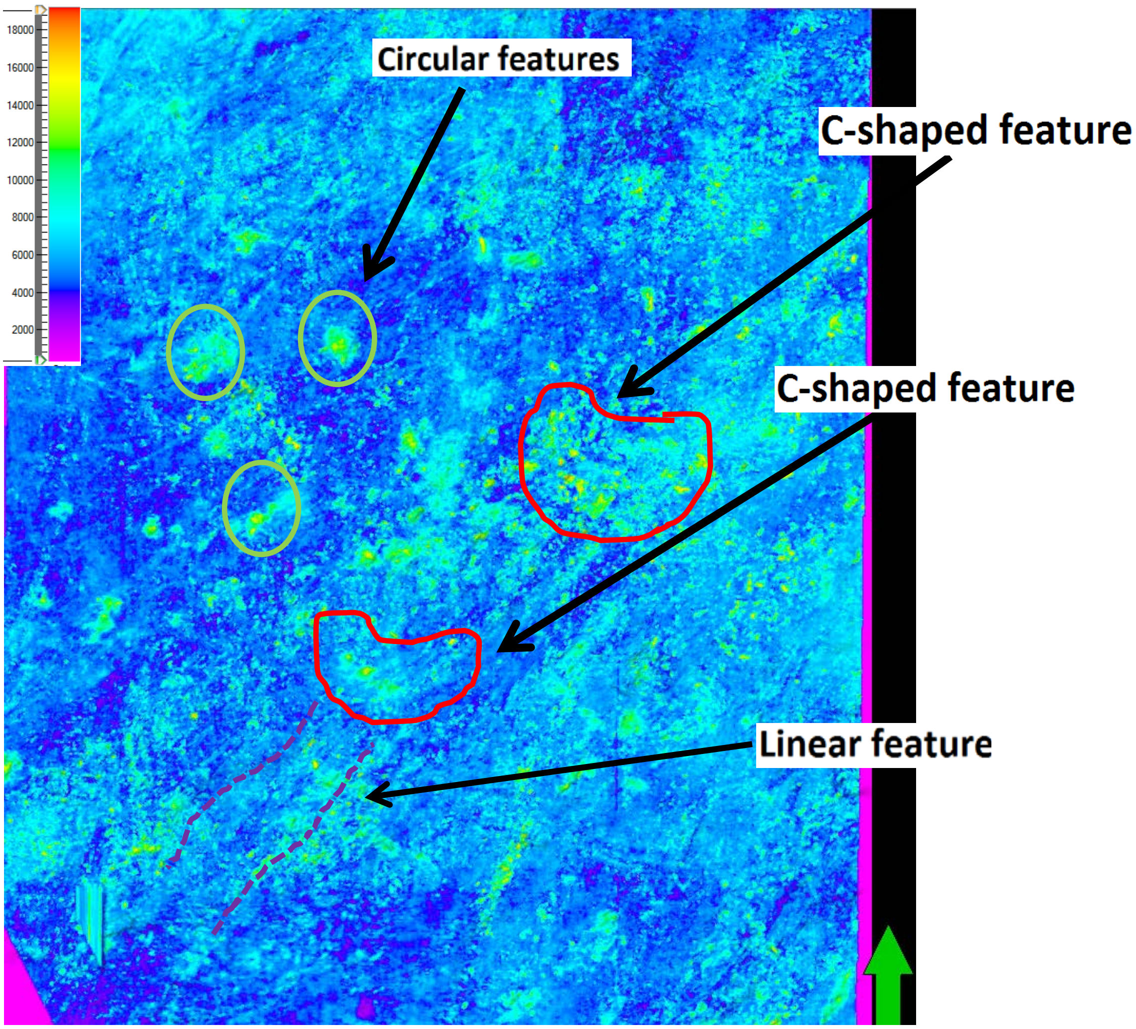


Illustration 4.12- RMS- amplitude map between "Intra Pliocene"-horizon and "Top Pliocene"-horizon. C-shaped feature and circular features indicated with arrows. Tendency of linear features is marked with dashed purple lines.

4.6.1 Description of linear features

Linear features with a curvilinear shape make distinct furrows in the horizon can be seen as indicated on illustration 4.12, as well as on the seismic section on illustration 4.14. These can also be seen on the intra-Pliocene thickness map (illustration 4.15). The features vary in length from around 1km to 10 kilometers. On the seismic section their depth can be estimated to 50-100m.

4.6.2 Interpretation of linear features

Looking further on the seismic section we can see that the linear features do not correspond with any of the underlying mud volcanoes, and is not connected to any feeder tubes for gas. The amplitude anomaly must be caused by something else than gas. The curved, linear nature and the furrow-like nature of the features lead to an interpretation of glacial plough marks. Glacial plough marks are thought to be formed due to detachment of icebergs from a glacier terminus (Andreassen et al. 2007b).

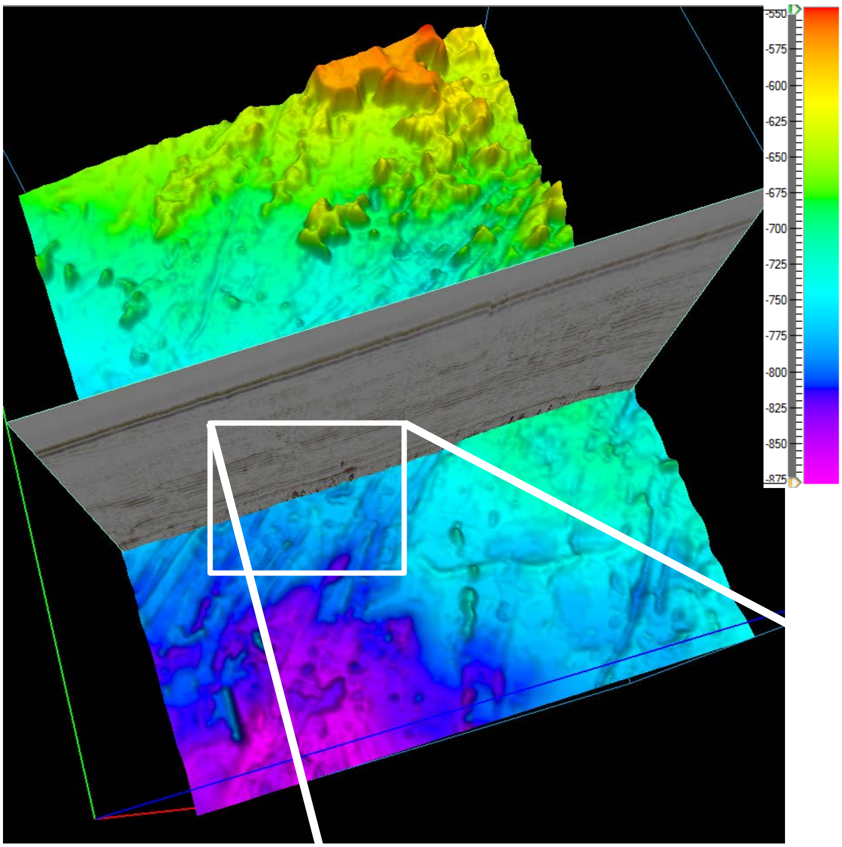


Illustration 4.13 Location of furrows on Intra-Pliocene topography map, white box indicates zoomed in seismic section on illustration 4.14.

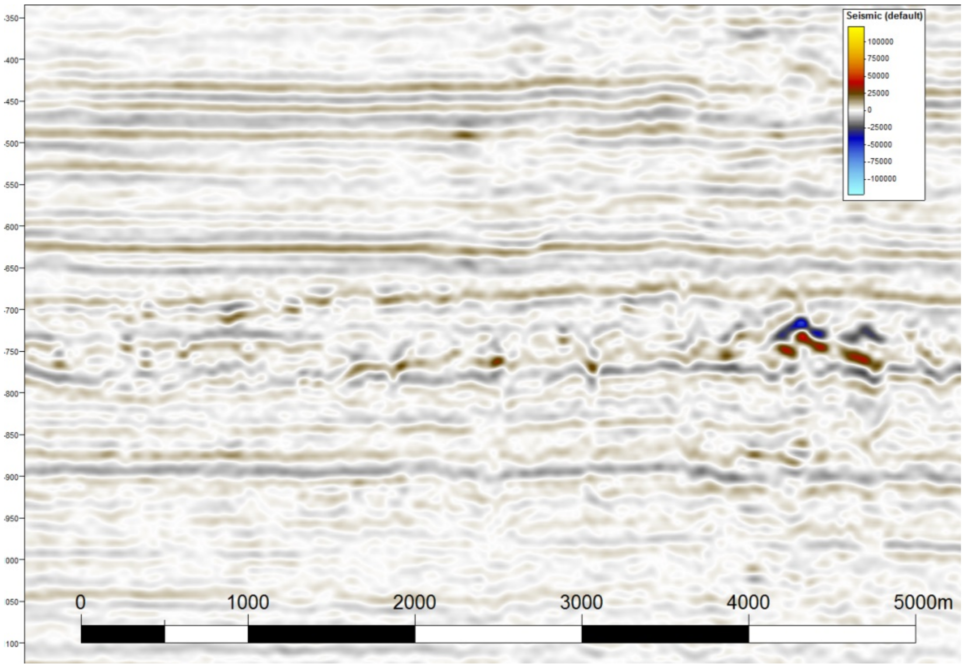


Illustration 4.14 – Furrows in the seismic can be seen marked by red circles. (Seismic line: 3184)

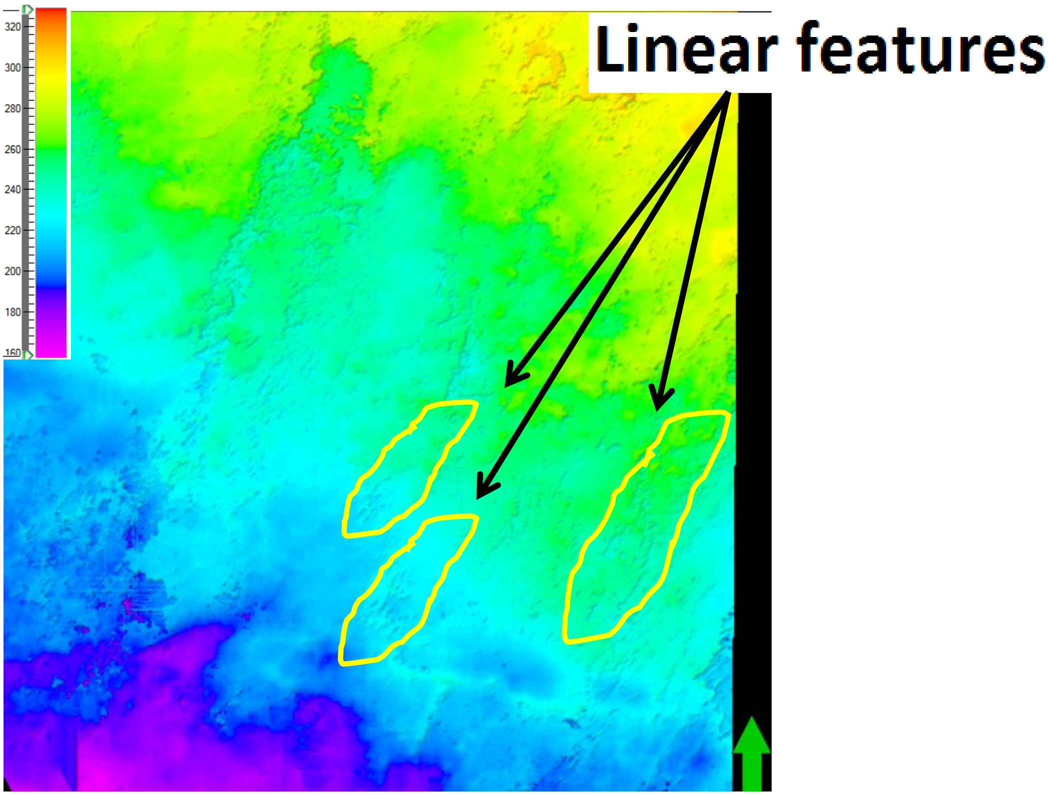


Illustration 4.15 – Isochron thickness map, of taken between the "Intra Pliocene"-horizon and "Top Pliocene"-horizon.

4.6.3 Description of amplitude anomalies

Another distinct linear trend is the broader amplitude anomalies which can be seen indicated on illustration 4.12. They seem to be aligned in a slightly more ENE-WSW than the interpreted glacial plough marks. They can be connected with the previously mentioned ENE-WSW shallow linear features from the "Intra Pliocene"-horizon. They are interesting features because in the center of the cube they are very concentrated and form almost a "C-shape" in the ENE-WSW direction. The C-shaped features have heights of approximately 15-30 meters.

4.6.4 Interpretation of amplitude anomalies

The features are interpreted as two separate features, as is shown in illustration 4.12. The first feature is 4 km wide and 11,5 km long, the second feature is 2,7 km wide and 7,5km long (measured from front of first feature). From the second feature to the cube edge it is ~13km of linear amplitude anomalies. Looking at a seismic cross section through these wide high amplitude anomalies formed like a "C", a mound-like chaotic reflection is clearly visible. A cross section through the biggest C-shaped feature is illustrated on illustration 4.16. These build-ups of chaotic seismic internal reflection cover several kilometers. The seismic visualization together with an RMS amplitude map from base to top Utsira, leads to a possible interpretation as collections of glacial material - moraines. The two C-shaped features of high amplitude anomalies in center of the cube is interpreted as being end moraines. From Andreassen et al. 2007b, these typically look like chaotic mounds with higher amplitude, and this corresponds with the observations in this cube. The interpretation of glacial origin is supported by the observation of glacial plough-marks in the southwestern part of the cube, together with high amplitude anomalies.

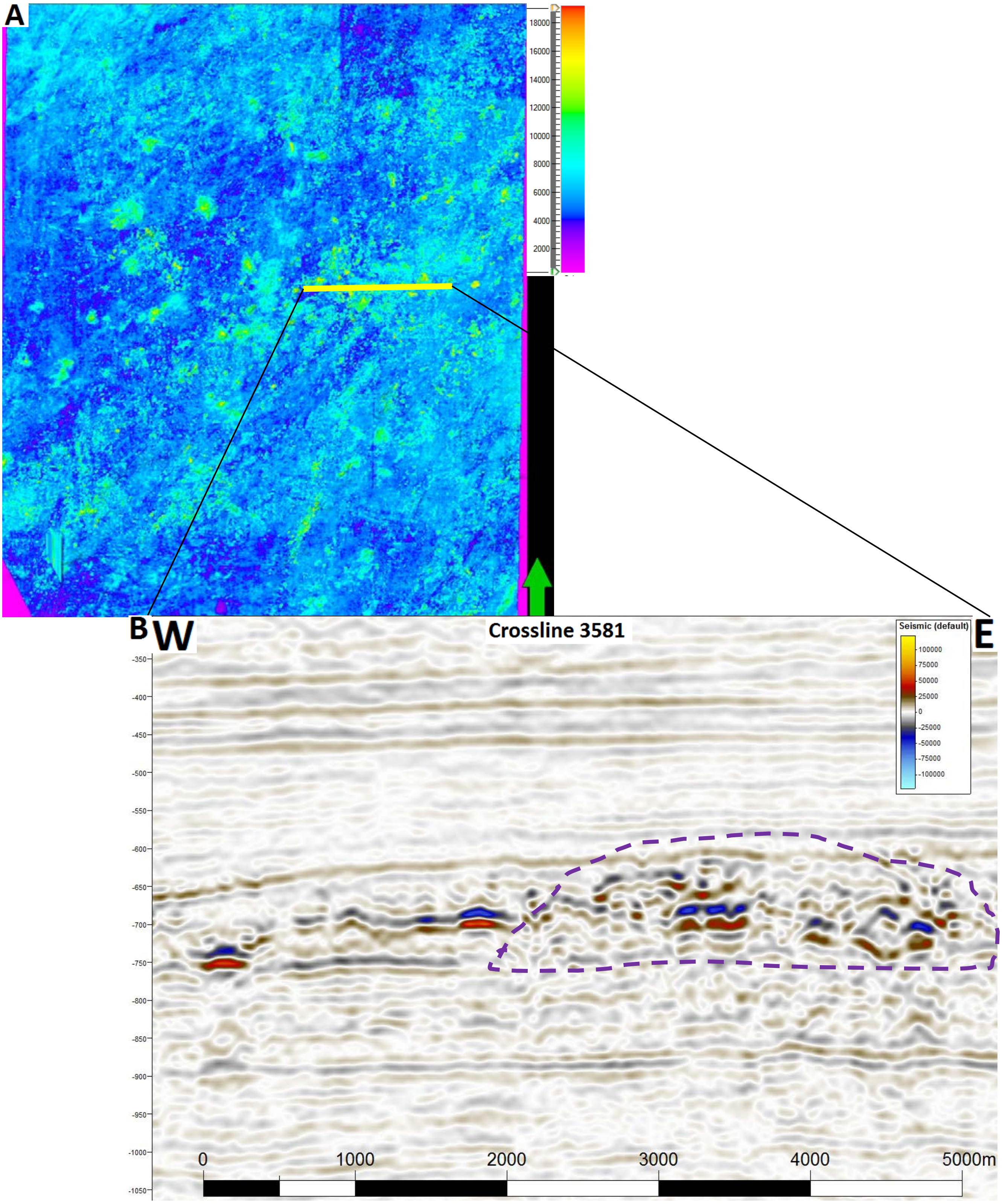
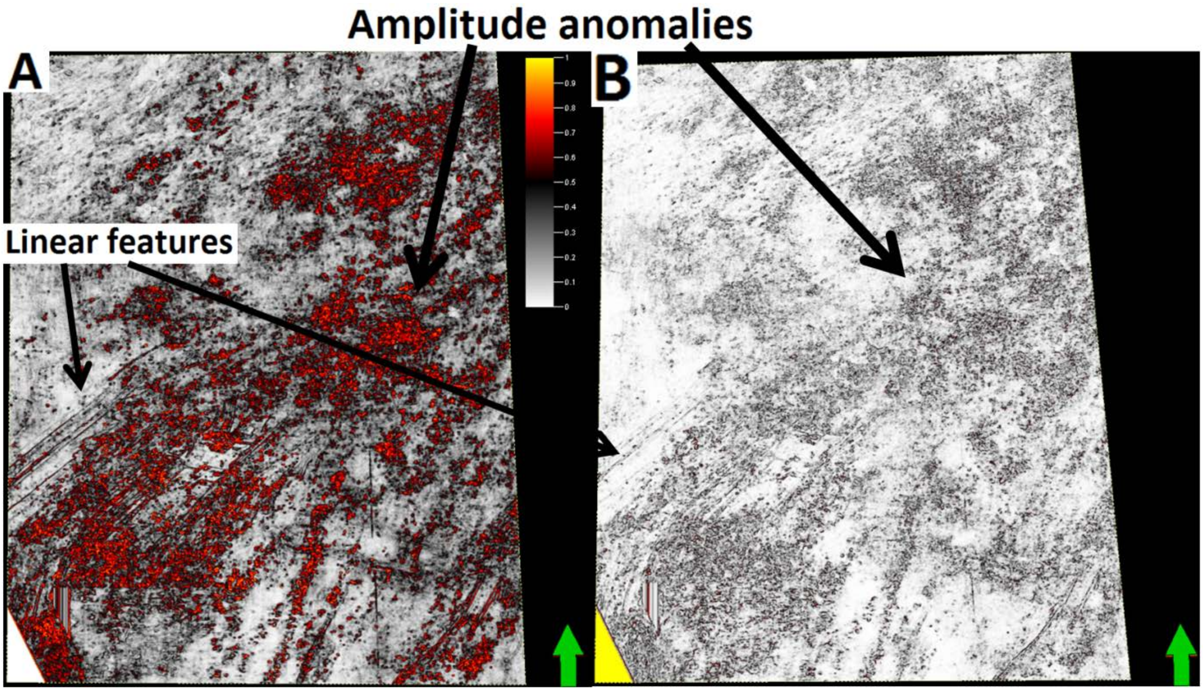


Illustration 4.16 – A: RMS amplitude map between "Top Utsira"-horizon and "Top Pliocene"-horizon. B: Seismic cross section through the biggest C-shape amplitude anomaly, where the outline of the proposed moraine can be seen.



Illustraton 4.17 - Timeslice 796 shown by A: Variance attribute map B: Chaos attribute map. Linear features and amplitude anomalies are seen, amplitude anomalies easier seen on variance and linear features easier seen on chaos attribute map.

4.6.5 Circular features

On the RMS amplitude map (illustration 4.11) from base to top Pliocene, amplitude anomalies of a circular pattern can be observed. They reach the lower part of the Pliocene package (averaging ~880ms]. On seismic cross sections there are no signs of chaotic reflection patterns beneath them, no disrupted reflectors or wiped out reflectors. There are very few to none active "feeder pipes" (gas pipes or acoustic masking) into the features at the time of the seismic survey. The features are interpreted as accumulations of gas. The biggest anomalies are a little over 1km in diameter, whilst the smaller ones are as low as 200-300meters in diameter. Illustration 4.18 (p.41) shows the result after plotting the outline of the amplitude anomalies (black circles) and overlaying it on the base Utsira horizon. We can see a slight correlation to the areas of diapirism. Although some of the outlines do not directly overlay the diapirs, it can be argued that migration into traps over time can be to blame for the slight offset. It is therefore likely that the gas accumulations have some form of link to the mud diapirs / mud volcanoes.

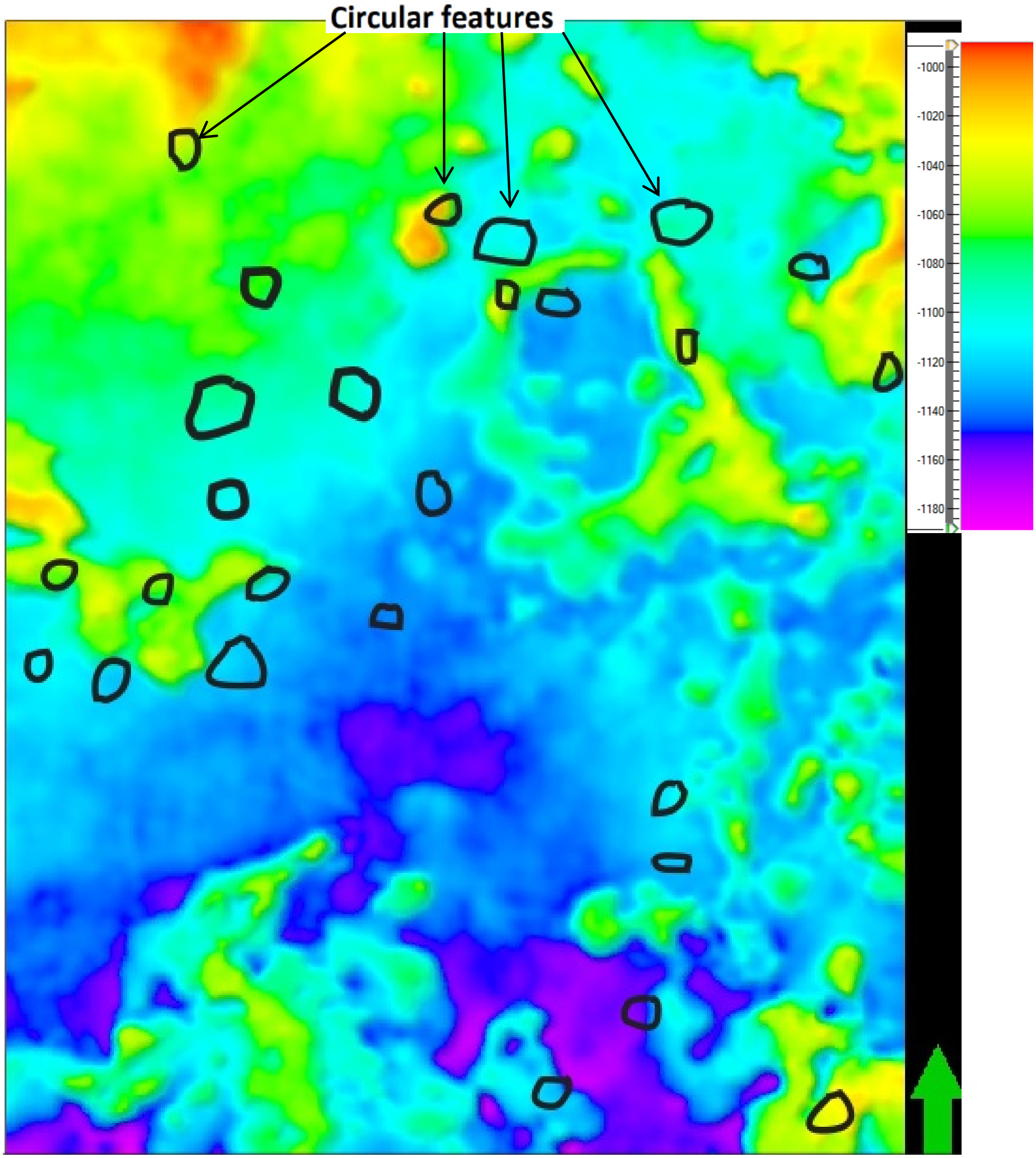


Illustration 4.18 - Correlation between "Base Utsira"-horizon topography map and the circular amplitude anomalies from the Pliocene-RMS map marked with black circles as pointed out on the figure.

4.7 "Intra Quarternary"-horizon

The horizon ranges from ~200ms to ~320ms. It is a fairly weak reflector with a slight north-western dip, and can be located on illustration 4.3 as horizon 5.

4.7.1 Meandering features description

By looking at chaos and variance attribute time slices intra the Quarternary unit (defined as the area between "Top Pliocene"-horizon and "intra Quarternary"-horizon) we can see a distinct area of curvilinear features between ~550ms to ~200ms. An example of this is seen in illustration 4.19. They are E-W and NE-SW oriented, stretching across the cube with lengths of up to ~30km. Their outlines as very distinct and the seismic cross-section show a clear U-shape or V-shape with chaotic internal reflectors and sometimes high amplitude outline.

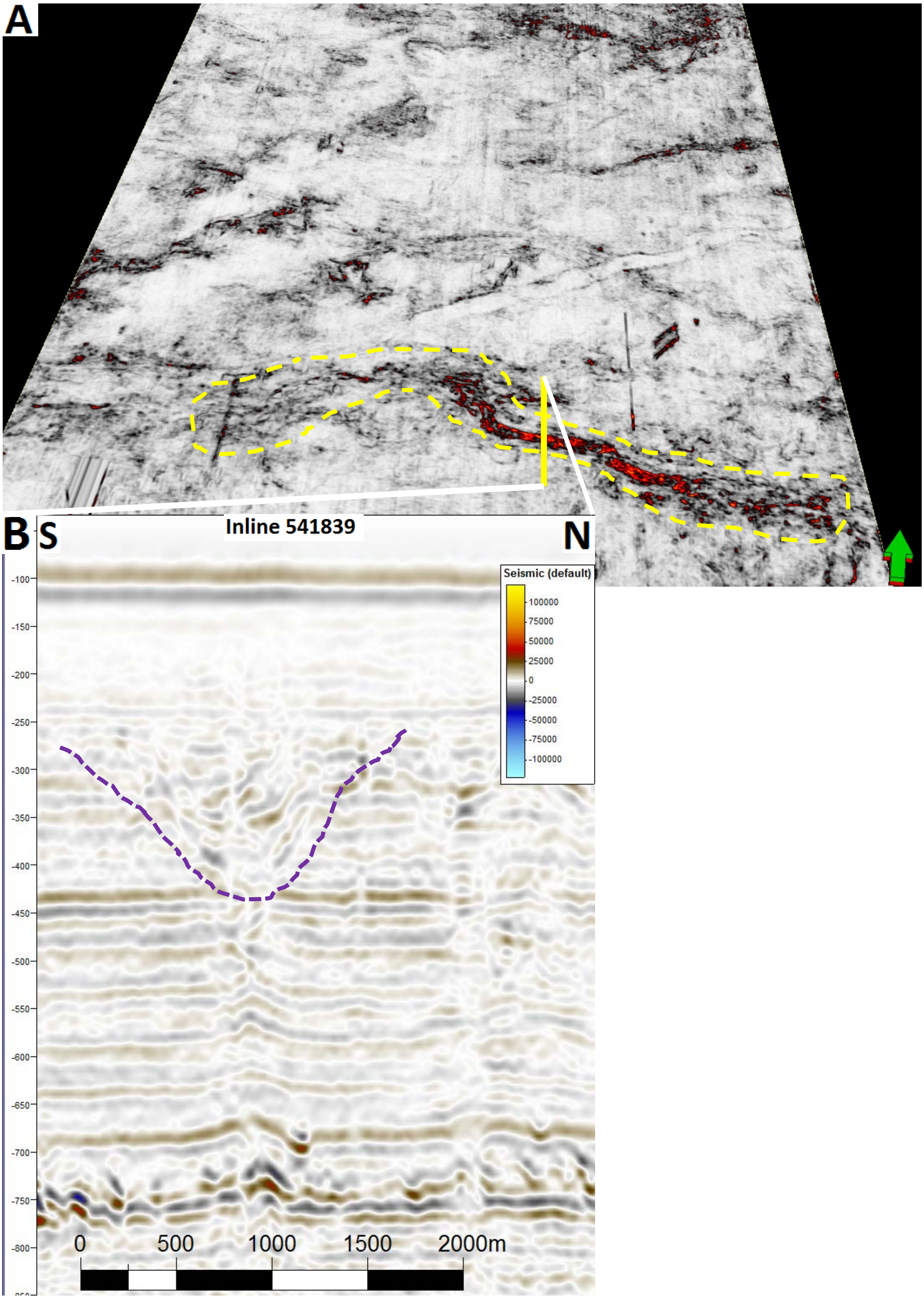


Illustration 4.19 – A: Variance attribute map shows timeslice 432 ms, and a meandering feature marked in yellow. B: Seismic cross-section through the feature showing a U-shaped feature.

4.7.2 Interpretation of meandering shapes

The clear curvilinear shapes with distinct borders on both chaos and variance attribute maps indicates an interpretation as channels. Their meandering shapes point towards a flat fluvial environment, possibly linked to deltaic environments. The high amplitude anomalies on the sides might originate from channel levee complexes (Andreassen et. al., 2007b).

4.8 Fluid flow structures

4.8.1 Description

Across the entire cubes seismic sections several curvilinear features is seen rising from certain reflectors, often ending up in amplitude anomalies. An example of this can be seen in illustration 4.20. These can sometimes be correlated on the RMS amplitude map seen in illustration 4.12. They range from 200m to 1000m in length and have a diameter of generally 250-400meters. Common for all of them is a dominating tendency of vertically chaotic and/or discontinuous reflection patterns and vertical wiped out reflectors. Many of these features also show signs of local depressions in the vertical anomalous area. Around half of all the structures end up in a high amplitude anomaly around a depth of 200-250ms (TWT time), whilst 3 structures reach 400-500ms (TWT time). They are evenly distributed and do not appear in any given pattern or clusters. They do however seem to trend around the southern part of the seismic cube, with a majority in the south-western part of the cube. Some of the features reaching 250ms seem to have a high amplitude anomaly which is reverse of the seafloor-reflection, see figure 4.25.

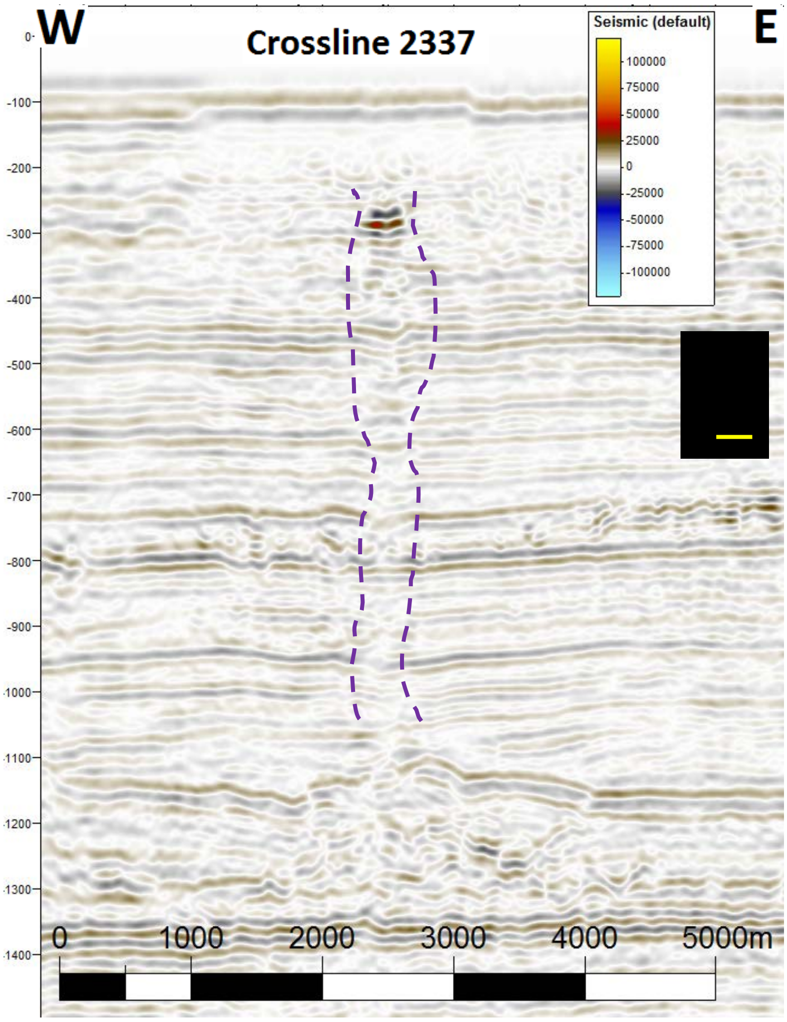


Illustration 4.20: A vertical linear feature is seen emerging from a mound feature on the "Base Utsira"-horizon and reaches an high amplitude anomaly at 300ms.

In two areas there are several vertical features closer than the average spread of features across the cube. Both are located in the lower south-eastern corner of the cube. See precise location on the black square on illustrations. The first seismic section is seen on illustraton 4.21. This cross-section contains two vertical features in close vicinity to each other. There is an estimated 1000meters distance in-between them. They both reach about the same maximum height, with an amplitude anomaly in the top. Both seem to originate intra Utsira, with chaotic reflection patterns and wiped reflectors stretching from about 1000ms to 200ms. The bigger one averages at around 1400meters in diameter, whilst the smaller one averages at 400meters in diameter.

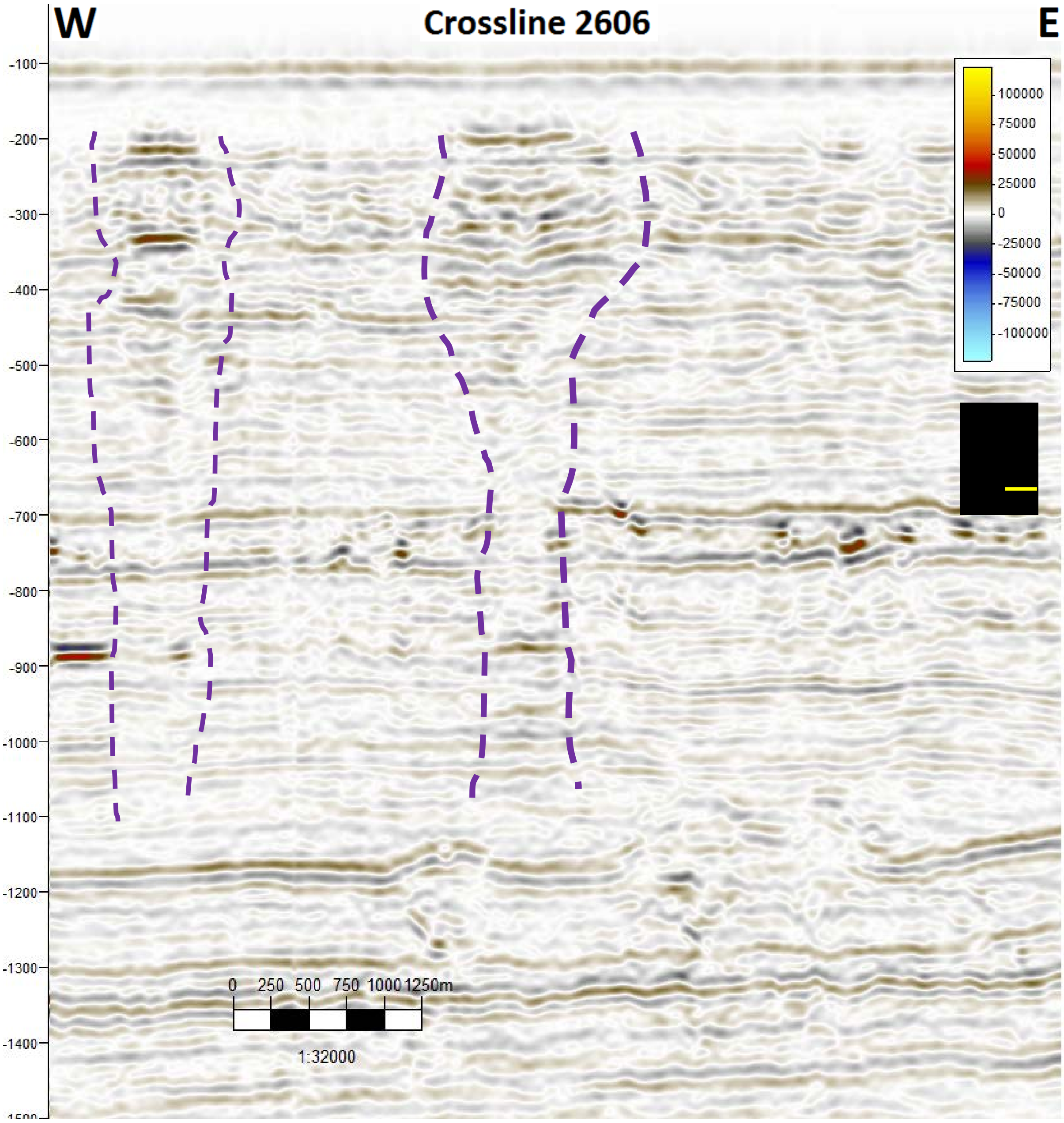


Illustration 4.21 – The two interpreted features, highlighted in stippled purple lines.

Another area, very close to the just discussed area, we have two vertical features appearing in close vicinity. This can be seen in illustration 4.22. They are both emerging from the "Top Pliocene"-reflector and reaches around 200-300ms depth, as indicated by the green arrows in ill.4.22. The northernmost feature is slightly smaller in diameter than the southernmost, but they both reach a U or V shaped feature. They are both more diffuse than most of the vertical features discussed, dominated by wiped out reflectors and areas of no reflection. The internal reflection of the U / V shapes is chaotic and they have defined outlines.

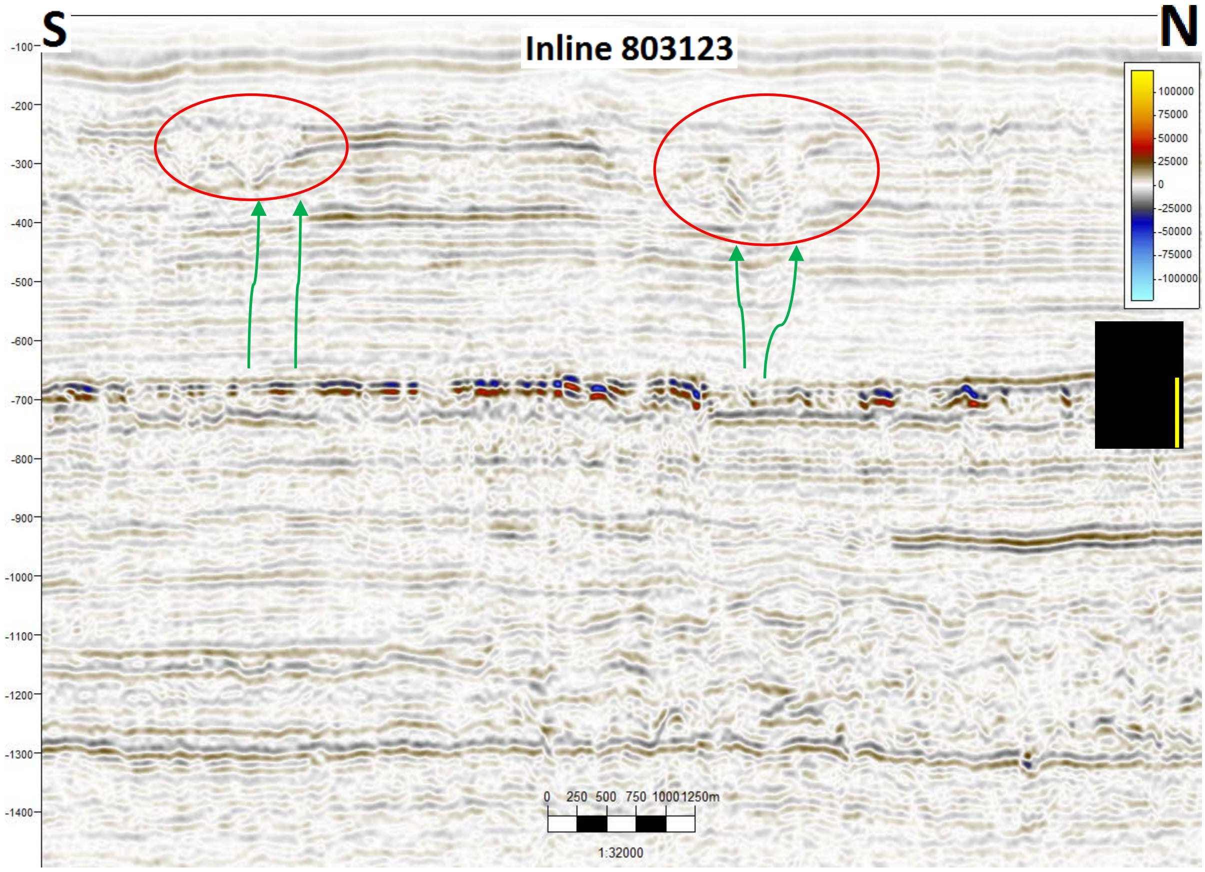


Illustration 4.22 – Two features of slight wiped out reflectors / faded reflectors in a vertical pattern indicated by green arrows. U/V-shapes indicated by red circles.

Some of the features stand out from the others. One of them is pictured on illustration 4.23. This feature is approximately 1400m max in diameter, with high amplitude anomalies spread across a large area, in an upwards widening appearance. The feature seems to originate around top Utsira where it is only 400-500 in diameter. It has a less chaotic reflection pattern than the others in the area. The flare-like (upwards widening) feature seems more dominated by continuous reflections with high amplitude rather than wiping and chaos which are more common.

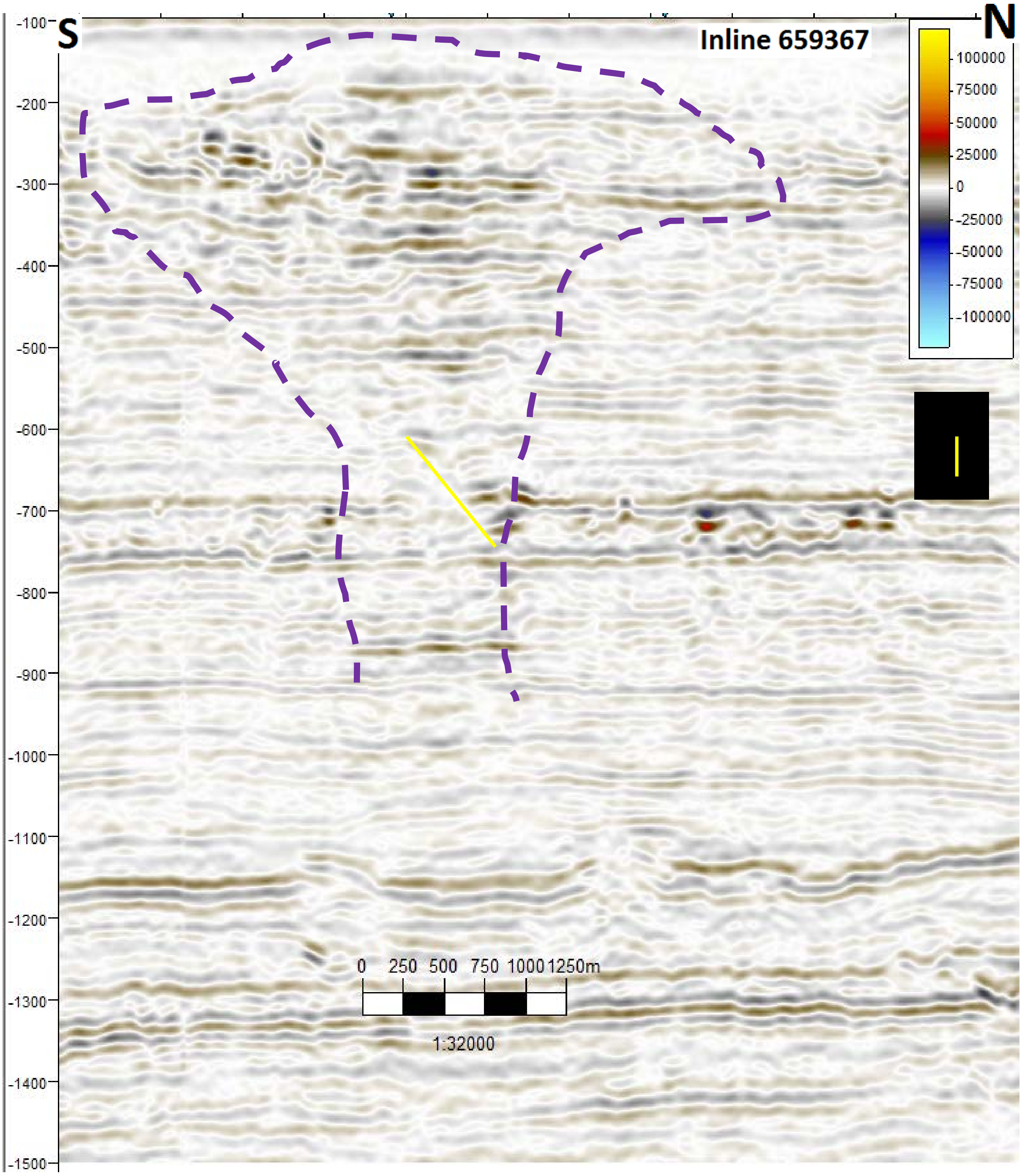


Illustration 4.23 – Purple dashed line indicates flare-like feature which seems to emerge from "Top Utsira"-horizon. Yellow line indicate a possible fault.

Another feature (illustration 4.24) seems to originate from top Pliocene, reaching around 200ms. The feature is dominated by chaotic reflection patterns and some wiped reflectors in the deeper reflectors. It seems to be upwards broadening, and it has a slight high amplitude anomaly in the center of the feature with chaos towards the edges, and is around 600meters in diameter in the widest area which is around 300ms. There is a slight disturbance in the seafloor reflector above the feature.

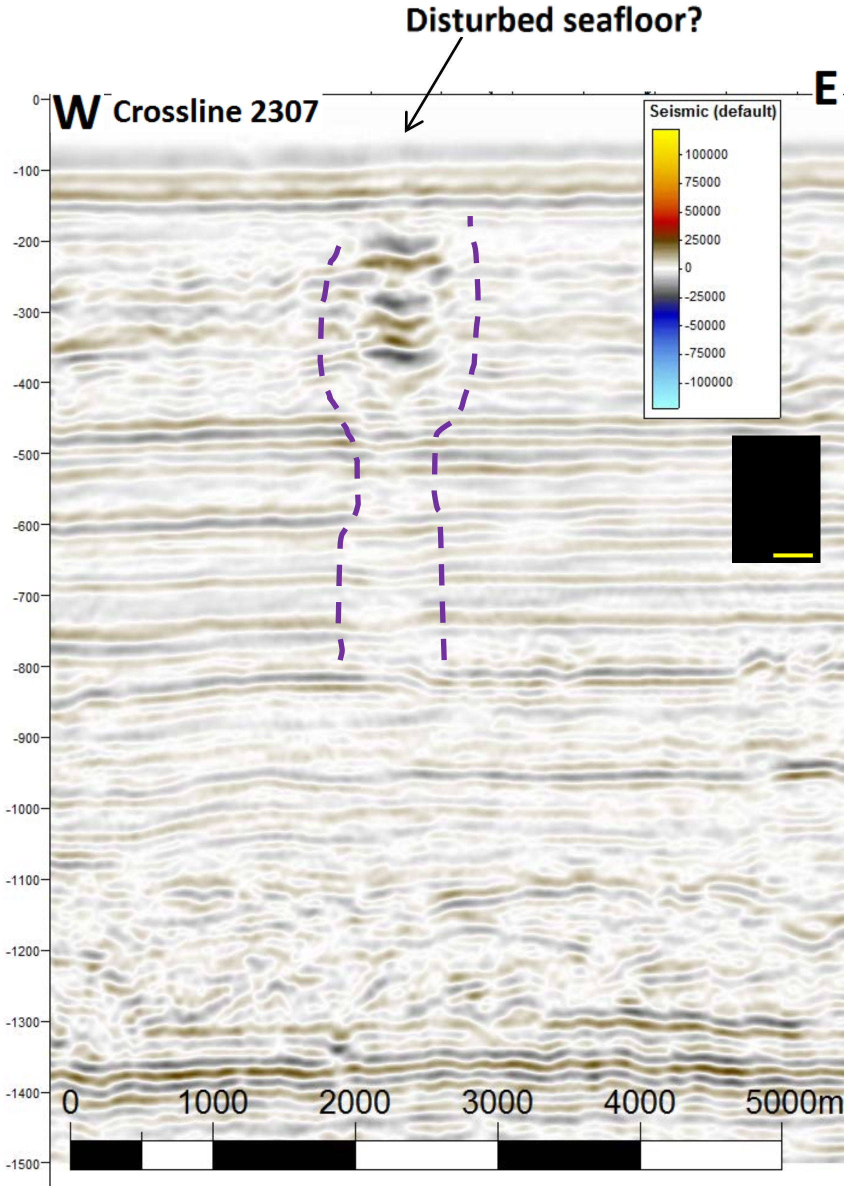


Illustration 4.24 – Purple dashed line indicate a vertical feature.

In general, the features do not seem to reach the seafloor and breach it; there are no structures similar to pockmarks or chaos in the seafloor reflector. There is one feature observed which seem to have some sort of influence on the seafloor. See illustration 4.25. This feature seems to originate from the top Pliocene reflector, having a constant diameter of around 200m. The feature looks like it ends at the seafloor with a slightly less strong reflection especially in the reflector just below the seafloor reflector.

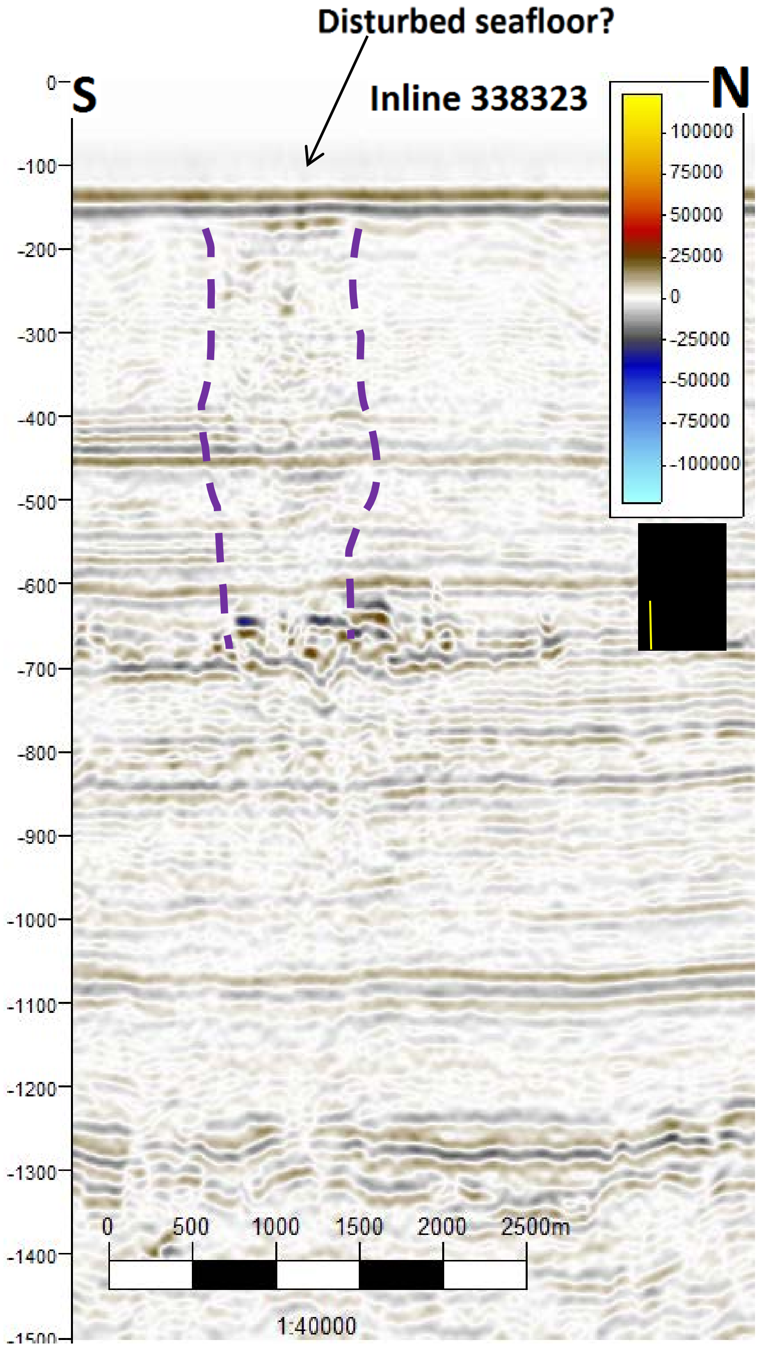


Illustration 4.25 – Purple dashed line show vertical feature.

Several of the vertical structures seem to be connected with U-shaped horizontal features on the seismic. An example of this is in illustration 4.26. The horizontal features are present in the upper part of the cube, at around 200-300ms - trending at 250ms. They are recognizable both on in-lines and cross-lines, as a U or V shape with a clear high amplitude anomaly outline, and an inner chaotic reflection pattern. Sometimes spots of high amplitude anomalies appear on the bottom and the inside of these features, when seen in connection with curvilinear vertical features below. About 1/3 of the main curvilinear, vertical features discussed in this thesis seem to be located directly beneath or bending towards these distinct U/V-shaped features.

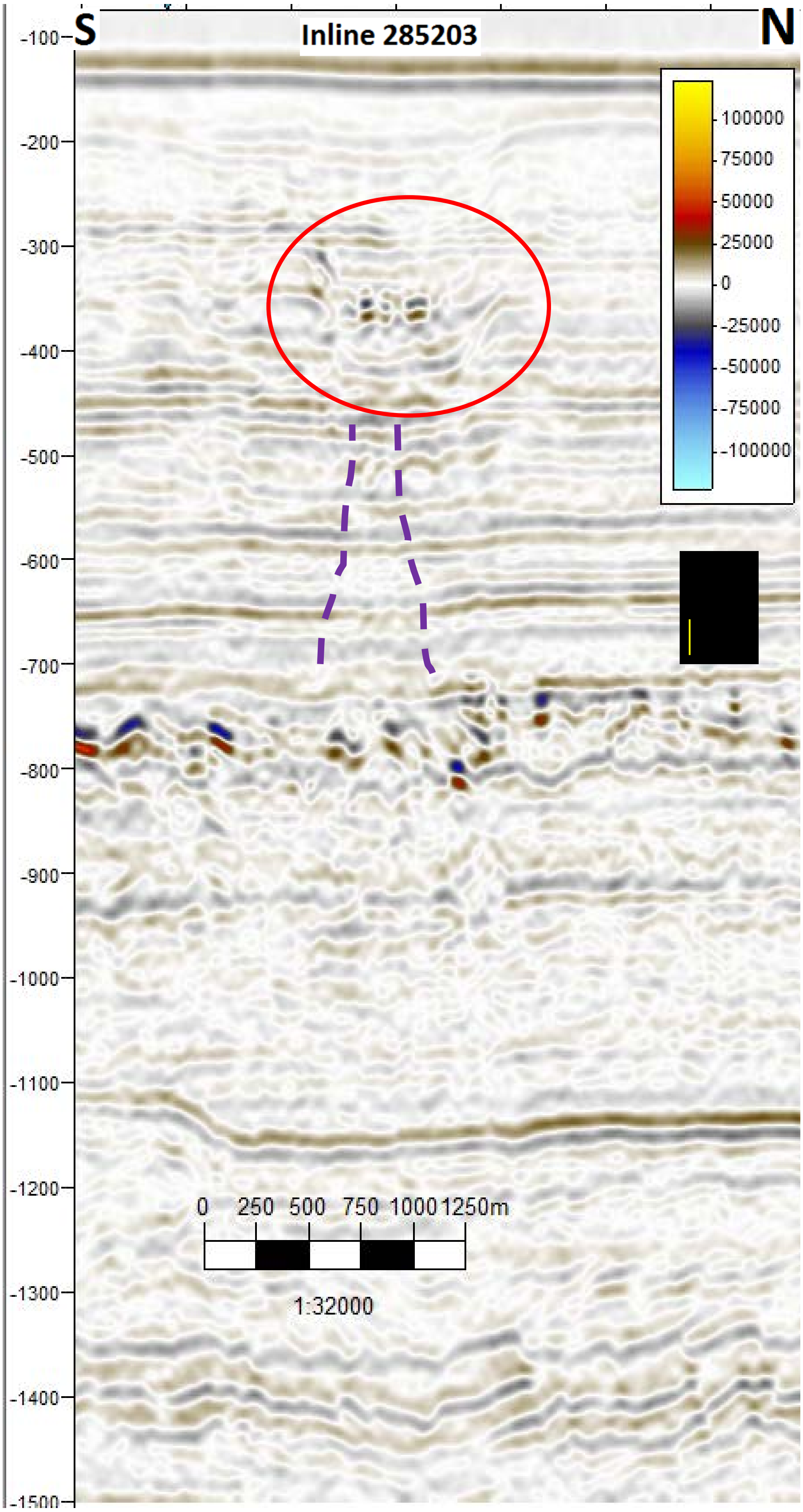
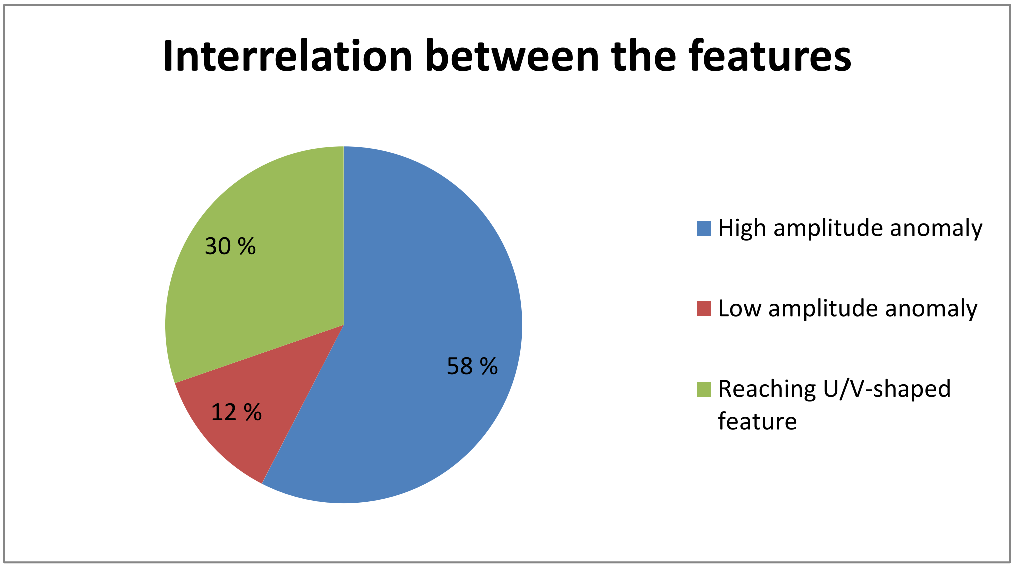


Illustration 4.26 – U-shaped feature marked with a red circle, possible vertical feature marked by purple stippled line.

Given by graph 1, we can see that almost 50% of the features end up in a high amplitude anomaly. The low amplitude anomalies are harder to distinguish because of their obvious "transparent" nature, and the sometimes similar appearance to other features described. Low amplitude anomalies seem to appear as elliptic features of semi-wiped out reflectors and slight chaos internally. The low amplitude anomalies are often seen in relation to/inside the U/V-shaped features. They are not big in size, averaging at the same as the other features; around 250m in diameter.



Graph 1 – Percentage of observed features ending up in a high amplitude anomaly, low amplitude anomaly or a U/V-shaped feature.

The regional distribution of the vertical features interpreted can be observed on illustration 4.28, p. 53. Their regional distribution might be linked to the thickness of the Pliocene unit, which you can see in illustration 4.27.

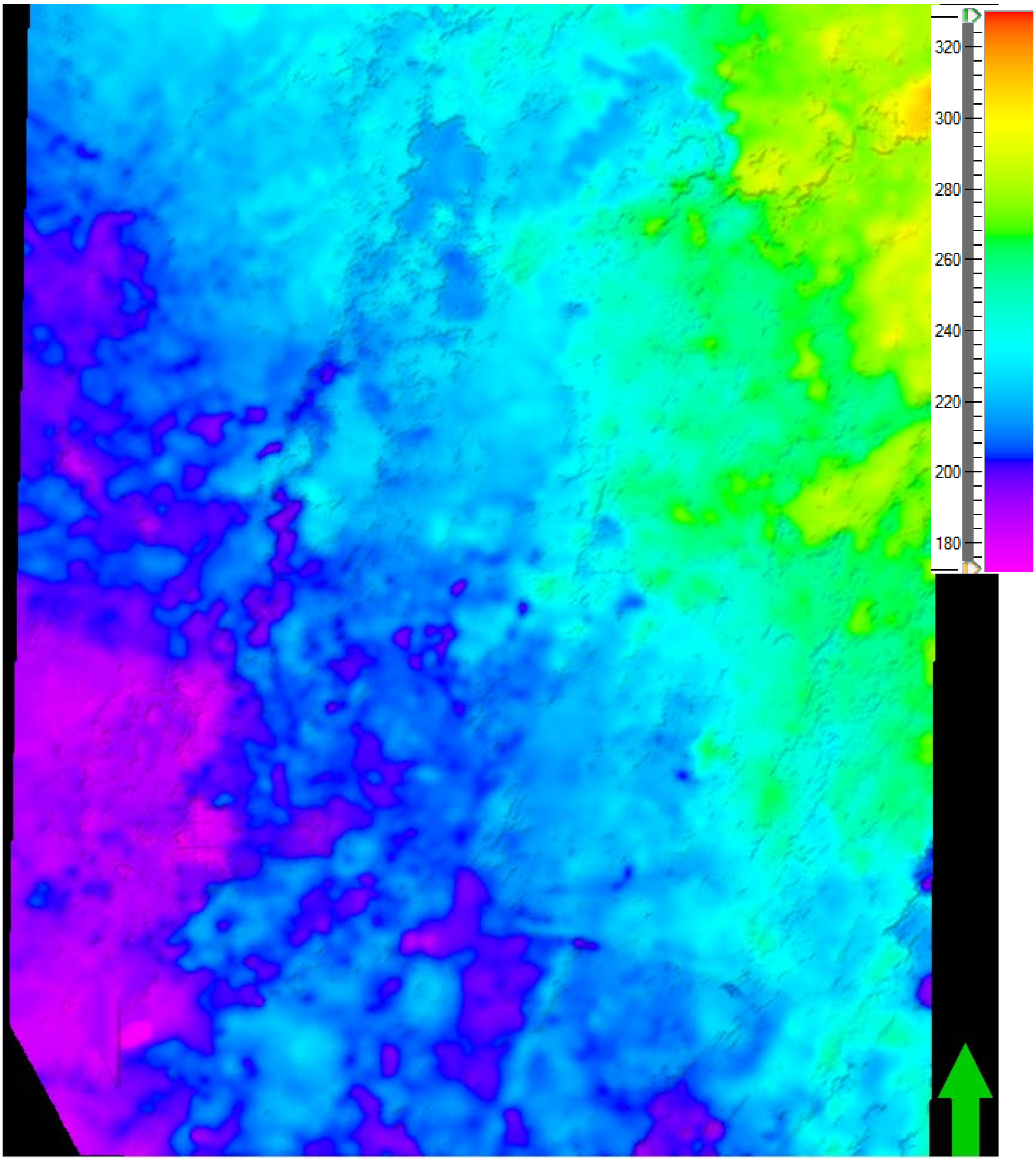


Illustration 4.27 – An isochron thickness map from "Top Utsira"-horizon to "Top Pliocene"-horizon.

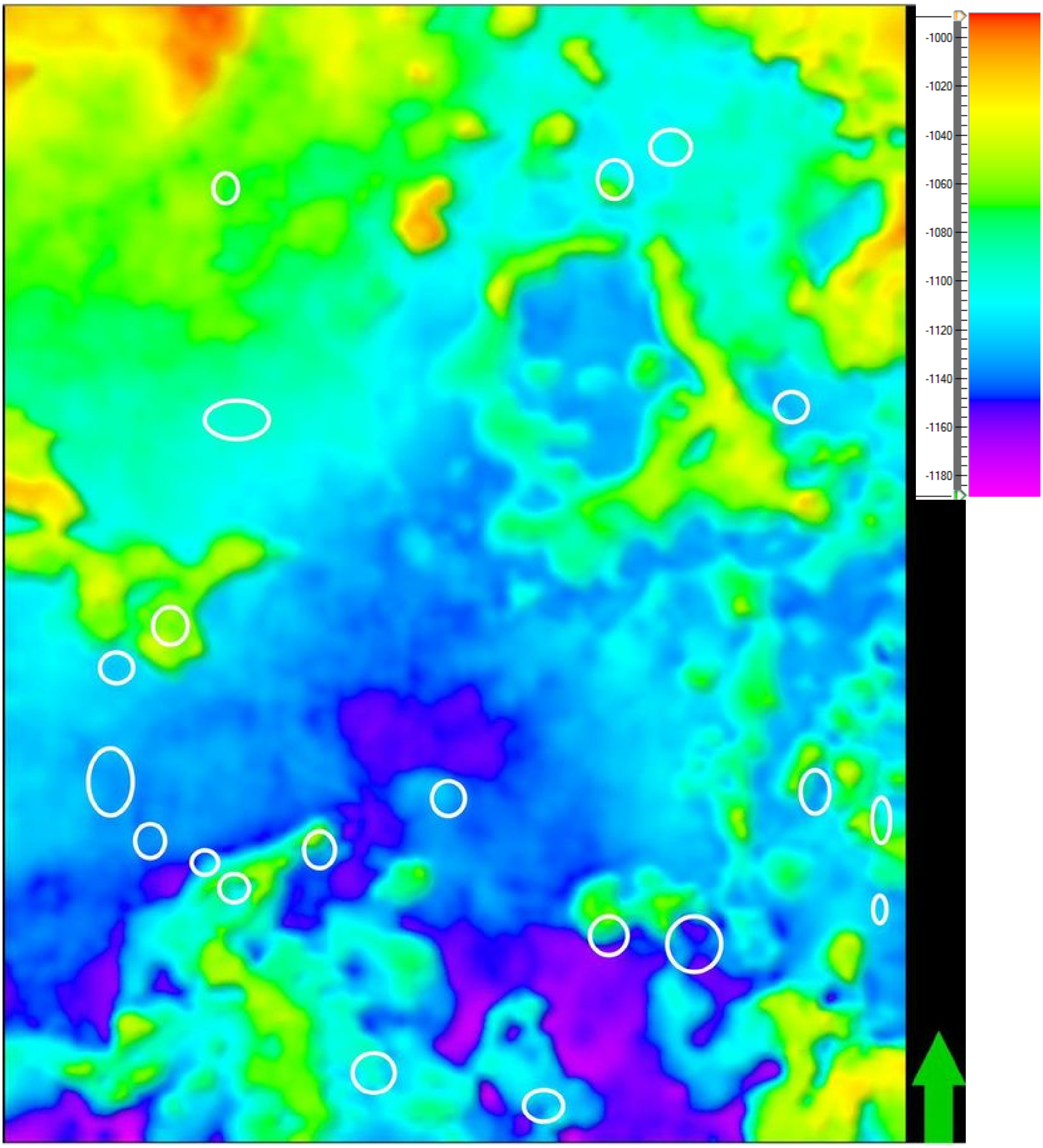


Illustration 4.28 – Overview of all vertical features shown in white circles, overlain the "base Utsira"-horizon topography map. The yellow-red areas of the topography map shows highs on the map, indicating the presence of what has been interpreted as mud diapirs. White circles might indicate one or more fluid flows, due to the small nature of some of the fluid flows they have been combined for practical reasons.

4.8.2 Interpretation of the fluid flows

The general appearance of the curvilinear features all point towards these structures being typical fluid flows. This interpretation is as previously mentioned in chapter 4, supported by the works of Løseth et. al. 2009 and Andreassen 2009. The following typical tendencies of fluid flows on seismic data has been observed; vertical wipe-out zones, vertical dim zones, high amplitude anomalies, discontinuities, chaotic reflection patterns and push downs.

The majority of the vertical fluid flows are interpreted as possible leakage from the Pliocene unit into the more porous Quarternary deposits above. This is due to their regular pattern of emerging from the "Top Pliocene"-horizon and rising to a high amplitude anomaly between 300-200ms below the seafloor. Because of the seismic resolution it becomes increasingly difficult to interpret the actual vertical extent the closer to the seafloor we observe. It is therefore possible that the interpreted fluid flow structures can be far more elaborate in the uppermost 200ms of the seismic.

In the observations, many of the fluid flows seem to connect with U or V shaped features, 30% as seen on Graph 1. These U/V shapes are interpreted as channels, due to their quite distinct and sometimes high amplitude outline with a chaotic internal reflection pattern. Under pressure, from fluid dynamics we know that fluid flows will try to find the path with less resistance. The close connection with channel-features can indicate that the channel features have characteristics which have higher potential for fluid flow than the surrounding sediments.

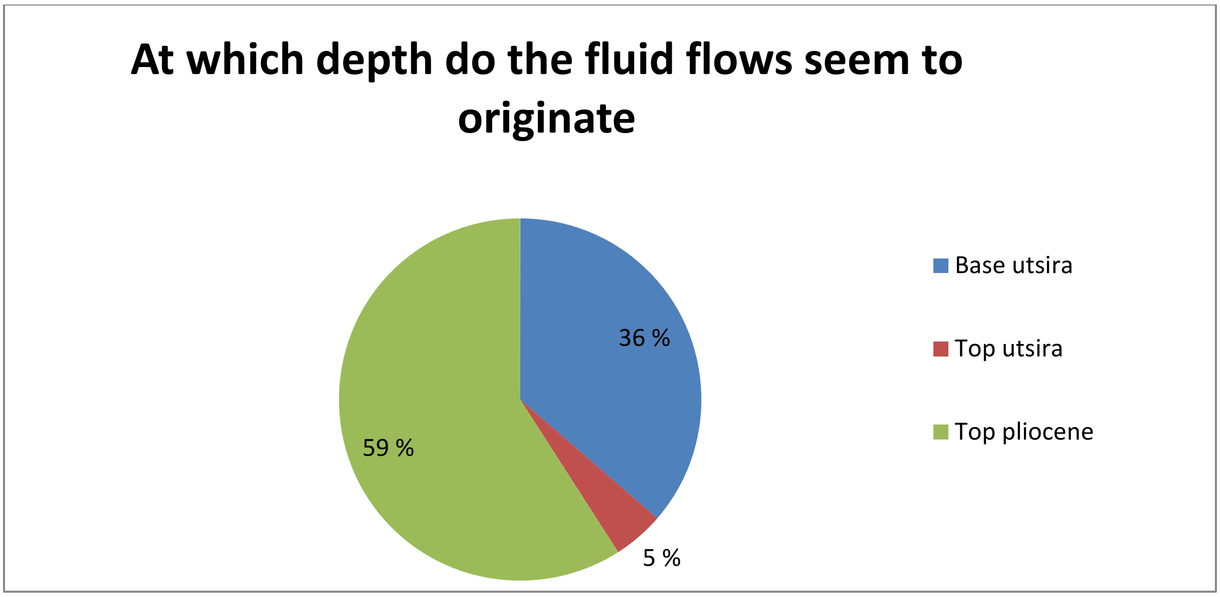
The flare-like fluid flows are interpreted as a clear sign of the fluid flows not being controlled by faulting in the overburden, but rather of stratigraphic control. The areas of flare like structures are close to each other, and are not found in other parts of the cube. This can indicate a local area of softer and/or more permeable sediments.

Fluid flows ending with a low amplitude anomaly have an opposite polarity to the seafloor. An example of this can be seen in illustration 4.29 (p.56).The low amplitude anomalies can be indications of areas where the trapped fluid in the layer makes the change in reflection contrast from the overlying rocks which have lower velocity than the underlying rocks less obvious. This decrease in amplitude causes an area of almost "no reflection", and are therefore called dim spots. The dim spots seem to correlate to the internal reflection in the channels, which can indicate that the channel sediments have less seismic velocity than the underlying layers.

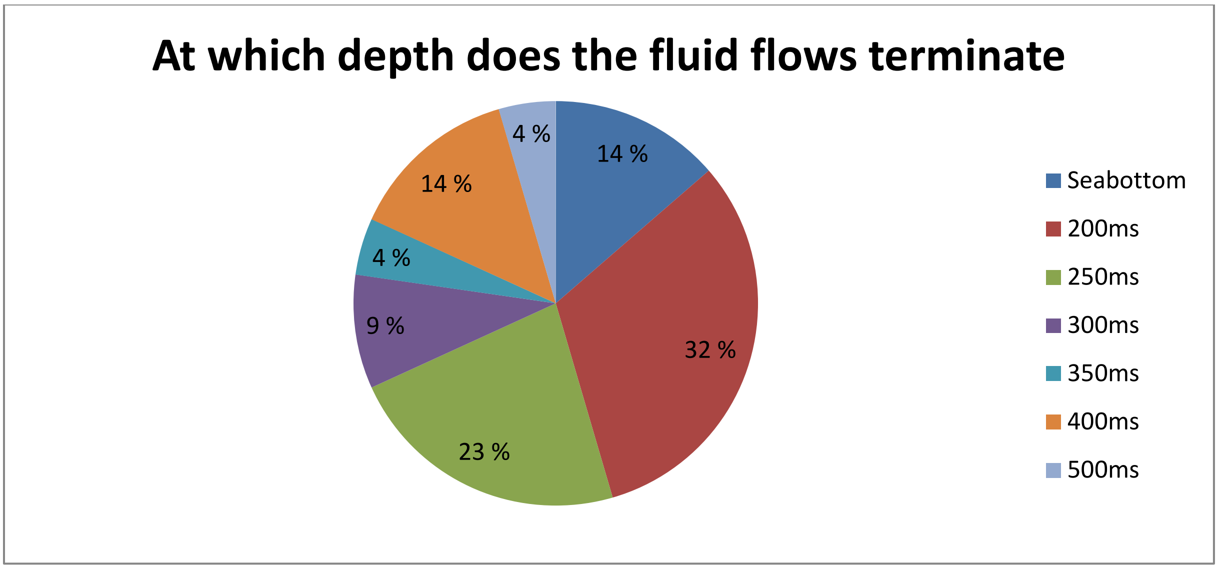
The situation where a seismic wave passes through a rock which has lower velocity than the underlying rock, but hydrocarbons have made the underlying rocks' layer velocity higher, can cause a polarity reversal. An example of this might be seen in illustration 4.29. It can be interpreted that the reflector at around 280ms represents a change in seismic velocity, since more of these polarity reversals very similar to the one in illustration 4.29 can be spotted around the cube. Due to the poor resolution of the shallow seismic it is difficult to say for certain.

Regarding the actual origin of the fluid flows it is difficult to establish for certain due to the reflectivity of fluids as we move through fluid saturated layers. The seismic wave will lose intensity and strength, making the deeper reflections less reliable. Especially when obscured by high anomalies in more shallow layers. Graph 2 shows the statistics from the data set, where 59% of the fluid flows seem to originate from the top Pliocene layer, and 36% seem to originate from base Utsira. This is an even distribution, considering the total number of fluid flows (32). The 5% from top Utsira probably can be considered erroneous. It is unlikely that the fluid flows originate from the top of the Utsira layer due to the nature of the unit, which we know from chapter 2.1 is mainly sorted sands. It is likely that the observed fluid flows from that layer in fact are "artefacts", from the overlying structures which cause distortions in the reflections deeper than what exists in reality.

Graph 3 shows the distribution of where the fluid flows terminate. Over half of the fluid flows seem to terminate in the interval 200-250ms, indicating a potential sealing unit in this area of the intra quarternary-unit.



Graph 2 – At which depth do the fluid flows seem to originate.



Graph 3 – Percentage of the total fluid flows which reach the different depths of the data set. Note that "seafloor" is used as a collection term for all fluid flows which reach depths above 200ms, due to the quality of the seismic it is hard to determine if they actually reach the seafloor or not.

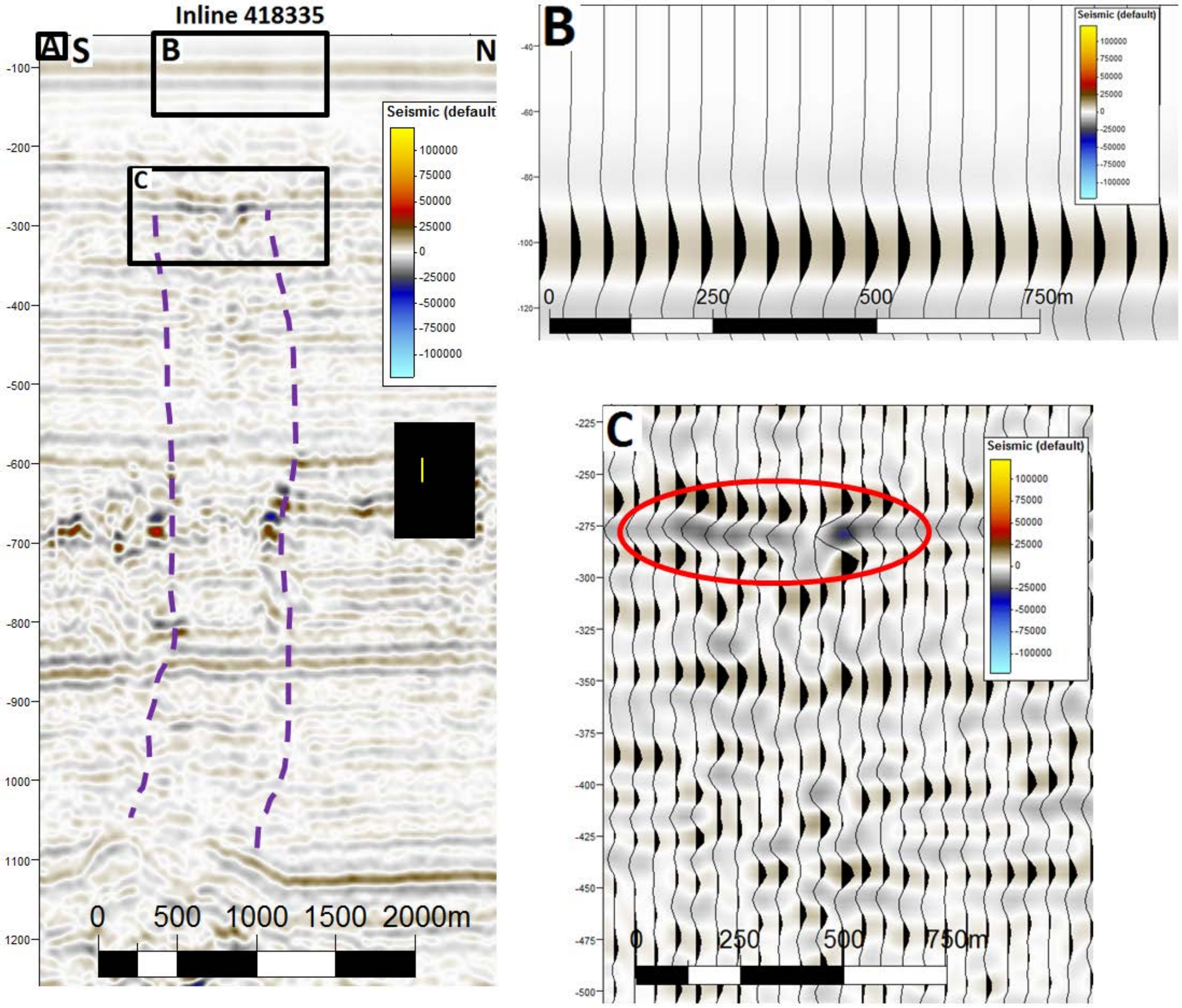


Illustration 4.29 - Possible polarity reversal. A: Overview of whole fluid flow structure, B: Closeup of seafloor with wiggles C: Closeup of bright spot with possible reversed polarity.

5. Discussion

Fluid flows have been interpreted across the overburden of the seismic cube. The general geological setting, the control of the fluid flows, their possible origins and the distribution of these will be discussed in the following.

5.1 Geological influence on flow

The data set has a clear set of geological units, as interpreted in chapter 4. From the interpretation it can be debated whether the different units each pose a role in the overall look at how the fluid flows move through the cube or not. The Utsira unit has a clear set of boundaries, where the "Base Utsira"-horizon with its mud diapirs seem to have contributed to the expulsion of fluids into the cube at some point in time. The "Top Utsira"-horizon has depressional features which is thought to act as traps and lead the fluid flows away from the source. The Pliocene-unit is dominated by high amplitude anomalies, thought to be of both glacial influence and gas accumulations. The Pliocene-unit seems to have clear sealing properties, and the lower layers of the Pliocene unit is defined as the actual seal of the CO_2-storage complex at Sleipner in literature (Chadwick et. al., 2002 and Zweigel et. al. 2004).

If fluids migrate into the Pliocene unit, the unit might pose as a temporary reservoir for the fluids in the fluid flows, as moraine material often is synonymous with high porosity (Andreassen, et. al. 2007b). This highly porous material can also potentially make amplitude anomalies due to the high seismic velocity the lithologies provide (Holloway et. al., 2000), but the appearance of features on and close to the “intra Pliocene”-horizon confirms the presence of glacial activity in the area at some point in the past. On the "Intra Pliocene"-horizon possible pockmarks can be seen in relation to the glacial plough marks (see illustration 4.10). This can indicate that when the icebergs scoured into the seafloor at that time, there was a sudden release of gas which was close to the surface. Presence of pockmarks in connection with glacial activity has been discussed in detail before (Andreassen et. al 2007b), and the similarity between illustration 4.10 and 5.1 leads to a strong belief of a similar event taking place in our study area. As the pockmarks were buried and the once active fluid flows into the pockmarks died out, the pockmarks could pose and can still presently pose as a weak spot in a layer. These could then be reactivated again during potential fluid flows later, acting as migration pathways.

The overburden mainly consists of the Quarternary deposits which overlies the Pliocene unit and reaches the seafloor. The sediments are dominated by regular medium-strength reflection patterns, interrupted in the interval between 200-500ms by U/V-shaped features. These were interpreted as channel systems, predominantly flowing E-W. Meandering channels are typically linked to deltaic sequences, with good porosity due to sorted sediments (Bjørlykke, 2010). See illustration 5.2. It seems that the fluid flows stop their vertical extent when hitting these channel-features, possibly due to a change from vertical to horizontal flow because of the good porosity, permeability and/or other characteristics in the channel sediments. In some of the seismic sections one can observe high amplitude anomalies within the channel cross section. This can indicate gas accumulation within the channels, due to stratigraphic entrapment (Bjørlykke, 2010).

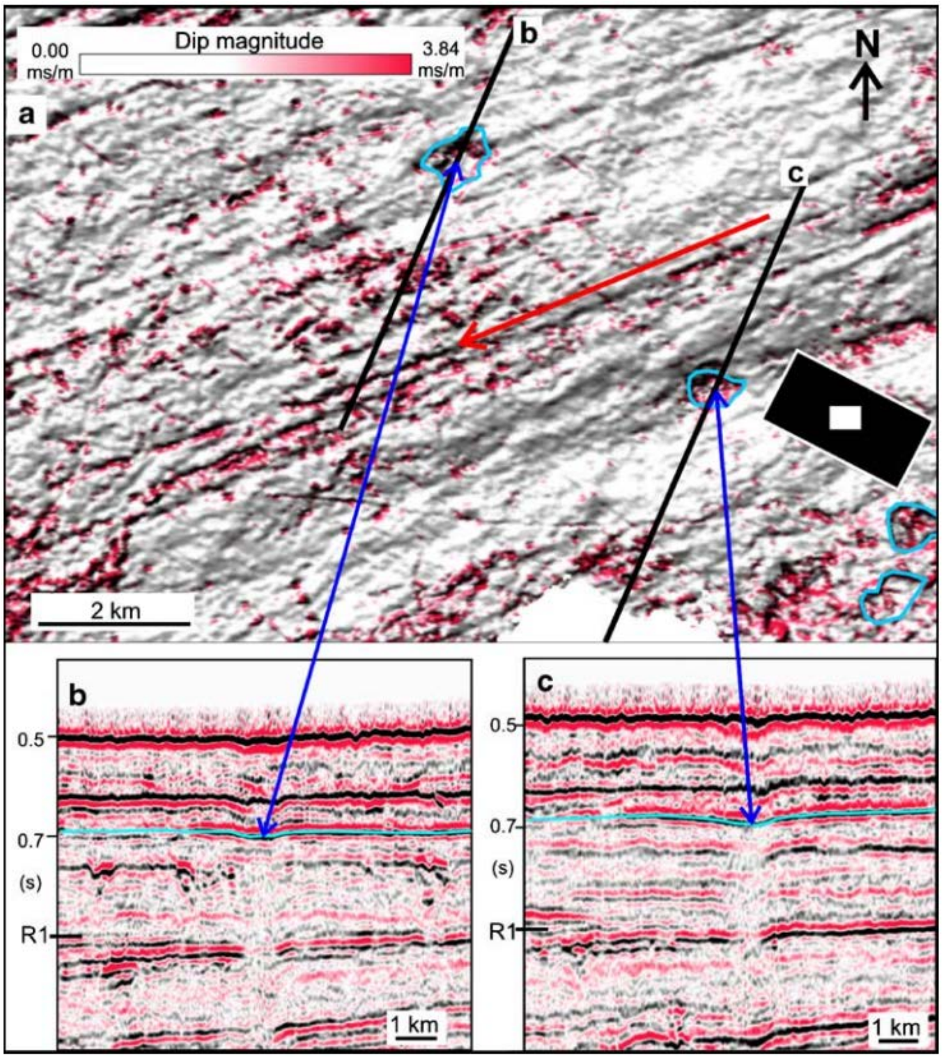


Illustration 5.1 – a) dip map of a horizon showing MGSL (mega scale glacial lineations) b) & c) Seismic cross sections of pockmarks as defined by Andreassen et. al. 2007b, found on a horizon which bear signs MGSL.

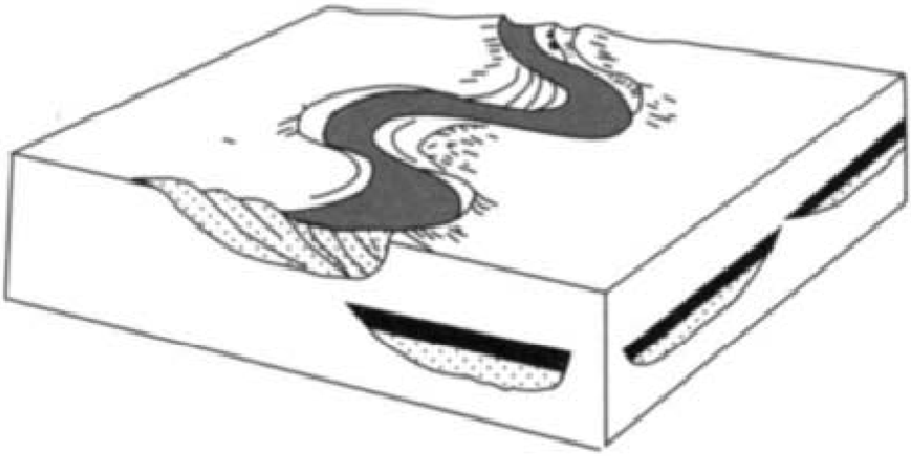


Illustration 5.2 – Visualization of channel deposits, from Petroleum geoscience (Gluyas & Swarbrick, 2004)

5.2 Flow of fluid through overburden

A total of 32 fluid flows were observed on the data set, but the possibility of faint fluid flows being missed is present. Due to the quality of the data set, the data was put through a structural smoothing before interpretation. This structural smoothing might have contributed to making very faint and/or diffuse fluid flows even more diffuse, or even removing them all together, as the smoothing is defined as removing noise and extreme peaks (Schlumberger, 2011).

Of the 32 fluid flows, over half of these - 55% - reach the interval between 250ms to 200ms, as we can see on graph 3 (p.55). There is a clear tendency of high amplitude anomalies in this region, as well as there being signs of channels in this exact interval. At around 200ms, there is a reflector of high continuity and strong amplitude. There are few signs of fluid flows reaching any more shallow depths – except for the ones possibly disturbing the seafloor – therefore the "intra Quarternary"-horizon was defined just above this majority of high amplitude anomalies. Another natural thought occurring when realizing that almost no fluid flows reach higher, is that the "Intra Quarternary"-horizon might acts as a seal for the fluid flows reaching this level. Another feature that supports this theory is the fluid flows which act like "flares", as seen in illustration 4.23 (p.47). These fluid flows are expanding upwards until reaching a level of around 300ms, where they flat out in-between 300ms and 200ms. The upwards expansion can represent an upwards increase in horizontal permeability, so the fluids spread horizontally as well as vertically. This increase in permeability might be due to the sedimentary composition, or due to the fact that the closer you move to the seafloor in the subsurface, the less weight lie on the layers and the less dense the layers are. The latter theory should give the same appearance on all fluid flows, which is not the case and therefore probably rules out this theory. It is more likely that it is a localized area of sedimentary rocks which has the prerequisites for horizontal flow as well as vertical flow. There could also be a possibility that the flare-like appearance comes from a high release of fluid into the fluid conduit, being stopped at the potential seal at 200ms, forcing the fluid to extent laterally.

When observing fluid flows, faults are often closely related to the structures. In many cases they can directly contribute to the fluid flows (Løseth et al, 2009). For this data set, there are few signs of any faulting. The fluid flows seem to pass through layers by diffusion or micro fractures, as there are few visible faults of the seismic sections both directly connected to the fluid flows and in general. One possible fault can be seen on illustration 4.23 (p.55, fault indicated in yellow), where it seems to be a disruption in the "Top Pliocene"-horizon. This disruption is seen in direct connection with the wiped out areas interpreted as a fluid flow, which would lead to the conclusion that the fluid flow passes through the otherwise strong continuous reflector by the crack in the reflector.

All of these things points to the main factor controlling the movement through the units are the stratigraphy and the composition of the sediments - and not faulting.

Because of the seismic resolution, the seafloor has not been interpreted. Low frequency seismic provides good resolution in the deeper areas, but provides poor seismic resolution in the shallow parts (Andreassen, 2009). Multi-beam data or high frequency seismic to map the seafloor is suggested for better control of the extent of the fluid flows above 200ms. The entire cube suffers effects from the poor resolution, and it is evident already on the more shallow interpreted horizons that we have noise, artifacts from the acquisition and mismatched/missing lines probably caused by the stitching of three seismic cubes (see illustration 4.7, 4.9, 4.11 pages 31-35 for examples of noise and artefacts due to the stitching of the seismic).

Despite the seismic resolution, we have possible indications of fluid flows reaching the seafloor in some areas. Some are more obvious than others, and while we only have about 4-5 cases of clear seafloor disturbances such as the one in illustrations 4.24 and 4.25 (p.48-49), the potential for more is of course there. Pockmarks and actual seeps into the water column would indicate that the fluid flows has breached the seafloor (Løseth et. al., 2009), at a point in time. The examples seen in the data set matches some of the typical indications of pockmarks, but the overall information is too poor in quality to interpret something definite. Therefore it can be stated that it is probable you could find pockmarks in the area, which is supported by the little that is mentioned in literature on the theme (global CCS institute, 2013).

5.3 Distribution of fluid flows

The fluid flows appear across the entire cube, but has a slight trend of clustering in the southwestern area. About 60% of the fluid flows are located in the lower left quadrant of the cube, as can be seen in illustration 4.28 (p.53). An isochron time thickness map of the Pliocene unit might shed some light on the trend, as we already have established it seems the Pliocene unit acts as an intermediate seal. A thickness map of this unit is seen in illustration 4.27 (p.52). This "sealing unit" has a clear thinning to the south-west, as observed on the figure. A difference of 160ms roughly calculated to be 320meters thickness difference using a seismic velocity of 2000m/s. This thinning might contribute to easier passage through the "seal", as less resistance often equals higher fluid flows (Bjørlykke, 2010). It can therefore be determined that the thickness of the sealing-unit and the distribution of fluid flows probably is related to each other.

The Pliocene unit has been interpreted as highly influenced by glacial erosion, with possible glacial moraines, plough-marks as well as potential pockmarks. These interpreted structures can pose as conduits for fluids, even as temporary reservoirs, as glacial material have good porosity and permeability (Andreassen et. al., 2007b). The "upper Pliocene"-unit shows clear signs of high amplitude anomalies, as we see in illustration 4.16A (p.39), indicating that there indeed is trapped fluids within this unit. Therefore the Pliocene unit seems to pose as a permanent or temporary seal for any fluid flow coming from beneath it and trying to pass it. It also seems like the glacial features contribute to the actual migration pathways through the unit, iceberg scouring might at one point have put pressure on the sediments causing sudden surges of release of gas in the sediments, causing pockmarks.

Another way to understand the distribution of the fluid flows is to correlate them with the "Base Utsira"-horizon, as we know from chapter 4.2. Mud diapirism has been identified as a possible contributor to fluid expulsion from this horizon in the past. A question which quickly comes into mind is: are the fluid flows spotted in the overburden directly connected with these mud diapirs? The topographic map known from illustration 4.4 (p.28) is used as a base, while an identically scaled outline of the occurrence of fluid flows across the study area is overlain this map. The result is seen in illustration 4.28 (p.53). Here we can see a slight correspondence between the topographic highs, interpreted as mud diapirs, and the white circles, marking what is interpreted as fluid flows. There are no areas of the data set where the correlation is better than other areas, which can be interpreted as a sign that the fluid flows are not wholly dependent on interpreted mud diapirs to appear on the data set. The ones that do match a positive feature on the "Base Utsira"-topography map might be connected to the proposed expulsion of fluids from the mud diapirs, but the rather low correlation percentage could just as well be coincidences. A slight offset between the white circles and the interpreted mud diapirs can be seen in some instances - this can be a result of the fluid flows not migrating directly vertical through the layers, but also flowing horizontally. As mentioned in chapter 4.7.1 we have channels with good permeability which can contribute to such horizontal flow. From graph 1 (p.51) we can see that 30% of the fluid flows observed, tend to end in these channel structures. Why the fluid flows seek out these structures is uncertain, but it can be debated whether some of these fluid flows interpreted really are fluid flows. Some of them might just be artifacts from the high amplitude anomalies within the channels, but the location of the fluid flows in the actual cube should be within medium to good resolution range.

5.4 Origin of the fluid flows

The actual origin of the fluid flows is difficult to determine due to the effect of acoustic masking (Løseth et al. 2009), nevertheless the following discussion is based on observing acoustic masking as deep as it goes and relating it to a logical surface. Statistics done on all the interpreted fluid flows show that the observable origin of the fluid flows is predominately from the "Top Pliocene"-horizon, closely followed by the "Base Utsira"-horizon. This can be seen in graph 2 (p.63).

One of the already discussed origins of the fluid flows is the mud diapirism which has been interpreted on the "Base Utsira" horizon. The correlation done in illustration 4.28 (p.61) is vague, but there are definite indications that some of the fluid flows have their origin from a depth of 1200ms TWT. This can especially be seen on illustration 4.20 and 4.21, where acoustic masking is seen rising from an interpreted mud diapir, passing through the Pliocene unit before passing through the upper overburden and a bright spot at around 200-300ms TWT.

From the interpreted features and what can be observed, the most likely scenario is something like the following. Mud diapirism lead to fluid expulsion from the underlying layers during the late Oligocene, but the diapirs collapsed as the Utsira sands were deposited over them. The fluids remaining in the Utsira reservoir migrated upwards, reaching the Pliocene unit (defined as the middle seal from Chadwick et. al., 2004) where the fluid has a temporary accumulation before it seeps out into the overburden as defined as what is above “Top Pliocene”-horizon in this thesis.

From chapter 4.8 and our statistics on graph 2 (p.55) we can see that a substantial amount of the fluid flows seem to originate from the “Base Utsira”-horizon at the time the seismic was shot. But the fact that the Sleipner reservoir has an effective overlying seal which has been proven safe enough to store CO_2 in the Utsira sands (Chadwick et. al., 2004) makes the connection between fluid seepage from “base Utsira”-horizon to the overburden in the present time unlikely. The actual injection point of the Sleipner facility is shown in illustration 5.3 (p.62), but the seal has been tested across its extent, 50km west and 40km east beyond the Sleipner facility injection point (Chadwick et. al., 2000b). It could be that there still are fluids seeping out of the collapsed mud diapirs, but the acoustic masking and features in the seismic indicating seepage might just as well be extended shadows from the fluid flows within the Pliocene unit.

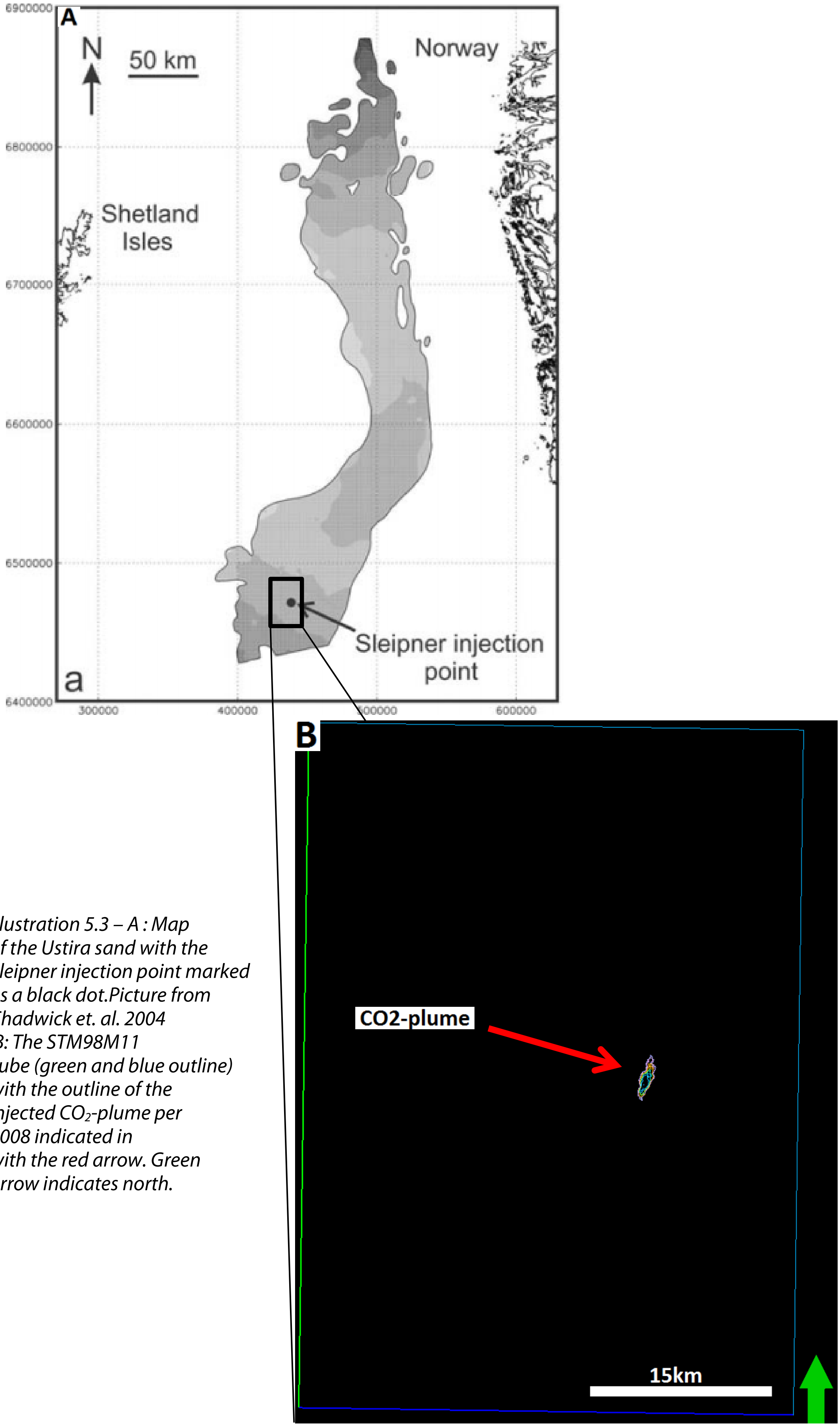


Illustration 5.3 – A : Map of the Ustira sand with the Sleipner injection point marked as a black dot.Picture from Chadwick et. al. 2004
B: The STM98M11 cube (green and blue outline) with the outline of the injected CO_2-plume per 2008 indicated in with the red arrow. Green arrow indicates north.

6. Summary & Conclusion

The seismic dataset ST98M11 with some stitched data from ST98M3 has been mapped and interpreted using Petrel software, for signs of structures indicating fluid flow.

- 32 occurrences of vertical features were identified and interpreted as fluid flows across the cube.
- It is believed that there are more features, which could be detected using seismic data better tuned for shallow areas.
- The majority of these fluid flows are found to appear in the south western corner of the data set.
- The occurrence and location of the fluid flows seem to be influenced by some degree by the Pliocene unit, and especially its thickness.
- It is difficult to determine the distribution of the fluid flows in the shallower parts of the cube due to the vertical seismic resolution.
- Channels in the upper part of the cube might contribute to horizontal flow in the data set.
- The origin of the fluids seem linked with mud diapirism found on the “Base Utsira”-horizon.
- The Pliocene unit might act as a temporary accumulation area for fluids leaked from the mud diapirs in the past, seeping into the overburden in present time.
- Multibeam bathymetry data might be useful for further research, to determine possible gas seepage from the seafloor.

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