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# Mapping of shallow Tunnel Valleys combining 2D and 3D Seismic Data

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## Abstract

In this study 19 tunnel valleys within block 2/4 in the central North Sea basin have been mapped. Furthermore, the possibility for these valleys to act as migration paths for leaked gas has been evaluated. In January 1989 a kick occurred while drilling well 2/4-14 in the area of study, hence the pertinence of evaluating this hypothesis at this locality is evident. The work has been performed using multichannel 2D lines and a conventional 3D seismic survey. The quality of the 2D and 3D data is clearly dissimilar at shallow burial depths, as the 2D data is considered to be high-resolution while the 3D data is low-resolution. However, both data sets have proved to give valuable information on the valley morphology. Great details about the extent and basal morphology have been retrieved from the conventional 3D volume; whereas seismic characteristics of the valley infill have been interpreted from the 2D lines.

Tunnel valleys are major, elongated incisions carved into sediments or permeable bedrock during glaciations. They tend to be sinuous in planform, but might also appear as straight valleys. Tunnel valleys often consist of several cut- and fill-structures, both laterally and vertically, and thus form a network of interconnected valleys. This has also been observed in the area of study. No sedimentological logs have been available in the study. Hence, the interpretations of valley fill lithologies are based on the seismic characteristics, and thereby they are quite cautious. The typical fill sequence observed correlates fairly good with similar valleys mapped in the area previously. A lower part of chaotic reflectors, believed to be glaciofluvial sands and gravels, is overlain by sub-horizontal layers of glaciomarine mud. Moreover, velocity pull-up effects are seen in the underburden of some of the valleys. These indicate relatively high velocities of the infill sediments, and hence, it is likely to be clayey tills. Even so, the possibility of gas migration within the tunnel valley system is believed to be conspicuous.

# Sammendrag

I denne studien har 19 tunneldaler i blokk 2/4 i den sentrale delen av Nordsjøen blitt kartlagt. Videre har muligheten for at disse dalene kan fungere som migrasjonsveier for gass blitt evaluert. I januar 1989 fant en gassutblåsning sted under boringen av brønn 2/4-14 i området som her er studert. Det er derfor meget relevant å evaluere muligheten for gasstrømning gjennom tunneldaler i dette området. I arbeidet utført under denne studien er seksten seismiske flerkanals 2D linjer og en konvensjonell seismisk 3D-kube benyttet. Ettersom 2D dataene betraktes å være av høy oppløsning ved grunne begravingsdyp mens 3D-data er av lav oppløsning, anses kvaliteten av 2D og 3D dataene å være tydelig ulik. Imidlertid har begge datasettene vist seg å gi verdifull informasjon om dalenes morfologi. Detaljer om dalenes omfang og basalmorfologi har blitt hentet fra 3D kuben, mens de seismiske egenskapene til sedimentfyllet i dalene har blitt karakterisert fra 2D linjene.

Tunnedaler er vide, langstrakte depresjoner gravd ut i ukonsoliderte sedimenter eller permeable grunnsteiner av smeltevannsstrømmer under istider. De er ofte meandrerende i planform, men kan også opptre som rette daler. Tunneldaler består gjerne av flere utgravnings og innfyllings strukturer, både lateralt og vertikalt, og kan dermed danne et nettverk av sammenhengende daler. Et slikt nettverk har også blitt observert i området denne studien tar for seg. Grunnet at ingen sedimentologiske logger har vært tilgjengelig under studien har tolkninger av dalenes fyll lithologier blitt basert på de observerte seismiske egenskapene. Tolkningene er dermed rimelig forsiktige. Den typiske fyllsekvensen som er funnet korrelerer relativt godt med lignende daler kartlagt i Nordsjøen tidligere. Denne består av en nedre del med kaotiske reflektorer som antas å være glasifluvial sand og grus, dekket av en øvre del karakterisert av sub-horisontale reflektorer som antas å være glasimarin leire. Videre er hastighets «pull-up effekter» sett i kontinuerlige reflektorer under noen av dalene. Disse indikerer fyllsedimenter med relativt høye seismiske hastigheter, og det er dermed trolig at dette kan være leirig-till. Selv om disse sedimentene trolig har begrenset porøsitet og permeabilitet anses muligheten for at deler av nettverket funger som migrasjonsveier for gass påfallende.

# Contents

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Last but not least I am very grateful for the support, smiles and laughter of my fellow students, friends and family. I appreciate you.

Hanne Sundgot Halvorsen

27.05.2012

# 1 Introduction

The study site of this thesis covers an area of 1080km$^2$ in the central North Sea near the boundary between the Norwegian sector and both the Danish and British sectors, marked by a yellow star in figure 1. The North Sea has several times during Quaternary age been partly or fully covered with ice sheets from the Scandinavian and Scottish highlands (Lonergan et al., 2006). The erosion caused by movement of the ice sheets and meltwater flow during glaciations, and associated periods of growth and retreats of the ice sheets, have left several macro-scale features in bedrocks and sediments. Bennett and Glasser (2009) mention five different features: i) regions of areal scour, ii) throughs, iii) cirques, iv) giant stoss and lee forms and v) tunnel valleys.

Tunnel valleys are elongated depressions with some overdeepened areas along their floor cut into unconsolidated sediments or permeable bedrocks (Bennett and Glasser, 2009). The exact genesis of the tunnel valleys regarding the impacts of pressure, drainage, steady-state groundwater flow and catastrophic meltwater discharge is not yet fully agreed upon (Kehew et al., 2012). However, the valleys are generally considered to be products of subglacial meltwater erosion. Further, numerical modeling has indicated that tunnel valleys played an important role in drainage of the ice sheets, and hence, stability maintenance of the ice caps during glaciations (Kehew et al., 2012). The several periods of glaciation have resulted in multiple generations of tunnel valleys in the North Sea (Ehlers et al., 1984; Ehlers and Wingfield, 1991 as cited in Praeg, 2003).

Many studies have been made during the last decades in order to map and further understand the formation of the tunnel valleys. Ô Cofaigh (1996) defined and grouped the genetic of tunnel valleys into three general categories; this has recently been evaluated and further reviewed by Kehew et al. (2012). Jørgensen and Sandersen (2006), Kristensen et al. (2007) and Lonergan et al. (2006) and others have studied onshore and offshore tunnel valleys in different areas close to or within the North Sea basin. Huuse and Lykke-Andersen(2000) complied a map giving an overview of the interpreted Quaternary tunnel valleys in Northwest Europe (figure 1). This overview shows that in the Norwegian sector of the North Sea the distribution of tunnel valleys has been poorly constrained.

Clark et al. (2010) tried to date and constrain the pattern of the ice sheet covering the Scottish highlands and the North Sea basin during the last glacial maximum. The largest uncertainties were related to the ice cover retreat and break up in the North Sea. To improve constrains of the glacial stratigraphy of the area, it is crucial to develop good maps of the tunnel valley distribution and morphology. They can provide information which can be used to delineate ice marginal positions, and further, as evidence for hitherto unknown glacial activity during Pleistocene glaciations (Kehew et al., 2012).

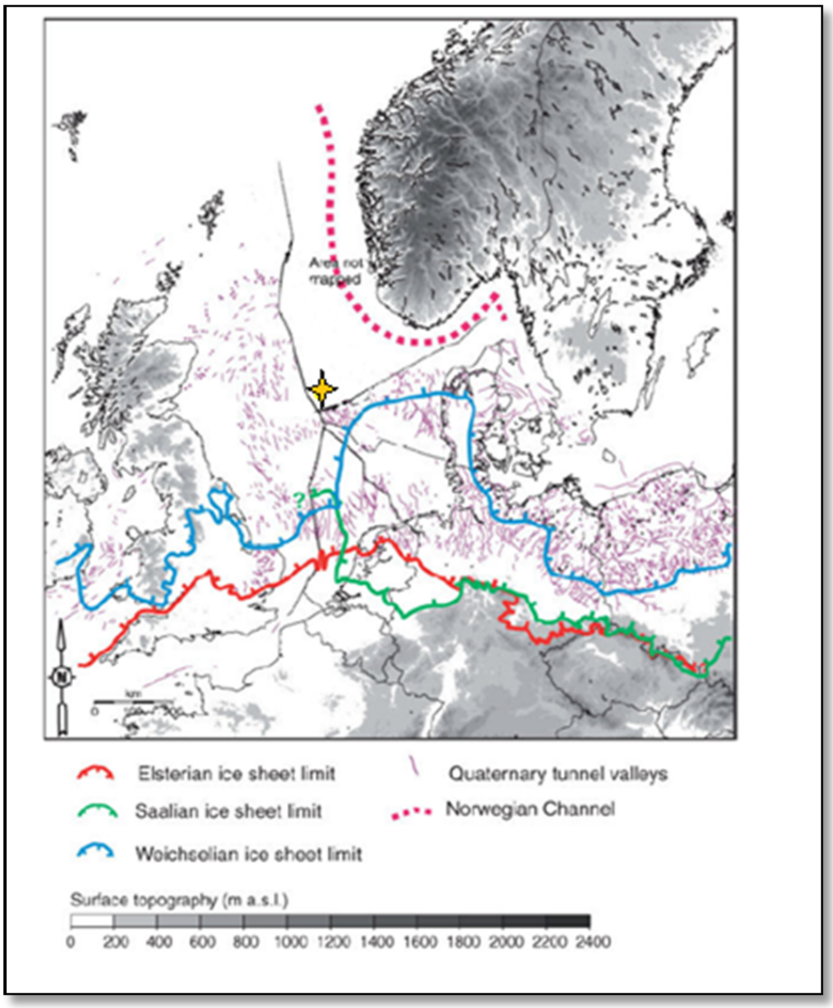


**Figure 1: Map showing the location of the study site in the North Sea, marked by the yellow star. One can see that Quaternary tunnel valleys have been mapped more severely on both UK and Danish sides of the borders in the North Sea (marked by purple lines). The assumed margins of the last glaciations in the North Sea are marked by red, green and blue lines (after Huuse and Lykke-Andersen, 2000).**

In January 1989 Saga Petroleum experienced a kick when drilling well 2/4-14, which resulted in an underground blowout. There are clear indications in seismic data of where some of the gas has migrated; however, the gas may spread in great distances from the well if there are high permeable pathways present. Tunnel valleys and other macro-scale glacial features which may have course grained and porous infill might act as such flow channels. If so, it can be important to map these systems when evaluating migration paths for leaked hydrocarbons from producing reservoirs, but also when considering future storage of environmental gases.

In this thesis a conventional multichannel 3D seismic cube, as well as multichannel seismic 2D lines have been utilized to map and evaluate tunnel valleys. Praeg (2003) compared the obtainable information from different seismic reflection imagery (high frequency vs. low frequency and 2D vs. 3D) of tunnel valleys in the North Sea and concluded that low-frequency content in the shallow succession not necessarily is a limiting factor. The possibility to use 3D seismic data with dense line spacing of typically 12.5 to 25m, in addition to high resolution 2D lines leads to a better understanding of the morphology.

In this paper the differences in quality and information provided from the dissimilar seismic data will be evaluated, overview maps of the tunnel valleys at the study site in the central North Sea will be presented, and finally, the infill stratigraphy and further the potential for hydrocarbon migration through these valleys will be discussed.

# 2 Geology

## 2.1 Study area setting

The study area is located at approximately 57°N 3°E in the central North Sea basin. In this thesis only the shallow parts within the upper 1km of the subsurface is examined. This sequence in the North Sea is considered to be within the Nordland Group of Middle Miocene to Recent age.

The Nordland Group is dominated by claystones deposited in open marine environment. The lower part incorporates sandstone considered to be the Utsira Formation, and the upper part of the group consists of unconsolidated clay and sand, with occasionally larger ice rafted debris. Further, the glacial deposits tend to increase in the uppermost part of the group (NPD fact-pages[1]; NORLEX).

### 2.1.1 Gas blowout Saga well, well 2/4-14

In October 1988 the drilling, performed by Saga Petroleum ASA, of exploration well 2/4-14 within the study area started. The main purpose was to assess the hydrocarbon potential of anticipated Late Jurassic Sandstone in block 2/4 (NPD fact-pages[2]). However, during the operation in January 1989 they experienced well control problems at a depth of 4734mRKB, and a kick occurred. The well flowed approximately 1 minute before being shut in by the fail-safe valves (Leraand et al., 1992). Several unsuccessful attempts to regain control of the well were made before the well was shut on January 20, 1989(NPD fact-pages[2]). The well developed into an underground blowout well though no hydrocarbons were discharged into the sea (NPD fact-pages[2]; Aadnoy and Bakoy, 1992). The spreading of some of the leaked gas is clearly indicated on seismic sections by bright amplitudes seen in figure2.

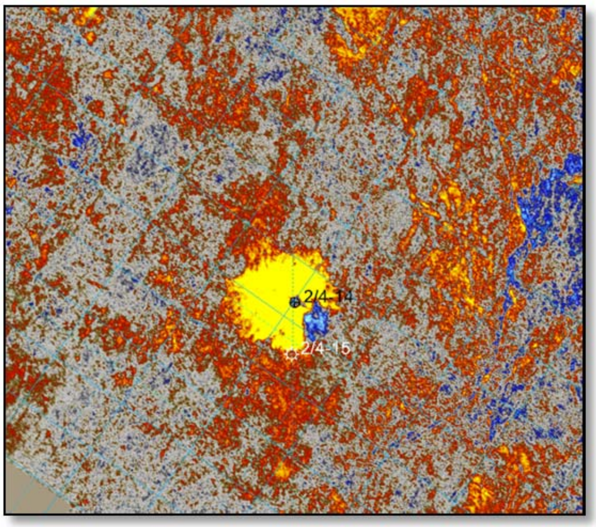


**Figure 2: The image is showing a part of the time slice at 540ms TWT. Bright amplitudes caused by the gas spreading from well 2/4-14 can be seen(yellow). The gas is visible approximately 1300m in radial distance from the well on this section.**

## 2.2 North Sea tunnel valleys

### 2.2.1 Tunnel Valley genesis

Tunnel valleys or major incisions are elongated depressions cutting into permeable bedrocks or underlying unconsolidated sediments, with some overdeepend areas along the valley floor (Bennett and Glasser, 2009). They are commonly sinuous in planform, and might form anostomosing patterns build up by coeval valleys; however, they can also exist as straight isolated valleys (Bennett and Galsser, 2009; Ô Cofaigh, 1996). In greater detail the morphology of the valleys is generally characterized by steep-dipping sides and highly irregular floors creating several sub-basins along the valley (Bennett and Glasser, 2009; Kristensen et al., 2008). The valleys are filled with a variety of sediments including gravity flows and thick units of glaciofluvial sands (Bennett and Glasser, 2009).

There are a number of theories about the formation of the tunnel valleys (e.g., Huuse and Lykke-Andersen, 2000; Ô Cofaigh, 1996; Kristensen et al., 2008; Kehew et al., 2012). However, nearly all theories are related to the valleys being formed during glacial or inter-glacial cycles as a product of glacial drainage. Kehew et al. (2012) mention that a common hydrologic system, whose dynamics are controlled by glaciological and hydrogeological parameters, will be created under warm-based ice sheets as meltwater interacts with groundwater. Thus, the parameters controlling the flow and thereby the valley formation can be complex and hard to determine.

The study area in the North Sea was mid-latitude, low-relief during the last glaciations. In areas where the terrain is flat it is unlikely that large subglacial-lakes were present for long periods. Hence, in order to prevent large-scale surge, and in time total ice sheet collapse, the ice sheets probably switched to an efficient drainage mode by opening great subglacial channels which eroded the bed; hence, tunnel valleys were formed(Kehew et al. 2012).

Clayton et al. (1999, as cited in Kehew, et al. 2012) distinguished between the terms “tunnel channels” and “tunnel valleys”, as tunnel channels being formed by short periods of catastrophic meltwater release, and tunnel valleys being formed by more steady state flows of smaller depths and widths than the valleys. Since improved understanding of the origin of the valleys is not the main purpose of this thesis, but rather to examine the power of using 3D multichannel data in combination with 2D data when mapping the valleys, and further, the likelihood of hydrocarbon migrating through these structures, it will not be distinguished between “tunnel channels” and “tunnel valleys” in this paper.

### 2.2.2 Quaternary glacial history of the North Sea basin

As tunnel valleys are formed during glaciations and inter-glaciations, the movement and retreat of the ice sheets can be important when interpreting glacial marks. Three episodes of regional glaciation has been recognized in the Middel- and Upper Pleistocene sediments in the North Sea basin; the Elsterian, Saalian and Weichselian glaciation(e.g. Cameron et al., 1987; Kristensen et al. 2007, Wingfield, 1989). Last global glacial maximum is defined as occurring about 21ka BP, during the Weichselian glaciation, as large areas in the upper part of northern hemisphere were covered by ice sheets (Clark et al., 2010). Further, in this period of glaciation the British-Irish and Fennoscandian ice sheets, which were covering large areas in the North Sea, coalesced and experienced its maximum 28ka -22ka BP (figure 3)(Sejrup et al., 1994; Sejrup et al., 2000; Clark et al., 2010).

Clark et al. (2010) tried to constrain dating and pattern of the Britsh-Irish ice-sheet and presented two different scenarios regarding the breakup of the North Sea ice cover. It is uncertain if the break up was a catastrophic event or a more measured reduction. In one of the scenarios they hypothesized that as the ice elevations lowered during deglaciation water from ice-dammed lakes may have penetrated beneath the ice (figure 3), causing a collapse of the "ice bridge" between Norway and Britain by creating subglacial valleys. Whingfield (1990) among others suggests that some of the tunnel valley in the North Sea can be the erosional record of such event.

### 2.2.3 Dimensions and fill stratigraphy

The dimensions of previous mapped tunnel valleys vary somewhat. However, work done by Jørgensen and Sandersen (2006) of open and buried tunnel valleys in Denmark showed that the typical widths of the tunnel valleys were between 500 and 1500m, and further, the typical depths fell between 20 and 200m. Nevertheless, the maximum widths and depths observed were significantly higher. Cameron et al. (1987) describes the youngest system of buried valleys to be widespread across the central North Sea area, with some of the valleys having an erosional base reaching a depth of about 150m below present day sea level.

The infill and thus the seismic character of the reflectors, within the tunnel valleys can vary somewhat, but it is mainly dominated by sediments deposited during gravity flow or glaciofluvial sands (Ô Cofaigh, 1996). The typical sequence for Quaternary valleys found in the North Sea is a lower part of chaotic, disrupted seismic facies followed by well- layered seismic facies (Huuse and Lykke-Andersen, 2000).The sequence may be comparable to sedimentary infill of Elsterian valleys onshore northern Europe, which commonly consists of glaciofluvial sand and silt, followed by glaciolacustrine or -marine silt and clay, capped with thin interglacial deposits (Huuse and Lykke-Andersen, 2000).

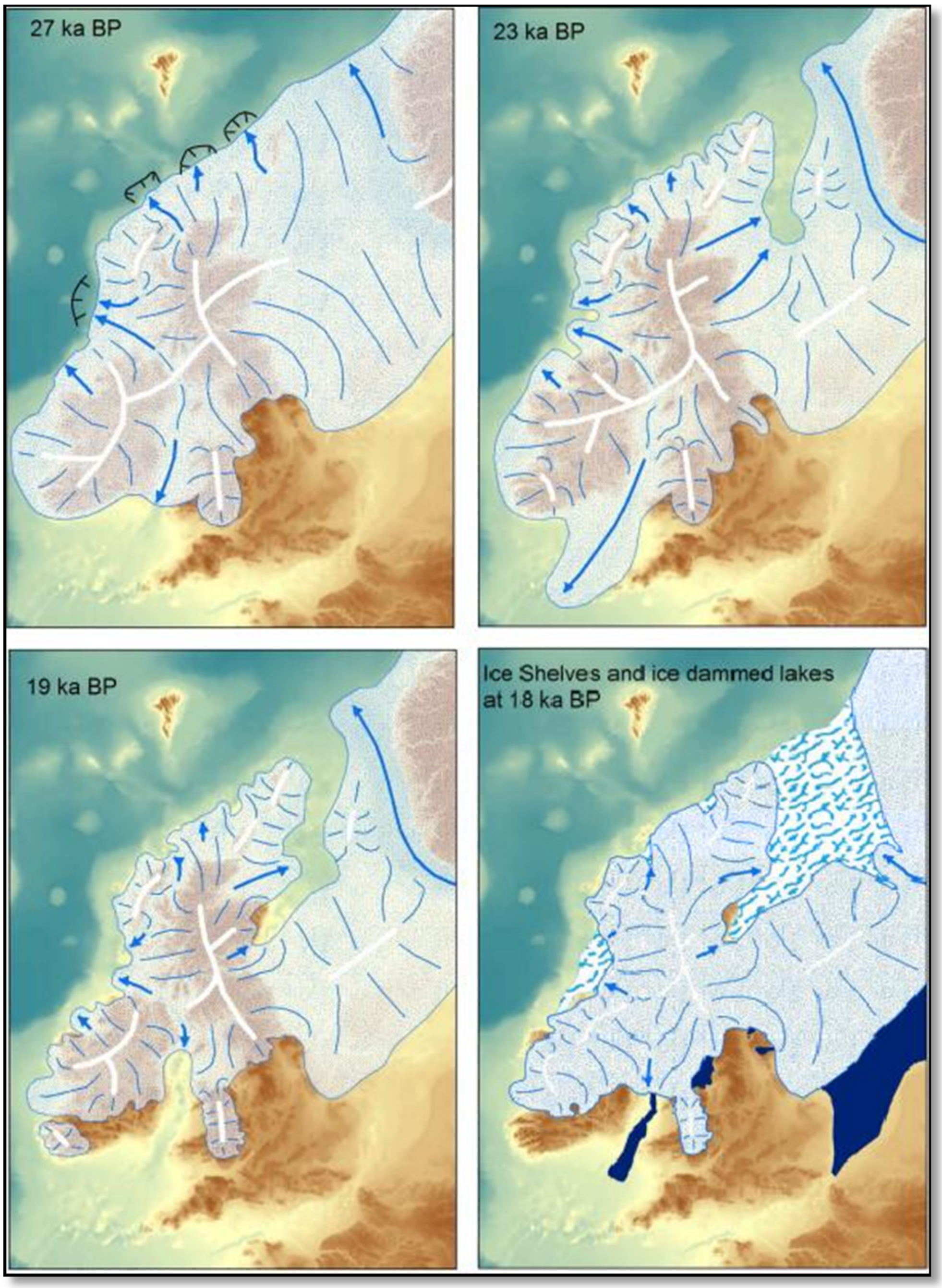


**Figure 3: Reconstruction of the immense British-Irish ice sheet and the North Sea ice cover. Ice (white), ice streams (blue arrows) and sheet flow geometry (thin blue lines) are indicated. At 18ka BP the ice dammed lakes which might lead to water flows beneath the ice cover are indicated (Clark et al. 2010).**

# 3 Seismic data

For this thesis a conventional multichannel 3D seismic cube and sixteen multichannel 2D seismic lines have been evaluated. The quality of the seismic data is significantly dissimilar resulting from the different acquisition parameters and processing flows. It is only the shallow reflection data that has been regarded, meaning the data within the first 500ms TWT.

## 3.1 Shallow seismic data

### 3.1.1 Recorded seismic reflections

When a seismic survey is performed a seismic wavelet is emitted from a source. The wavelet travels through the subsurface and at interfaces some of the energy from the wavelet will be reflected and recorded by the receivers. Hence, the recorded seismic trace(*y*) represents a convolution (*) of the outgoing wavelet(*s*) with the Earth impulse response(r), and additional noise (*n*) (Yilmaz, 2001)

$$y(t) = s(t) * r(t) + n(t)$$

where *t* represents time. Noise is all the unwanted recorded signals. It can appear random and completely unpredictable (e.g. wind motion or cable vibrations) or coherent and predictable from one detector to another (e.g. multiples) (Parasnis, 1997). Random noise will have a white spectrum, containing all frequencies. In a multichannel survey this noise can be significantly reduced through deconvolution, filtering and migration during the signal processing (Yilmaz, 1987 as cited in Praeg, 2003). However, coherent noise, like multiples, is rather difficult to remove completely. Multiples refer to energy that has been reflected more than once in its ray path (Yilmaz, 2001). The most significant multiples in a marine survey are largely caused by the seabed and water surface reflections (Parasnins, 1997).

The traces recorded in a multichannel acquisition will have increasing offset (i.e. source-receiver distance) about a series of common mid-points (CMPs) (figure 4a and 4b). Traces included in each CMP-gather will be transformed into zero-offset traces, through normal moveout (NMO) correction, before they are summed into one single trace (figure 4c and 4d). This stacking of the traces leads to reinforcement of primary reflections and destructive interference of noise, hence, an improved signal to noise ratio (Praeg, 2003). Further, as an undesirable consequence of NMO-correction the traces will be stretched in a time-varying manner causing a shift to the lower end of the frequency spectra. This shift increases with offset and at shallow times. Hence, to avoid degradation of the stacks in the shallow parts a mute is applied to zero-out these events (Yilmaz, 2001). The resulting decrease in data fold upwards in the CMP-gathers will be significant (figure 5); thereby upper parts of the data might appear as single channel data of rather poor quality (Praeg, 2003).

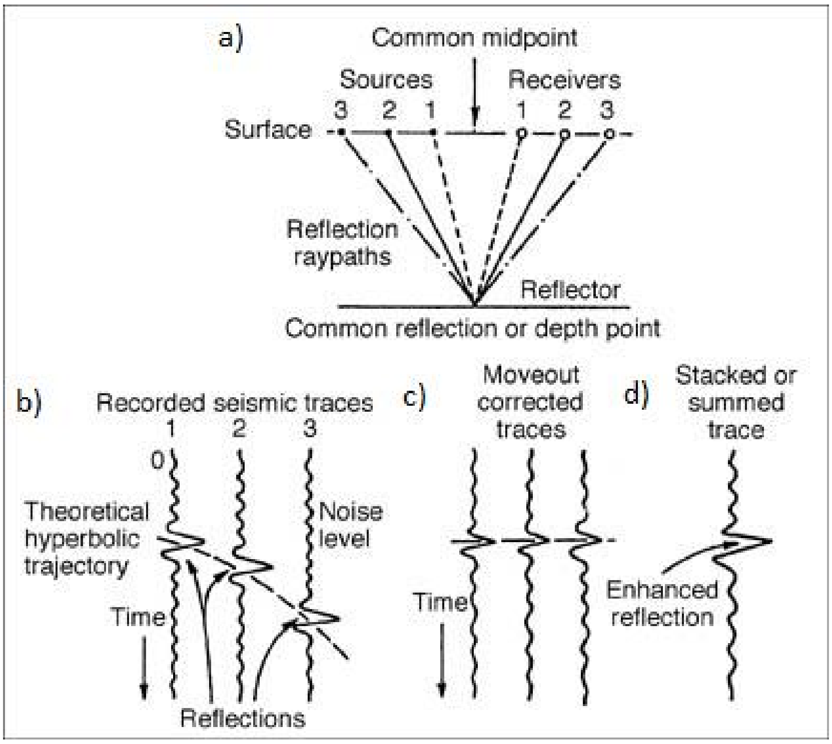


**Figure 4: a) Conceptual sketch of the common midpoint model. All traces recorded from one position in the ground are gathered. b) increasing offset will make the reflected signal appear hyperbolic in the tracegather before normal moveout correction and c) how the traces appear after . Finally, d) presents the enhanced signal after summing the traces in the gather (Schlumberger glossary).**

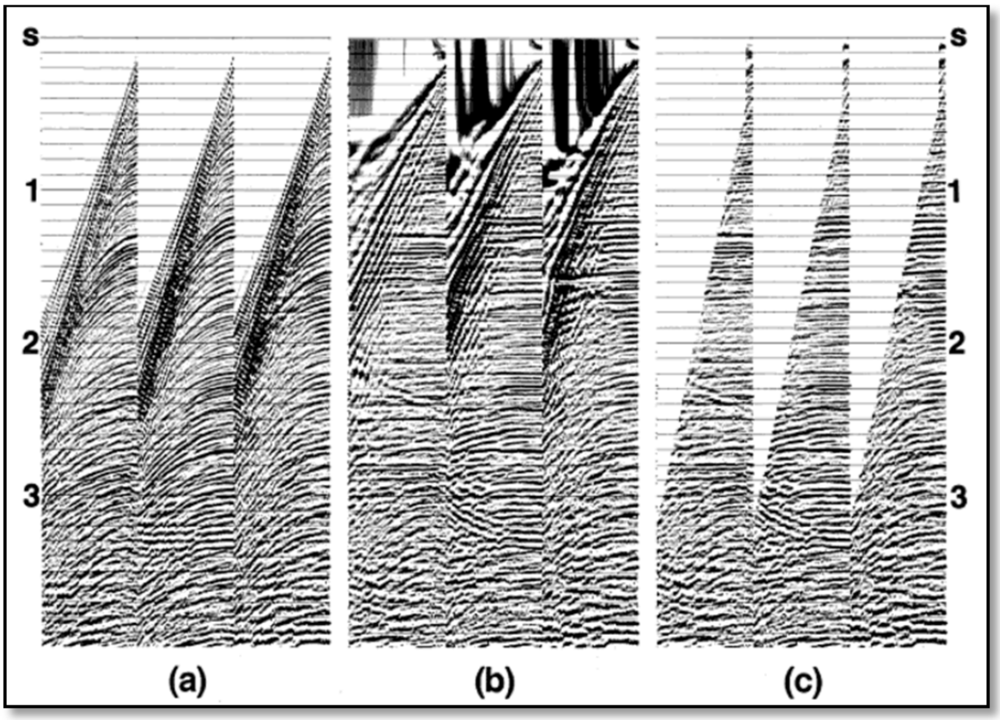


**Figure 5: Image showing how NMO stretching and mute can appear in field data; (a) CMP gathers, (b) NMO correction with stretched zones in the shallow sequence, (c) muted NMO corrected gathers (Yilmaz, 2001).**

### 3.1.2 Seismic resolution and migration

Seismic resolution determines the ability to distinguish between features on a seismic section; in other words, resolution is the minimum possible distance between two interfaces without destructive interference of the reflected signals occurring (Sheriff, 1989). Both lateral and vertical resolution is controlled by the frequency content of the signal. When mentioning resolution in relation to seismic one mainly considers the vertical resolution, however, the horizontal and spatial is just as important when interpreting subsurface morphology.

#### *3.1.2.1 Vertical resolution*

According to Rayleigh's resolution limit the vertical layer thickness needs to be one fourth of the wavelength for the layer to appear in a seismic image.

The dominant wavelength ($\lambda$) of a seismic wave is given by:

$$\lambda = V/f$$

where f is the dominant frequency and *V* is the interval velocity of the target layer (Avseth et al., 2005), indicating that a higher dominant frequency causes a decrease in wavelength, and hence, the resolution will increase(figure 6a). As a consequence of attenuation in energy as the wave propagates in depth the frequency content will decrease. Moreover, high frequencies are generally more attenuated than low frequencies, thus, the dominant frequency will decrease with depth, and thereby, deep events need a greater thickness to be imaged.

Another important reason why high dominant frequencies are seldom applied is the use of multichannel data and stacking. The minor time shifts between the reflected pulses of the different traces in a gather may correspond to appreciable fractions of a cycle causing out-of-phase addition for high frequency components, however, only pose minor effects on low frequency components (Sheriff, 1989).

#### *3.1.2.2 Horisontal resolution*

The reflected energy of a wave is returned from a region and not one single point, thereby, lateral resolution is an important issue in seismic imaging. The horizontal resolution of unmigrated seismic data is given by the Fresnel zone as a circle of radius, R, around a reflection point, insonified by the first quarter of the wavelength ($\lambda$):

$$R = \sqrt{\lambda z/2}$$

(Avseth et al., 2005). The equation indicates that the zone of reflection generally increases with depth (*z*) and consequently the horizontal resolution will decrease (Yilmaz, 2001) (figure6b). If a structure is smaller than the Fresnel zone it will have the response of a diffraction point (Avseth et al., 2005). Migration seeks to collapse diffractions and decrease the Fresnel zone, thus, the lateral resolution will be improved (Yilmaz, 2001). However, migration will only decrease the extent of the Fresnel zone in the direction of the migration (figure 6c), so if the migration is performed only on the inlines, the resolution will still be limited by the Fresnel zone in crossline direction (Avseth et al., 2005). Further, migration displacement decrease with proximity to the source, and thus, have the least effect on the shallow section, where the velocity field derived from NMO-correction will be poorly constrained (Praeg, 2003).

Lateral resolution also depends on the sampling interval in terms of line spacing and following bin-size in a seismic dataset (figure 6d). However, this is not the limiting factor for typical surface seismic wavelengths (~50-100m) (Avseth et al., 2005). Spatial resolution and, thereby, also the understanding of lateral shape and extent of geologic structures, is vastly improved by the use of 3D seismic data and, hence, the possibility of utilizing time-slices during interpretation.

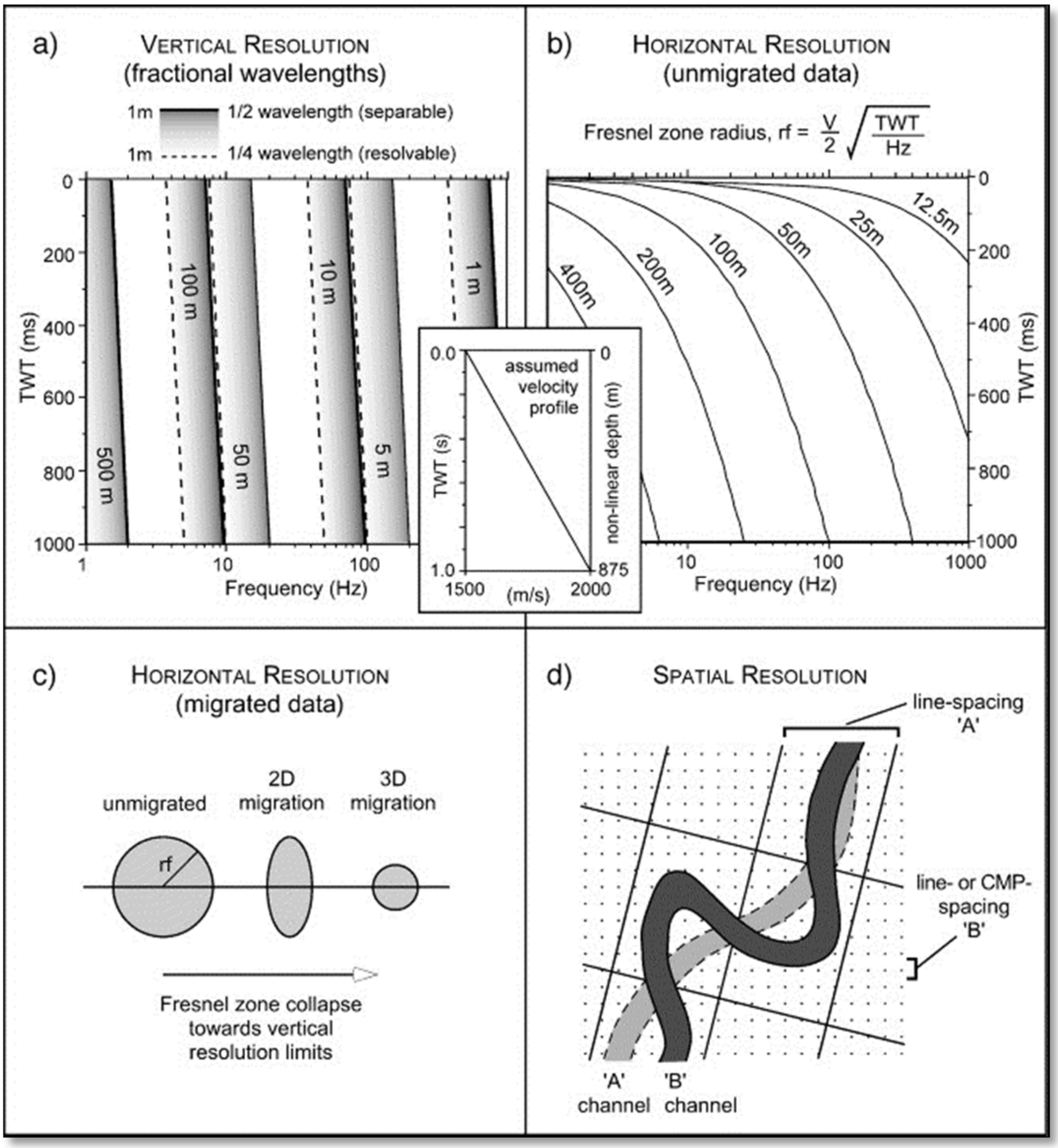


**Figure 6: Images showing different measures of seismic resolution. 3a) vertical thickness needed for a layer to be visible at given TWT for frequencies 1-1000Hz. 3b) horizontal resolution given in terms of TWT and frequency. In both a) and b) the decrease in resolution with depth due to earth filtering is neglected. 3c) the Fresnel zone collapse in response to 2D and 3D migration and 3d) spatial resolution in relation to line spacing and structure geometry. The resolution improves with closer line spacing (Praeg, 2003).**

## 3.2 Available data

None of the seismic data provided for this study are acquired with the aim of studying the shallow parts of the overburden where the Pleistocene tunnel valleys are present. The main quality difference between the 2D and 3D seismic data results from the dissimilar acquisition geometry. The 3D data has a significant lower vertical resolution in the upper parts compared to high frequency 2D data, due to the large offset from the source to the first receiver. Neither acquisition parameters nor processing flows are optimized for imaging the shallow section.

### 3.2.2 3D seismic data, SG9111

The 3D seismic data applied in this thesis covers an area of 1082.5 $km^2$ in the central North Sea (figure 7). The cube was recorded by Geco-Prakla AS for Saga/Phillips in 1991 with a shot point interval of 25m and 12.5 meters between the receivers, with a total of 272 receivers per streamer. Further, the sampling interval was of 2ms, and the total recording time 7000ms. The seismic has been migrated during the processing flow.

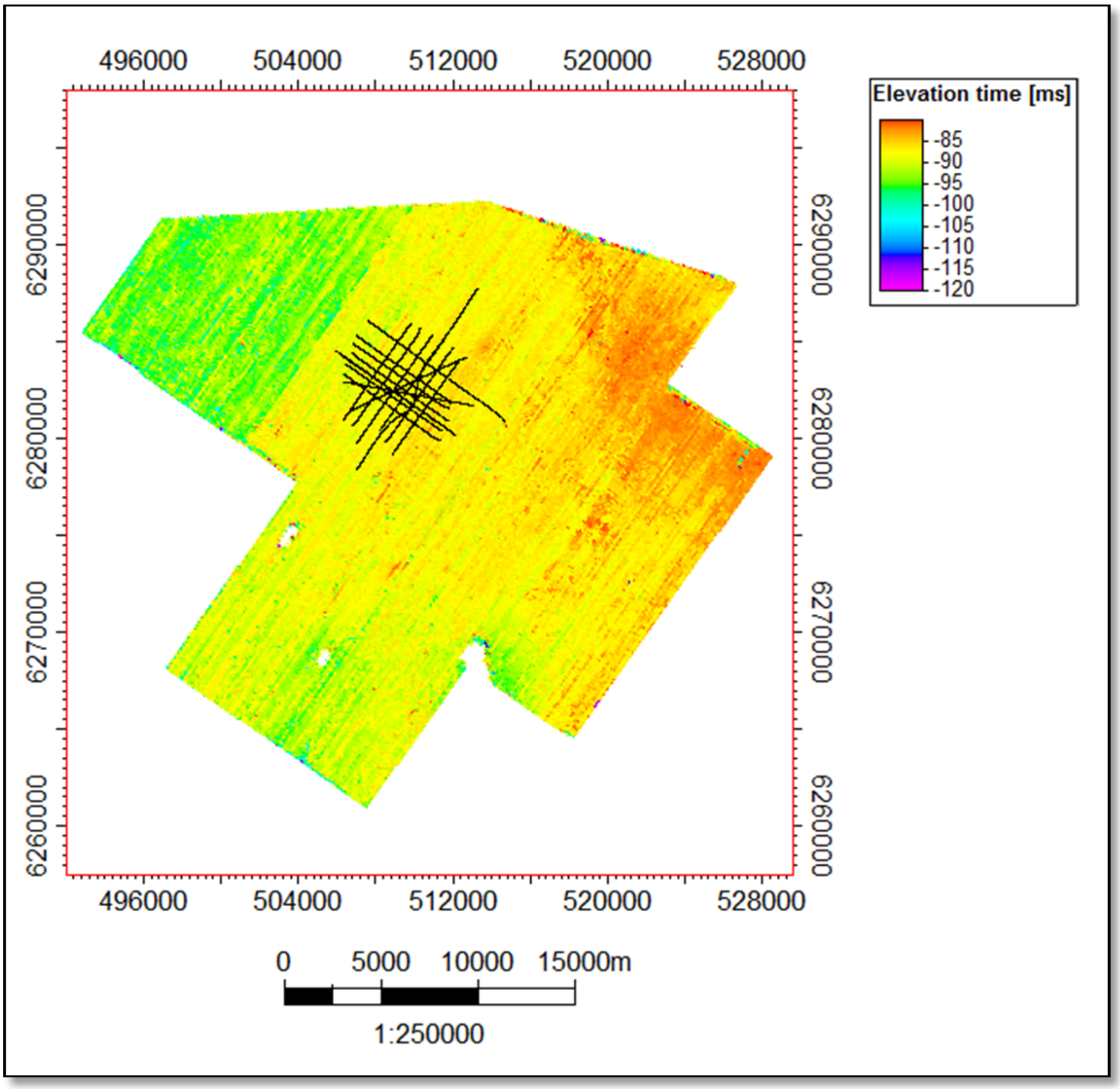


**Figure 7: The outline of the 3D seismic volume and the location of the 2D lines. The surface shown is the seabed. The shot direction of the seismic survey is evident NE-SW.**

The data set was acquired and processed with the objective of imaging deeper layers and possible reservoirs. Thereby, the distance between the source and the first receiver was as high as 121meters. The critical angle between water and seabed sediments in the area will approximately be 50˚. Since the water column at the study site is about 70 meters principally only the first four receivers will record the primary seabed reflection (figure 8). Further, some of the multiples caused by the interfaces at top and base of the water column will have an incident angle smaller than the critical angle which leads to multiple reflections being recorded by a higher number of receivers causing strong amplitudes in the seismic images. The resolution in the shallow parts of the cube is rather poor as well, containing only weak amplitudes due to muting and low frequency content. The frequency spectra form the upper 500ms TWT is shown in figure 9. The frequencies mainly range between 10-70Hz with a peak frequency around 40 Hz.

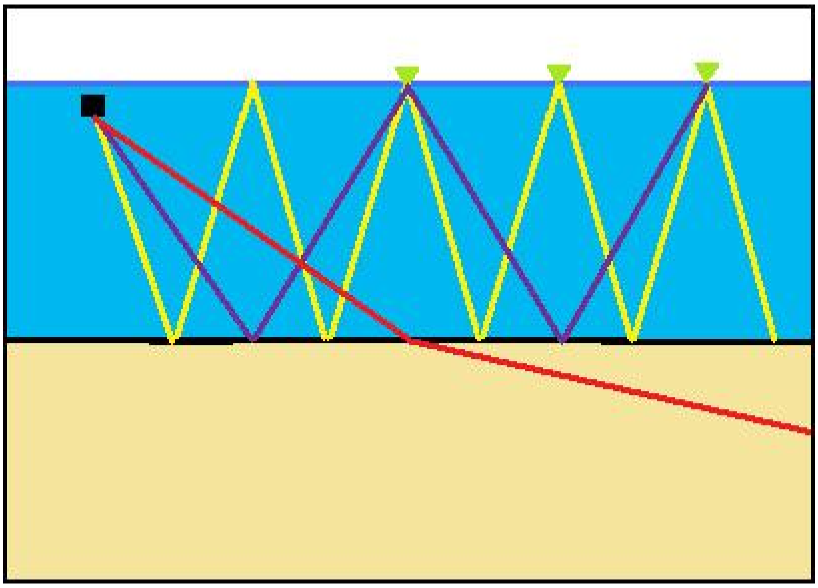

**Figure 8: Conceptual sketch of seabed multiples. Black box represents the source and green triangles represent receivers. The primary reflection of the ray with the lowest incidence angle (yellow) will not be recorded by any receivers. The purple primary signal is recorded by one receiver and the red ray has an incidence angle higher than the critical angle and thereby is refracted.**

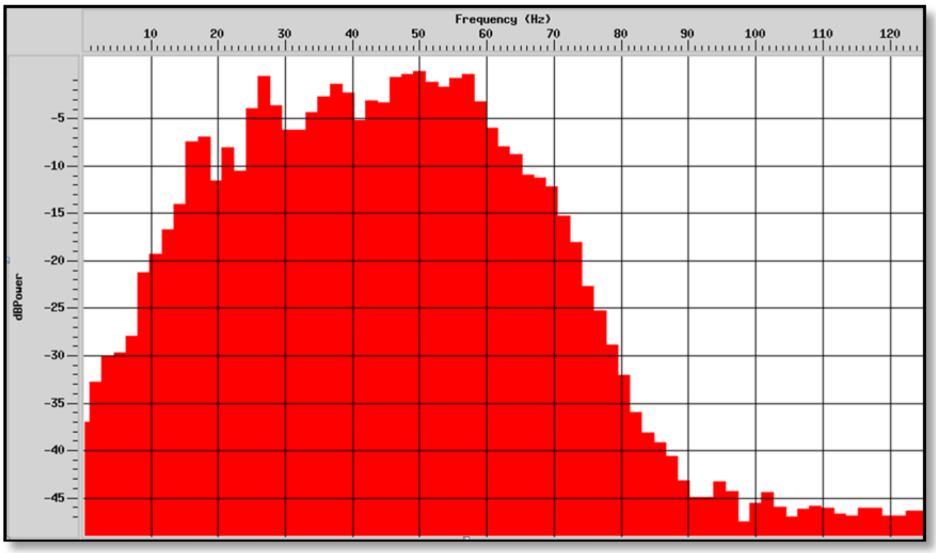


**Figure 9: The frequency spectra from the first 500ms TWT of the 3D volume. The frequencies mainly range between 10 -70 Hz with a peak frequency at about 40 Hz.**

### 3.2.1 2D seismic lines, SG8845, SG8945 and SG9010

The sixteen 2D vertical seismic sections (figure 10) investigated in this study are acquired in 1988, 1989 and 1990 by Racla M/V Bon Espoir for Saga Petroleum A/S. For all acquired profiles a shot point interval of 12.5 m was used and a total of 96 receivers in the 1188m streamer. The distance from the source to first receiver was 41.2m, giving a significantly higher number of receivers recording the primary seabed reflection. Further, a higher number of traces are summed in the shallow sequence resulting in stronger amplitudes.

The sampling interval used in the survey was 1ms with a total record length of 3000ms. Bandwidth applied in the profiles was 10-350 Hz. The data has been NMO corrected, pre-stack muted and deconvolved during processing, however, all but one (SG9010_4602) have not been migrated and diffraction hyperbolas are thereby evident in the sections.

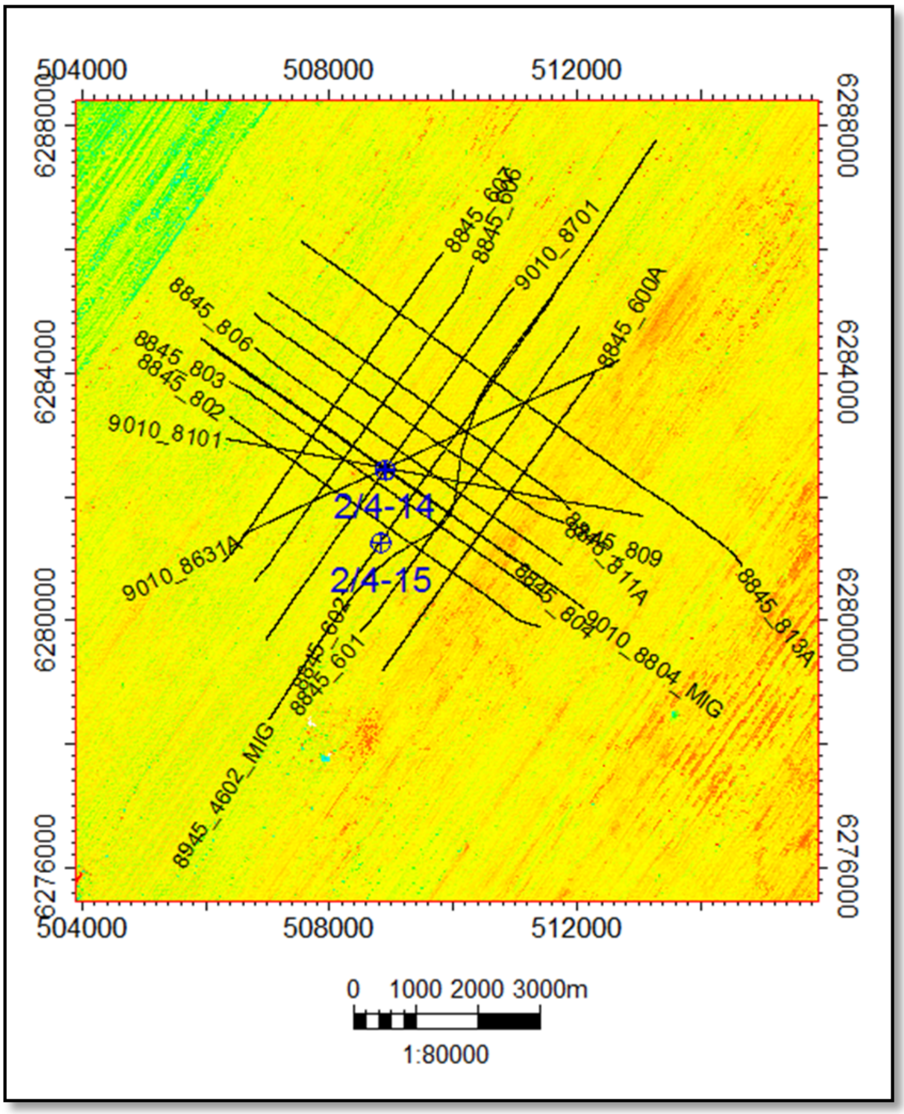


**Figure 10: 2D lines provided for the study. Location of well 2/4-14 and 2/4-15 is indicated. See figure 8 for location in relation to 3D volume.**

# 4 Methods

The seismic interpretation software Petrel 2011.1, developed by Schlumberger, was used when interpreting the tunnel valleys. Mainly the mapping of the tunnel valleys were performed through investigating horizontal slices (figure 11 and figure 13) from the 3D seismic volume in steps of 4ms. In these sections one can see reflectors from thalwegs, onlapping structures truncating the valley sides and the erosional base of the valleys. Thus, the planform morphology of the valleys at the time of the slice can be seen and mapped by polygons.  After the overview maps were constructed they were used as templates for identifying and interpreting the valleys in both 2D and 3D vertical sections. Further, the details and hence information obtainable from the sections were compared.

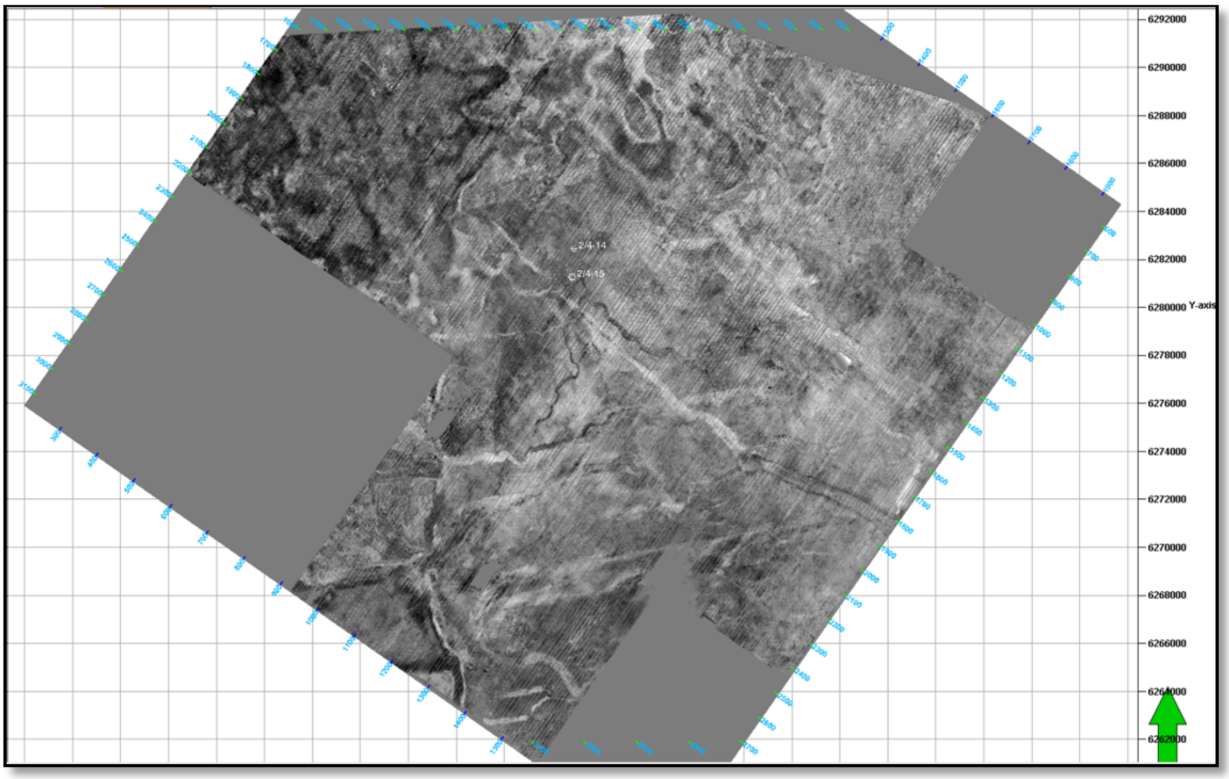


**Figure 11: Time slice at 136ms TWT, amplitude map. Greyscale applied, black negative and white positive. Tunnel valleys are clearly detectable.**

# 5 Results

The mapping of tunnel valleys in time slices has been concentrated on valleys in or close to the area of the 2D lines. Mainly because this is the area where direct comparisons between high- and low-resolution seismic data are possible to make, but also caused by the proximity to well 2/4-14 were the underground gas blowout occurred.

As mentioned the shallow water depths in the area cause strong seabed multiples (figure 12), thus it was decided to split the work of mapping into two main intervals; First interval from the seabed to approximately 180ms, where the first multiple occurs, and second interval the section below the first multiple and down to about 400ms TWT. Hence, in this chapter two overview maps of mapped tunnel valleys will be presented, some vertical profiles for resolution and quality comparison will be shown, and further some interpretations and comments on infill will be listed. The depths presented are approximates calculated using a seismic velocity of 1850m/s based on previous studies (e.g. Lonergan et al. 2006, Huuse and Lykke-Andersen,2000; Kristensen et al., 2008).

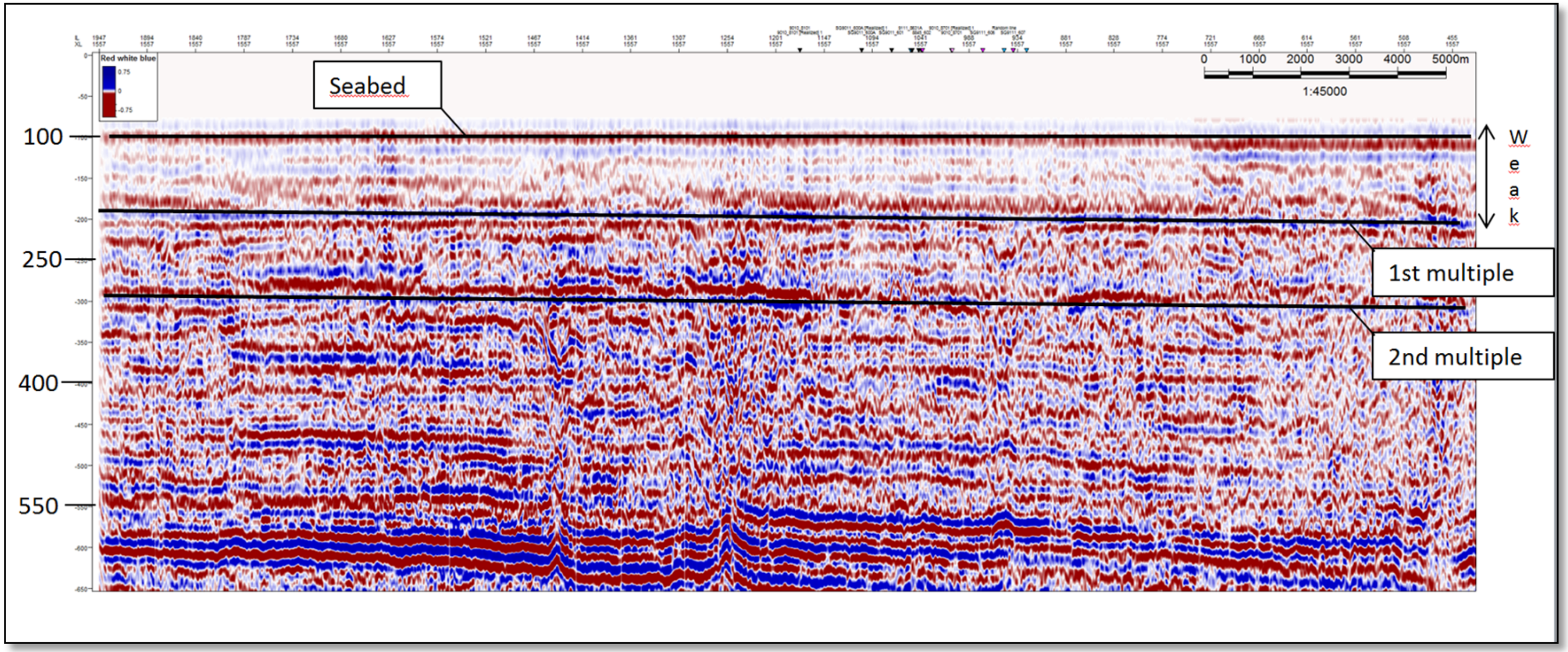


**Figure 12: Crossline 1557 from 3D volume SG9111. One can see the weak amplitudes in the upper layer due muting as well as the strong seabed multiples caused by the seabed and water surface contrasts.**

## 5.1 First interval- Seabed to first seabed multiple (~80-180ms TWT)

As the 3D data of this sequence has a low vertical resolution and very weak amplitudes (figure12) it was nearly impossible to identify any features by just inspecting the vertical seismic sections. The time-slices, however, could provide a good indication of where the buried tunnel valleys are present (figure 13). In figure 14 an overview map of the twelve tunnel valleys mapped in this sequence is presented, followed by the associated morphometric characteristics listed in table 1. Because of the weak amplitudes, and doubtlessly varying and sometimes small contrasts in acoustic impedance in parts of the valleys, the extents of the valleys have been hard to determine. Moreover, two of the valleys are continuing outside the study area; thus, the given lengths and dimensions are the ones observed and mapped within the study area. The first strong seabed multiple is evident at about 180-200ms TWT. The base of some of the valleys coincides or is situated just below or above this multiple in the seismic data causing the measures of valley depths to be uncertain. Generally, the shoulder depths of the valleys are placed about 35m below seafloor.

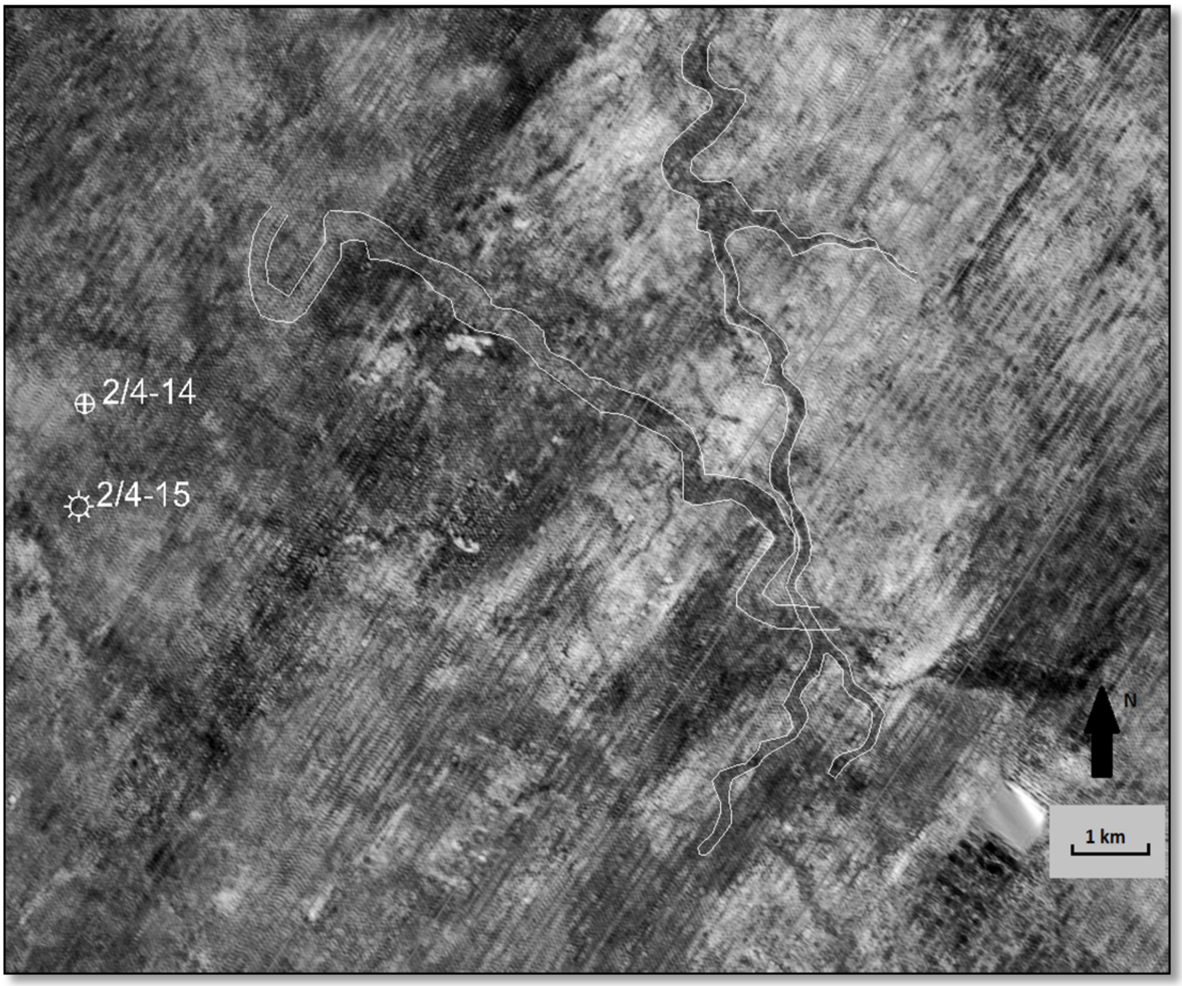


**Figure 13: Time-slice at 176ms TWT showing great details of valleys basal morphology. The shot direction is also evident by lineations (NE-SW).**

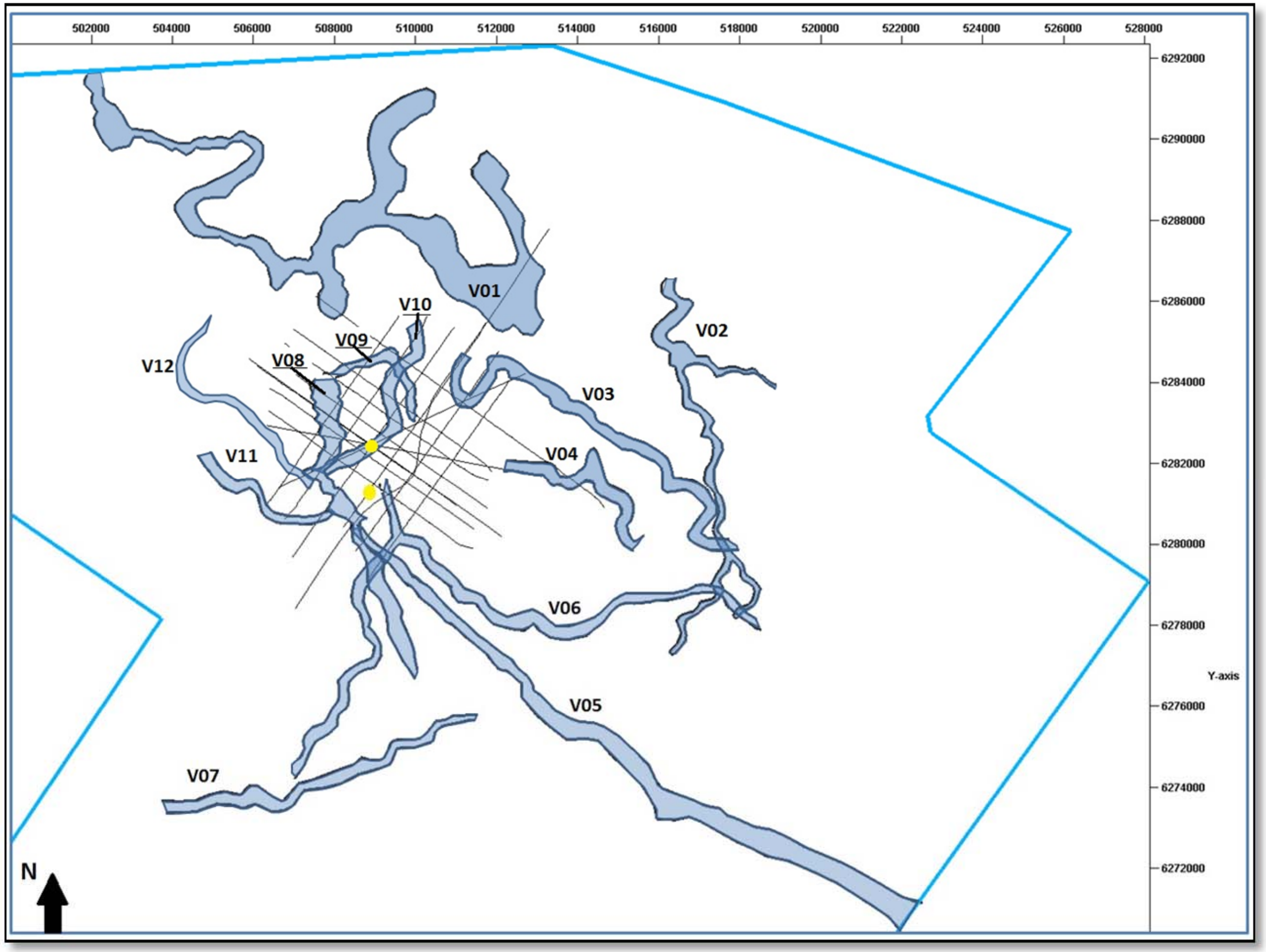


**Figure 14: Overview map of the 12 tunnel valleys mapped in the first interval (~80-180ms TWT). The clear blue line marks the boundary of the seismic 3D cube and black lines the 2D lines available. The yellow dots marks well 2/4-14 and 2/4-15. The numbering will be used for discussing the valleys further. The mapped valleys mainly stretch in NW-SE direction.**

**Table 1**

| Valley | Maximum measured width[km] | Approximate valley depth[m] | Mapped length [km] |
|---|---|---|---|
| **V01** | 2.25 | 82 | 12.7 |
| **V02** | 1.5* | 60* | 9.3 |
| **V03** | 1.3 | 45 | 8.2 |
| **V04** | 0.9 | 70 | 3.8 |
| **V05** | 1.1 | 45 | 16.8 |
| **V06** | 0.8 | 60 | 9.9 |
| **V07** | 1.1* | 105* | 8.1 |
| **V08** | 1.0 | 80 | 7.8 |
| **V09** | 0.9 | 50 | 2.5 |
| **V10** | 0.5 | 40 | 4.3 |
| **V11** | 0.5* | 40 | 3.4 |
| **V12** | 0.5 | 25 | 4.5 |

* Estimated by using vertical sections from the 3D cube, hence, quite uncertain.

## 5.2 Second interval- below first seabed multiple (~180-400ms TWT)

The tunnel valleys mapped in this sequence are generally of far greater size than the ones mapped in the uppermost sequence (figure 18). Although the amplitudes of the valleys are strong, they tend to have very chaotic seismic reflections on vertical profiles (figure 17). Caused by these strong seismic signatures, the shallow water column and large offsets strong multiples of the valleys are visible (figure 15, 16 and 17). The depths of the valleys are hard to determine due to the mulitiples interfering in this sequence as well. However, when using the time slices one can get an impression of where the valley shoulders and base are, and use these for calculating depths. Overall the valley depths and interfering multiples made it practically impossible to identify "new" tunnel valleys below 300ms TWT. The estimated dimensions of the valleys are listed in table 2 below.

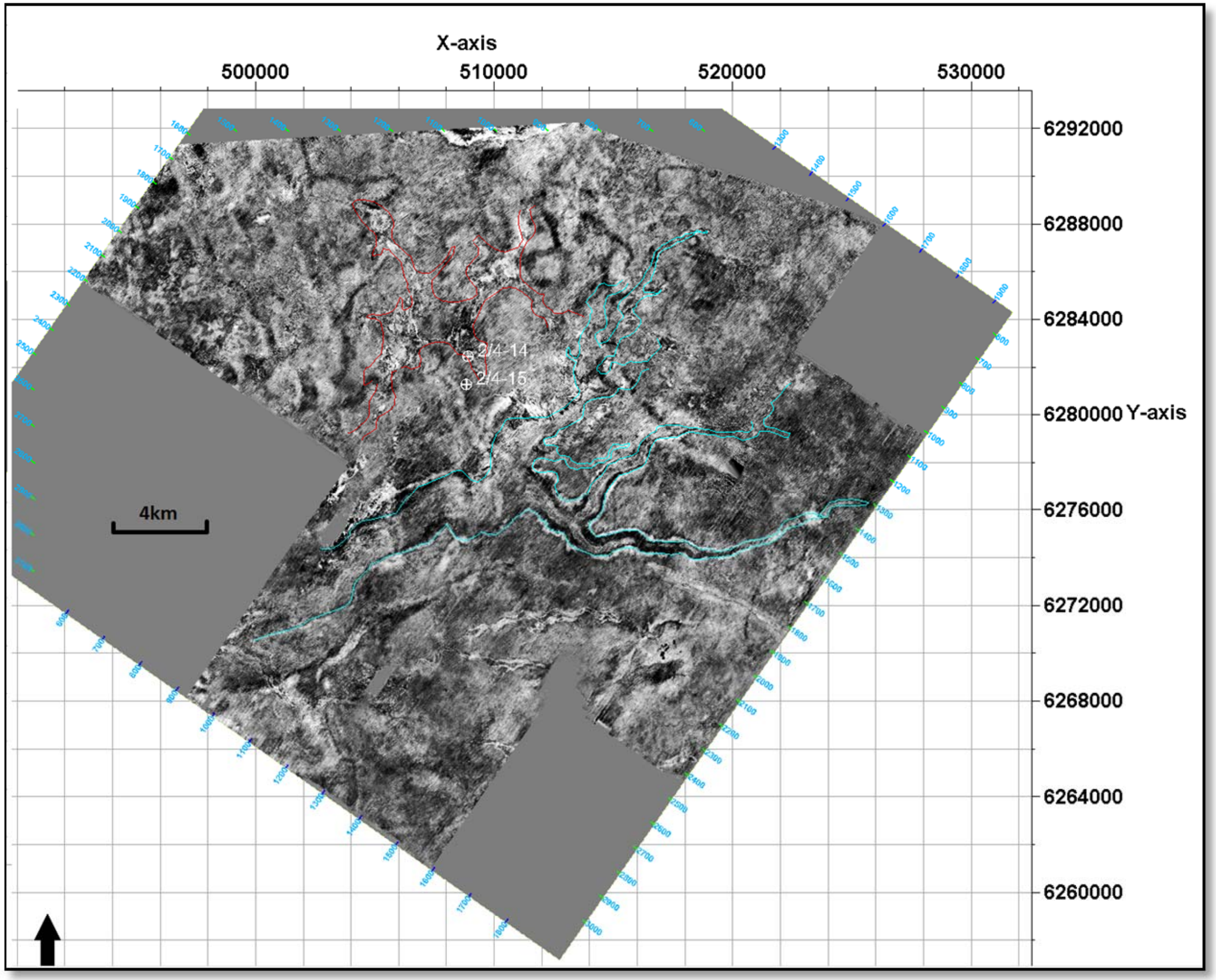


**Figure 15: Time-slice at 244ms TWT, amplitude map. Quite strong amplitudes and great dimensions of the tunnel valleys can be observed. Mainly primary reflections are seen.**

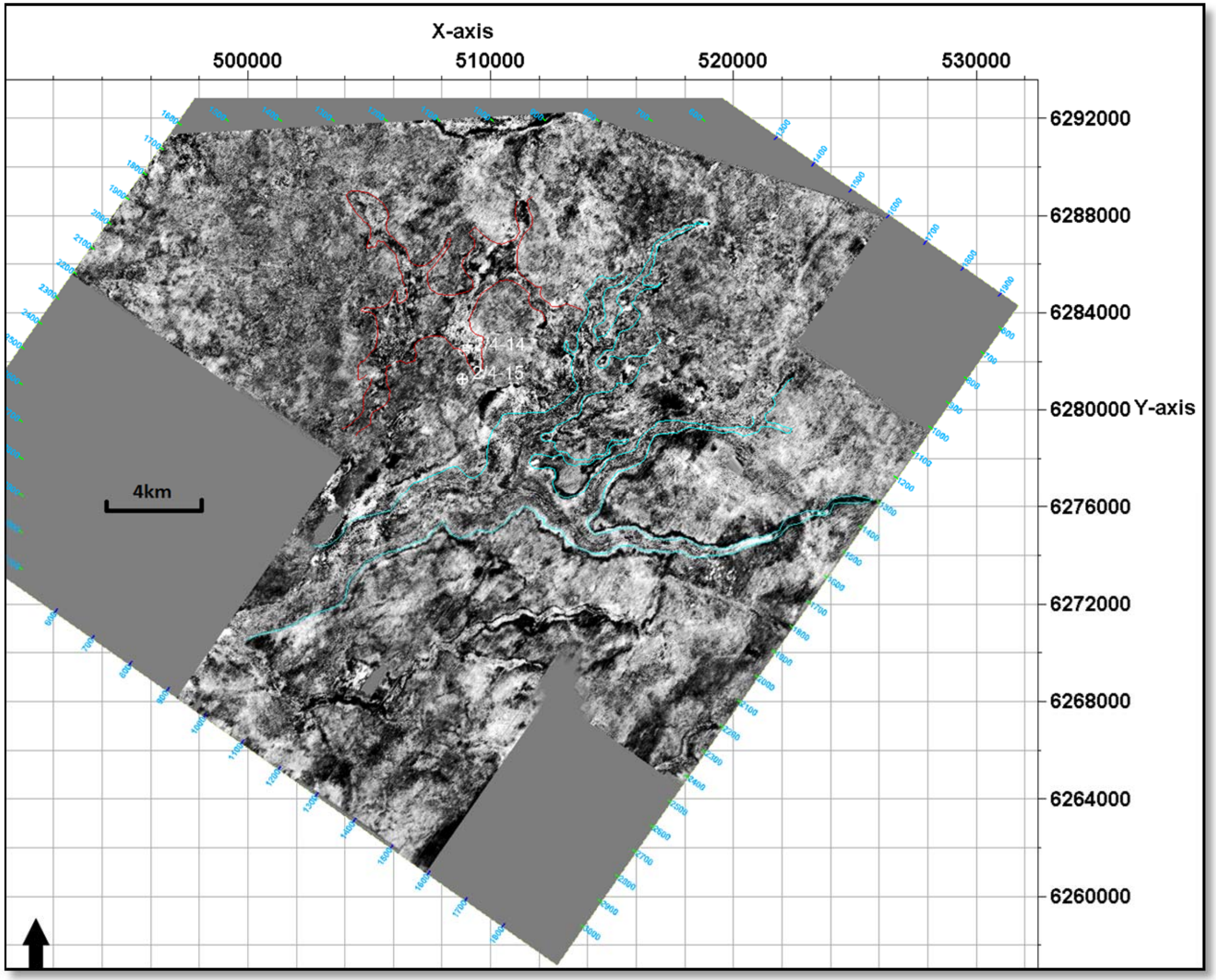


**Figure 16: Time-slice at 332ms TWT, amplitude map. The same tunnel valleys are observed as multiples in this horizontal section. The amplitudes of these multiples are even stronger than the amplitudes of primaries seen in figure 15. Same color scale applied as in figure 15.**

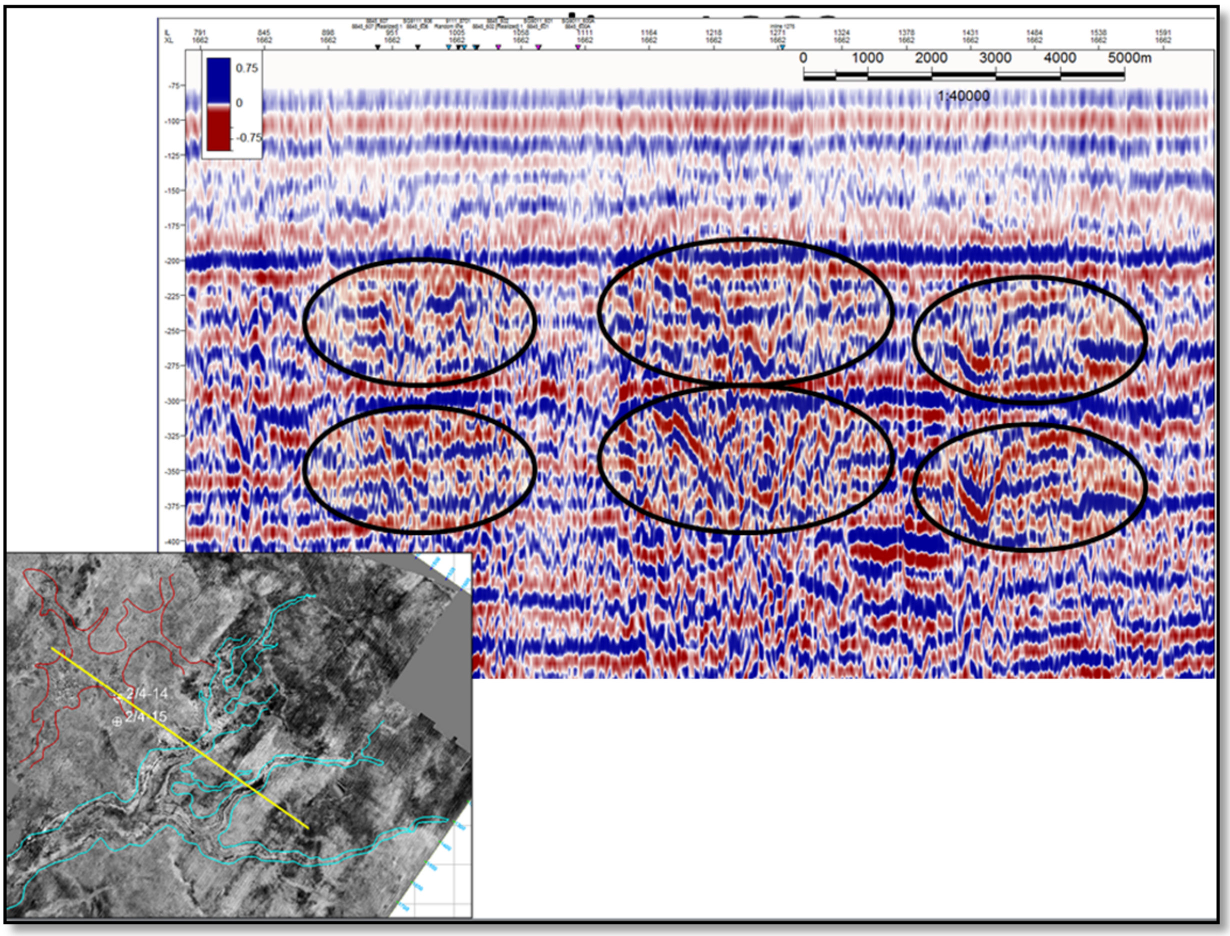

**Figure 17: Crossline 1662 from 3D volume SG9111. Strong "valley multiples" make it difficult to identify new tunnel valleys beneath second seabed multiple. The chaotic seismic reflections within and around the tunnel valleys are evident as well.**

**Table 2**

| Valley | Maximum measured width[km] | Approximate valley depth[m] | Mapped length [km] |
|---|---|---|---|
| **V13** | - | 132* | - |
| **V14** | 1.1 | 110 | 8.3 |
| **V15** | 3.5 | 110 | 26.0 |
| **V16** | 1.1 | 80 | 5.6 |
| **V17** | 0.9 | 110 | 3.0 |
| **V18** | 0.7 | 80 | 3.7 |
| **V19** | 0.7 | 60 | 1.4 |

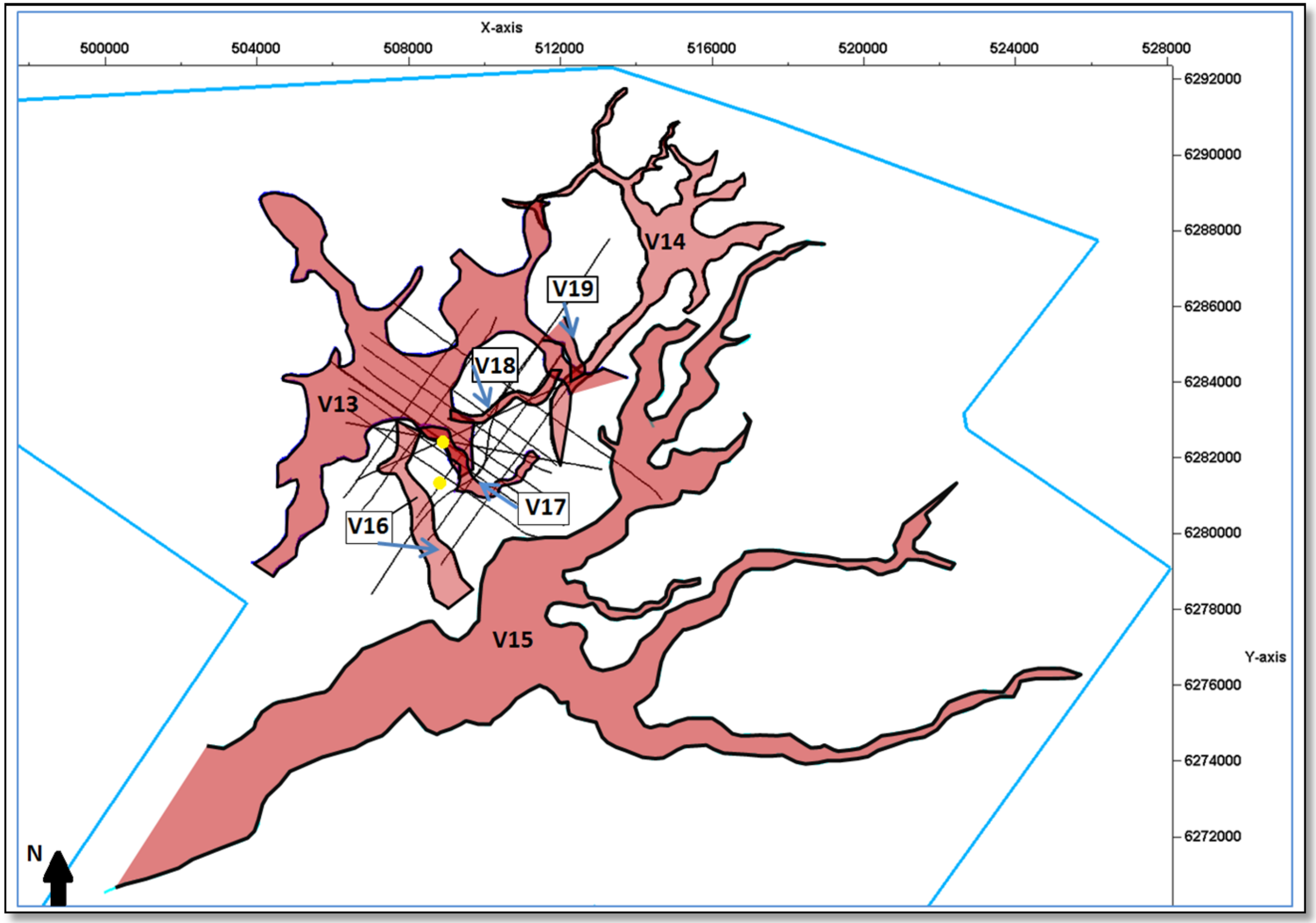


**Figure 18: Overview map of the seven tunnel valleys mapped below first seabed multiple (>180ms TWT). The clear blue line marks the boundary of the seismic 3D cube and black lines the 2D lines available. The yellow dots marks well 2/4-14 and 2/4-15. The sizes of the valleys are far greater than the valleys observed in the first sequence. The tunnel valleys have a different dominating direction (SW-NE) as well.**

## 5.3 Description of the valleys, character and infill

After the valleys were mapped in planeform the vertical profiles were investigated to see if the mapped valleys were observable, and further, the amount of details visible. All the mapped valleys in the area where high-resolution 2D profiles were available were identified on the vertical sections. However, the contours and size was sometimes hard to decide. The strength of the reflectors varies greatly, especially in 3D volume SG9111. Generally, the tunnel valleys mapped within the first interval would not be detectable if only vertical sections from this volume were available (figure19). From the 2D profiles the reflector strength and pattern within the valleys differ from chaotic to fairly well layered (figures 19 and 22). In this section some examples of vertical profiles will be shown.

As mentioned the details within the valley and of the shape of the tunnel valley itself are very limited on 3D profiles. Figure 19 clearly shows the difference in amount of information obtainable from the dissimilar data. On the 2D profile on the left side a lower chaotic sequence followed by a sub-horizontal sequence can be seen, however the 3D profile shows only chaotic reflections within the valley. Further, it is not possible to identify the structure of the valley in terms of valley shoulders, sides or base from this section. The black line indicating the tunnel valley structure is interpreted on the 2D section and based on this marked on the 3D section.

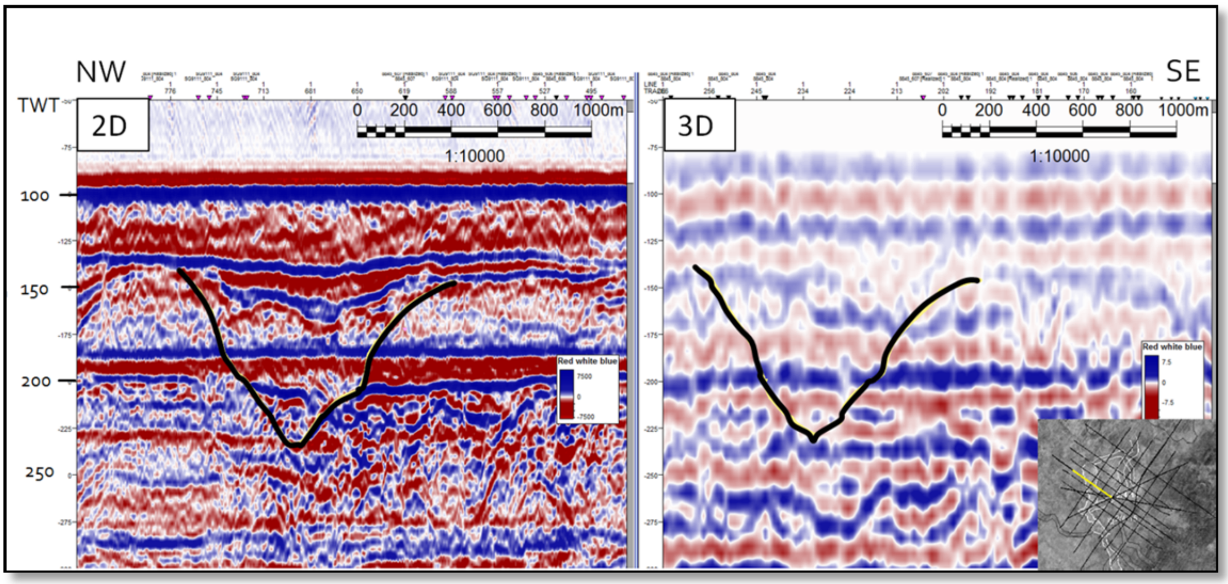


**Figure 19: Details of infill in tunnel valley V08 shown in SG8945_804 and SG9111_804 respectively. The amount of information obtainable is significantly different. One can interpret infill characteristics of the valley from the high-resolution profile, however almost no internal valley structures nor shoulders, base or sides on the 3D profile.**

On the contrary there are unexpected minor structures observable in the vertical profiles from the 3D volume. Figure 20 displays the identified tunnel valley with the least size. The valley has a shoulder depth about 20m below present seabed, an approximate depth of 25m and width 500m. The valley is possible to detect in the 3D vertical profile as an amplitude anomaly where it is mapped in planeform.

Further, figure 21 displays 2D section 8845_813A and the equivalent 3D section from SG9111. Clinoforms at an end of valley V01 are evident in 2D profile and can be observed in the 3D section as well.

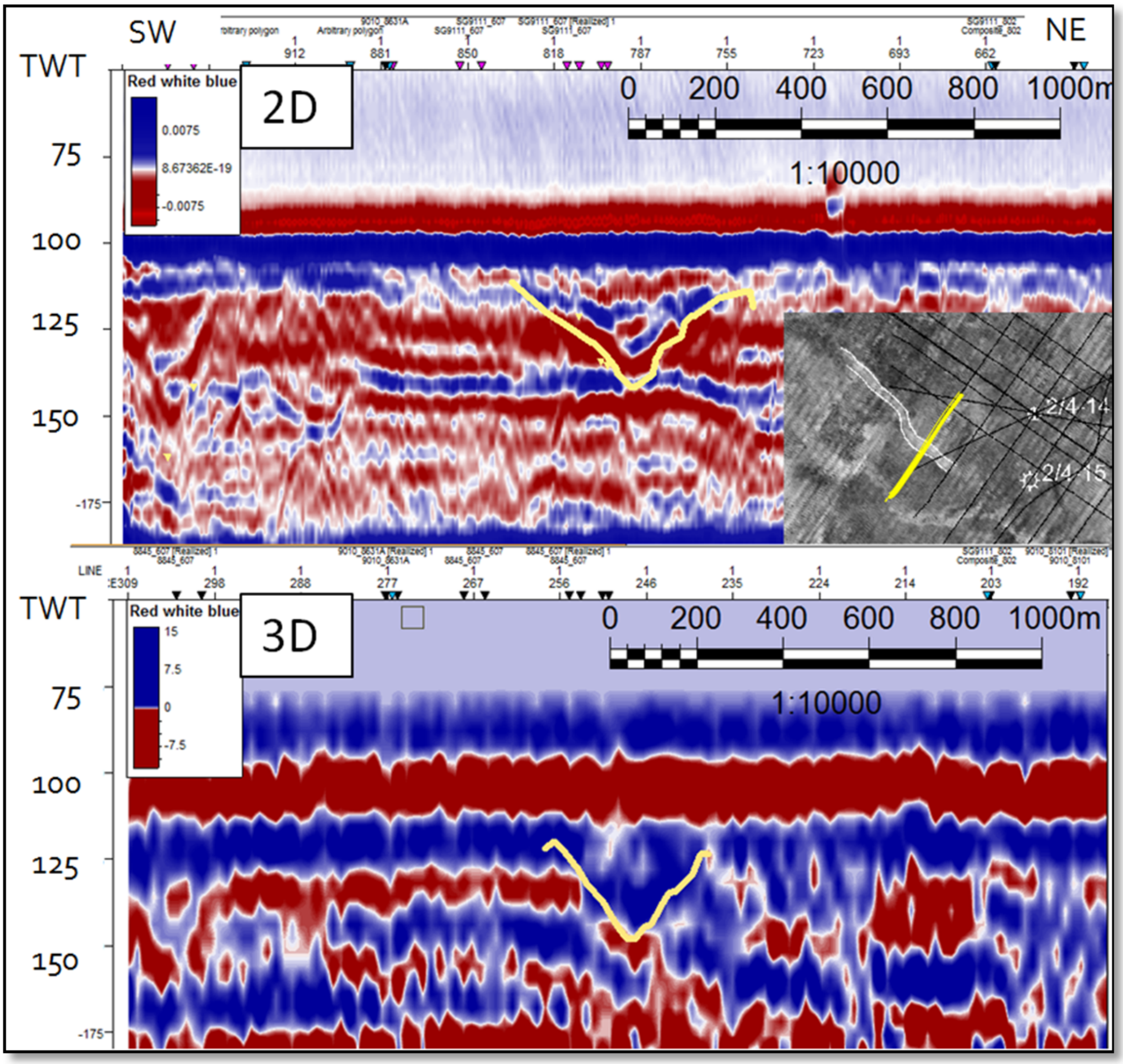


**Figure 20: Vertical profiles of the mapped tunnel valley with the least size. Here shown in section SG8845_607 and equivalent section from SG9111. The valley is included in the overview map from the upper section as V12. It is barely visible in the 3D section (lowermost), however, in greater detail on the 2D profiles (upper most). The valley is not more than approximately 25 m deep and the valley shoulders are positioned 20m below seabed.**

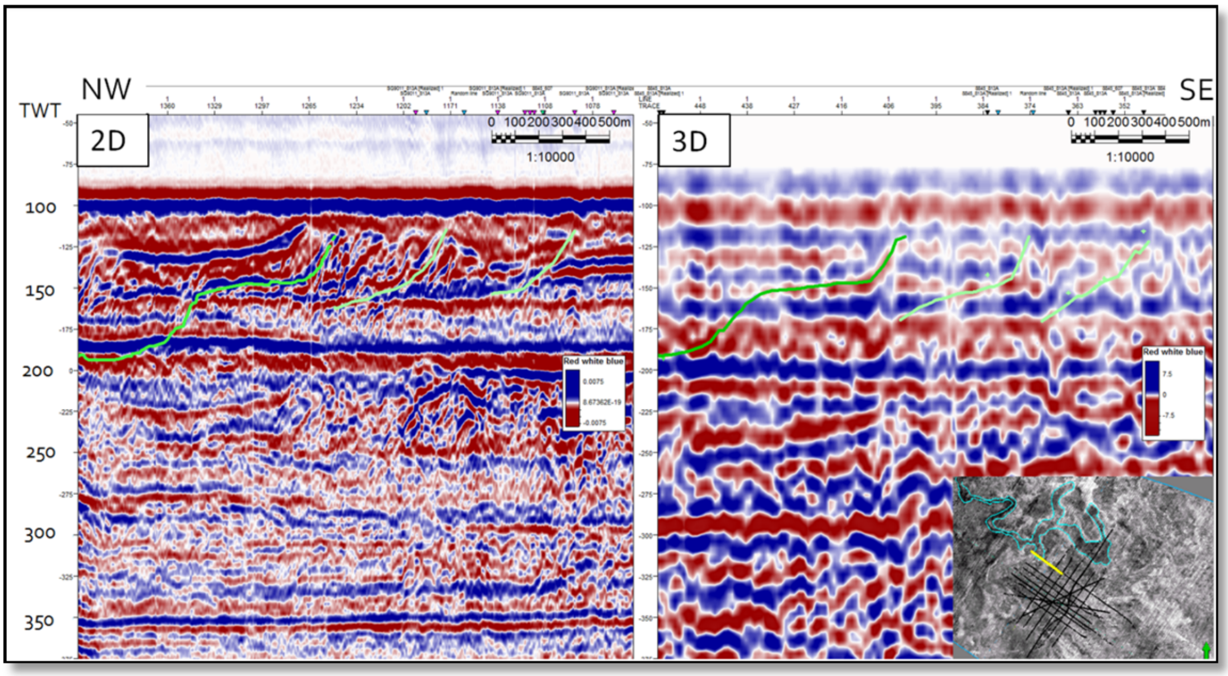


**Figure 21: Clinoforms at the valley side of V01 observable in both 2D (8845_813A) and 3D (SG9111) sections. However details are much more evident in the high-resolution 2D seismic.**

In the second interval the tunnel valleys are more complex as can be seen from the vertical profile of mapped tunnel valley V13 in figure 22. The valleys are characterized by chaotic reflectors in both 2D and 3D lines. However, there are evident such reflections in all locations were tunnel valleys are mapped in this interval.

All valleys mapped in planform presented in the overview maps in figure 14 and 18 can be observed as seismic anomalies, onlap structures, truncating reflectors or chaotic parts in the vertical seismic sections. Nonetheless, there are valleys which have not been possible to identify in planform from horizontal profiles. The size of these varies but they are mainly small or have disrupted reflections. Figure 22 shows a tunnel valley seen in section SG8845_804 and SG8845_803. Although it is of significant size and quite distinct shape it has not been detectable in horizontal nor vertical profiles from the 3D volume. The reflector from the base of this valley is likely to be interfered by the first seabed multiple. This may be the reason why it is not detected, or perhaps the contrasts between infill sediments and surrounding sediments are small causing a weak amplitude that will be very low in the weak part of the 3D seismic volume.

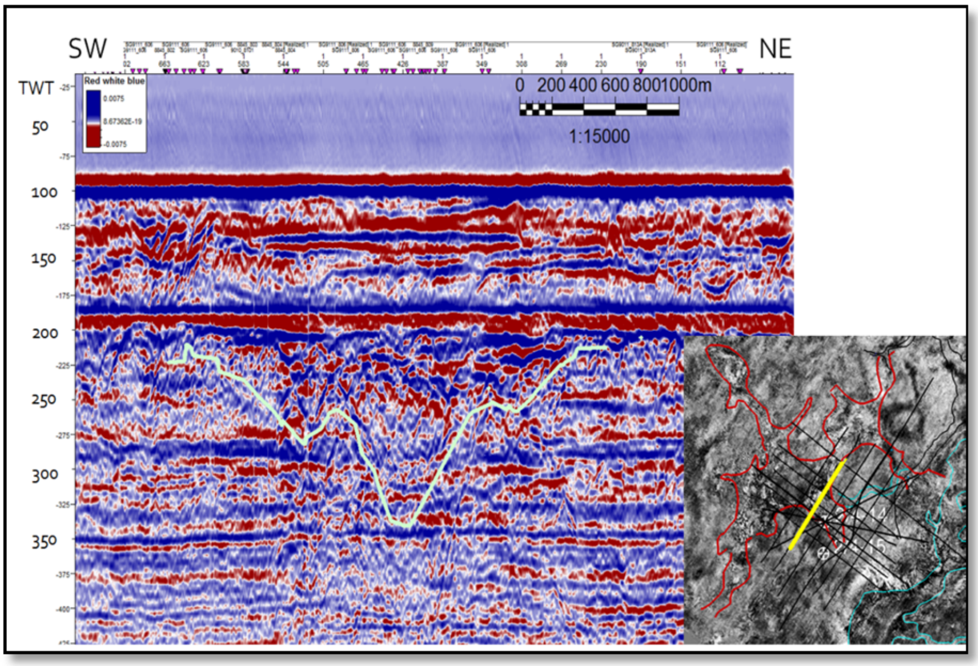


**Figure 22: A complex tunnel valley combining several generations of tunnel valleys stacked on top of each other observed in 8845_606 at site of tunnel valley V13.Very chaotic reflectors.**

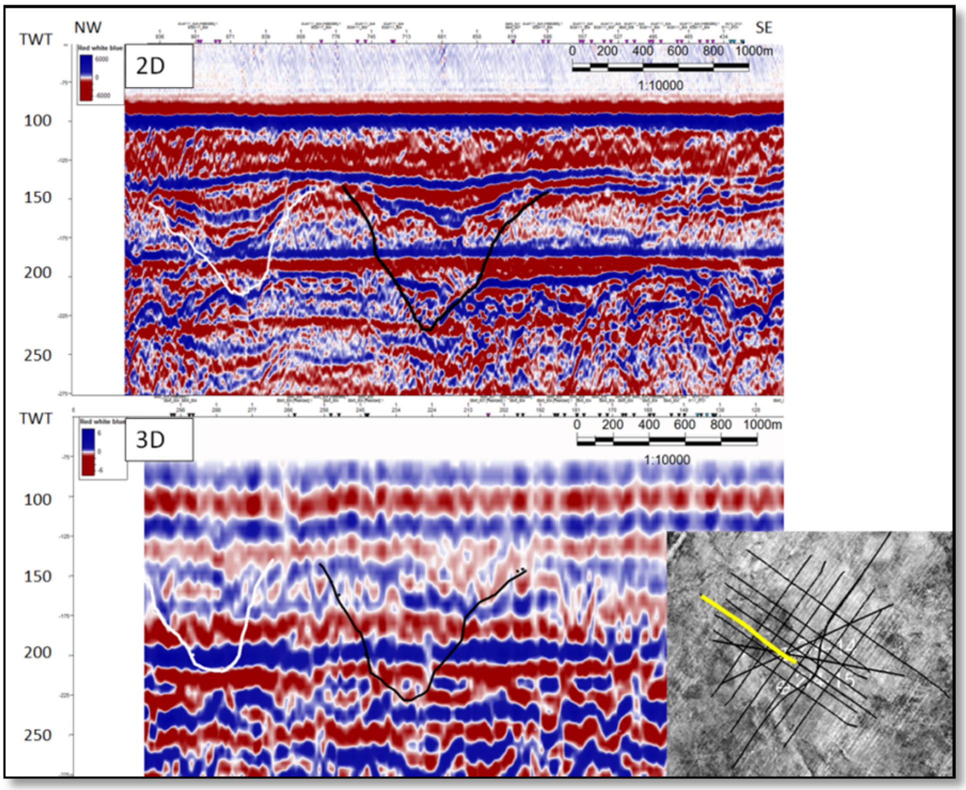


**Figure 23: Section SG8845_804 and equivalent profile from SG9111. Tunnel valley V08 marked by a black horizon is detectable in horizontal profile but the tunnel valley marked by white line has not been observed in the 3D volume despite thorough inspection. The small image is showing the line location marked by a yellow on time-slice at 160ms TWT. If the valley was observable in the time-slices this would probably be one of them.**

# 6 Discussion

There are some uncertainties related to the results in this study. In this chapter these will be evaluated. Further, the sediment infill of the valleys and the related potential for gas migration will be discussed.

## 6.1 Quality of seismic data

This study has shown that low frequency data containing weak amplitudes can contribute greatly to mapping and improved understanding of tunnel valleys basal morphology. All of the 19 valleys interpreted on time slices from the 3D volume have been detected on vertical profiles as well. This enhance Praeg's (2003) conclusion that low-frequency conventional seismic data from exploration areas can give a great amount of information about tunnel valleys presence and morphology. However, in Praeg's (2003) study of tunnel valleys in the North Sea basin the first 100-200ms TWT, containing the seabed, was not included when evaluating the tunnel valleys. This was because muting due to near source effects caused very weak amplitudes in this interval. In this study all seismic signals within the upper 400ms TWT were used for the interpretation. Even though the upper 200ms TWT of the 3D volume are considered to have a minor data fold, and hence very weak amplitude and low resolution, it is fully possible to obtain information on tunnel valley distribution from this part. However, other than the basal morphology one cannot say much about the stratigraphy and infill character based on this data, especially not in the upper sequence above first seabed multiple.

Some of the valleys have only been observed in one single time slice, probably depending on the valley's size as well as the contrast between infill sediments and surrounding layers. V12 is the smallest tunnel valley mapped in this study. The depth of the base is located at approximately 140ms TWT and the total depth is probably not more 25m. The valley is only observable by a minor amplitude anomaly in the vertical low-resolution profiles (figure 20) and would almost certainly not be detected in low-resolution data if horizontal slices were unavailable.

The reflections appearing on the time slices are often considered to represent the base of the valleys or bright amplitudes caused by continuous layers within the valleys. Hence, the widths measured from polygons interpreted on the horizontal slices do not necessarily correlate with the actual distance between the "valley shoulders" measured in vertical sections. Sometimes the measured width in vertical profiles is as high as 1.5 to 2 times larger than the one measured in planform.

Some valleys seen in high-resolution 2D data have not been possible to detect in the horizontal slices. As seen in figure 22 the size of the tunnel valley it is not necessarily the limiting factor causing this. It can be due to weak contrasts between sediment infill and surrounding layers, causing a slightly weaker reflected signal that will be insignificant after near source muting. Alternatively, the bright reflectors of the tunnel valleys interfere with the strong seabed multiples, and thereby, become undetectable in the low-resolution seismic profiles.

The strong multiples have been mentioned several times in this thesis. The multiples have in some cases been of great help when mapping the valleys, as they sometimes are stronger than the primary reflectors. Thus, the valley contours have been easier to detect. Removal of the multiples would probably not change the resulting maps significantly. The possibility of deeper buried tunnel valleys than the ones mapped is not prominent when considering earlier observed tunnel valleys in the area. However, the uncertainty related to measured time intervals, and thus, calculated depths of the mapped valleys, could be decreased by multiple removal.

Tunnel valley multiples could also cause placing of the valleys at the wrong depths. However, the valleys observed in the first interval are mostly oriented in Northwest-Southeast direction, and the valleys in the second interval are generally oriented in Southwest-Northeast direction indicating that the valleys originate from different episodes of meltwater release. Moreover, the characteristics of the valleys are quite different; hence, it is assumed that the valleys are correctly interpreted at shown depths. The 2D lines where the primaries are stronger also correlate well with interpreted depths.

## 6.2 Tunnel valley infill and possible gas migration

Since well 2/4-14 developed into an underground blowout well one of the main aims of this thesis was to evaluate if the tunnel valleys can act as flow paths for leaked gas. If so they might facilitate gas migration in great distances from the well. The porosity of a rock is determining the rock's capability to contain hydrocarbons or any other fluid. Further, it is the permeability that decides the ability for the fluids to migrate within the rock (North, 1985). Thereby, the valley infill is the crucial factor for making fluid flow possible.

### 6.2.1 Infill

#### *6.2.1.1 First interval*

As seen in figures 19, 20 and 21 infill structures on the 3D seismic lines are practically absent. Thus, the infill has been characterized from the 2D data provided. Because of the strong multiple reflections, caused by the shallow water layer, it has been challenging to identify the contours of the valleys. The reflection from the base of many of the valleys in the upper mapped part coincides or is imaged very close to the first seabed multiple. Additionally, the deeper parts of the valleys are often cut into deeper buried tunnel valleys, with chaotic reflectors, making the interpretation harder. However, the typical seismic characteristics of the valley fill observed in the first interval is a lower part with chaotic disrupted reflectors followed by sequence of sub-horizontal continuous reflectors that onlap and cap the valley margins (figure 23).

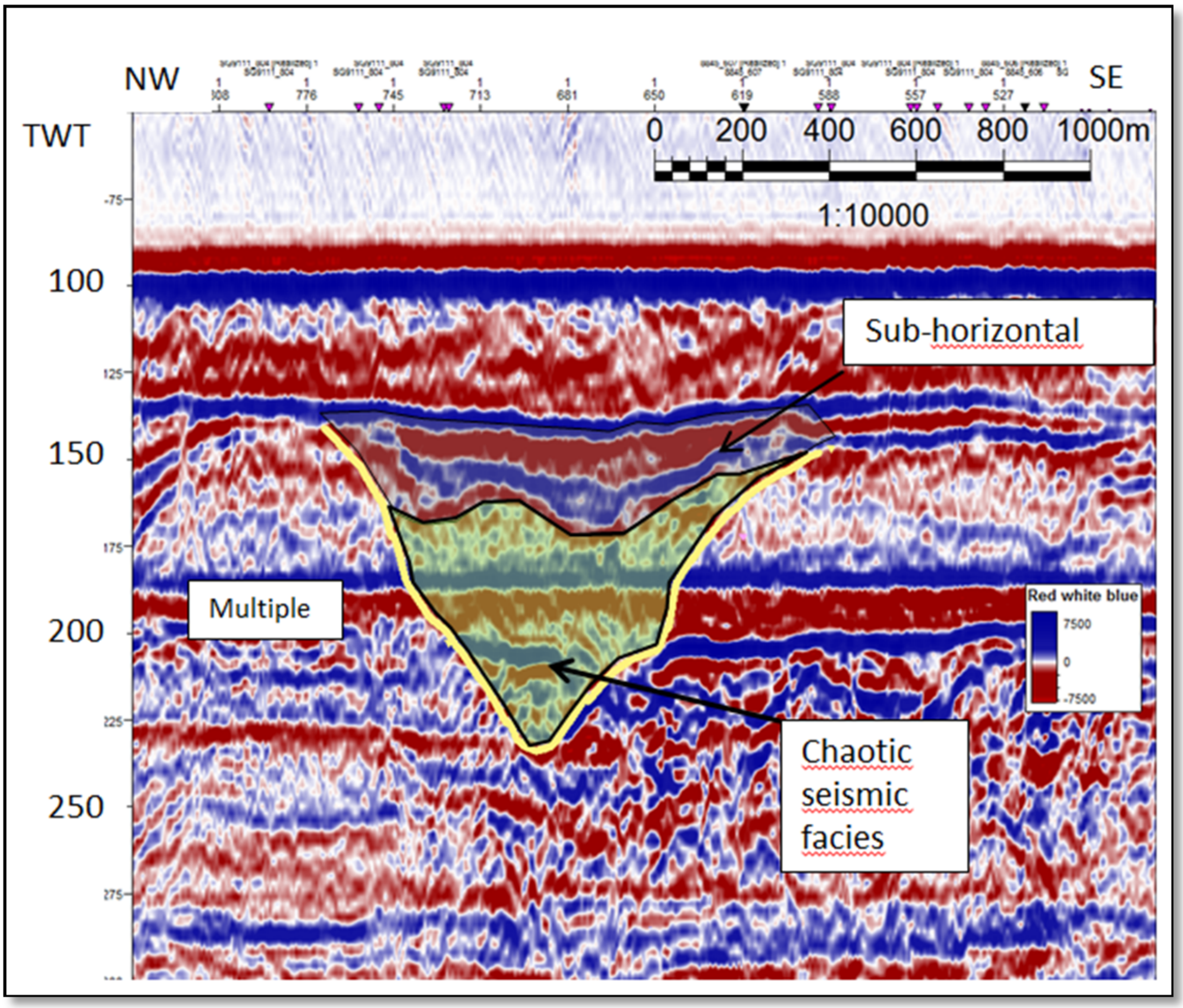


**Figure 24: 2D profile 8845_804 crossing tunnel valley V08. Upper sequence is sub-horizontal and the lower part is chaotic. The base of the tunnel valley probably cuts into a tunnel valley complex below. Hence, the interpretation is slightly uncertain.**

As no sedimentological logs from the area have been available in this study there is no direct information on the valley fill lithology. Thereby, the interpretation of the valley fill is very tentative. The recognized infill sequence of a chaotic lower part and more well layered upper part is likely to be comparable with the facies found in several previous studies of Quaternary buried tunnel valleys in the North Sea basin (e.g. Huuse and Lykke-Andersen, 2000; Graham et al., 2007; Praeg, 2003; Lonergan et al., 2006; Cameron et al., 1987). Generally, the chaotic disrupted part is interpreted to be glaciofluvial sediments and the well layered sequence glaciomarine or glaciolacustrine sediments. The small number of wells penetrating tunnel valley fill in the North Sea has also recovered sandy-silty gravel in the lower part overlain by glaciomarine muddy sediments (Lonergan et al., 2006). Fine grained sediments initialize low energy depositional environment, and thus, this facies is likely to be proglacial lacustrine, maybe gradually marine depositions (Lonergan et al., 2006). Lonergan et al. (2006) suggested that the lowermost unit, based on its seismic characteristics, is likely to be a coarse-grained facies deposited during the same meltwater release that caused the valley incision. Several of the valleys in this interval are connected as they cut into one another in some areas. A schematic illustration of a cut- and fill-process was presented by Lonergan et al. (2006) seen in figure 24.

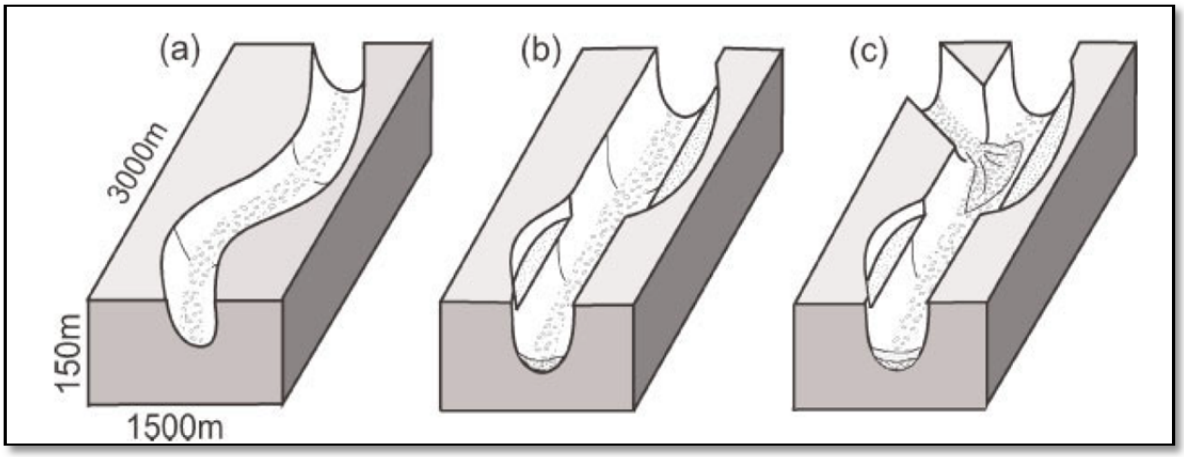


**Figure 25: Schematic illustration of tunnel valley evelution through time taken from Lonergan et al. (2006). a) shows the first episode of valley incision where lag deposits get deposited in the base. b) a new outburst flows in the same valley causing deepening of the base and straightening of the valley sides c) in time a tributary valley can join the main valley remaining as a haning valley in the landscape.**

### *6.2.1.2 Second interval*

In the second mapped interval of tunnel valleys the seismic is dominated by multiple noise and disrupted reflectors making distinct contours of each valley difficult to specify. Further, the complexity of the valley system is much more severe in this interval. For instance V13 is considered to be a valley complex consisting of several cut- and fill-structures. Jørgensen and Sandersen's (2006) study of tunnel valleys in Denmark showed that buried valleys often were composed of a series of cut-and fill-structures, and further, that most of these structures are narrower than the overall buried valley. The formation process of such valleys is described by Kehew et al. (2012); after great releases of meltwater the water pressure will drop and ice closes in to fill or partially fill the meltwater channel. As the next surge of the ice cover occurs the presence of the ice will lead the water flow, and thus, erosion to an adjacent position. Hence, large valleys can result  from several minor events (figure 25). If the formation of the major valley happens within several glacial cycles the resulting composite valley can be composed by several minor valleys of different sedimentary fill (figure 25B). This could be the case in the study area as at least three glacial cycles are believed to have been present. Hence, the mapped valleys of chaotic reflectors and great size might be considered to represent such composite valleys.

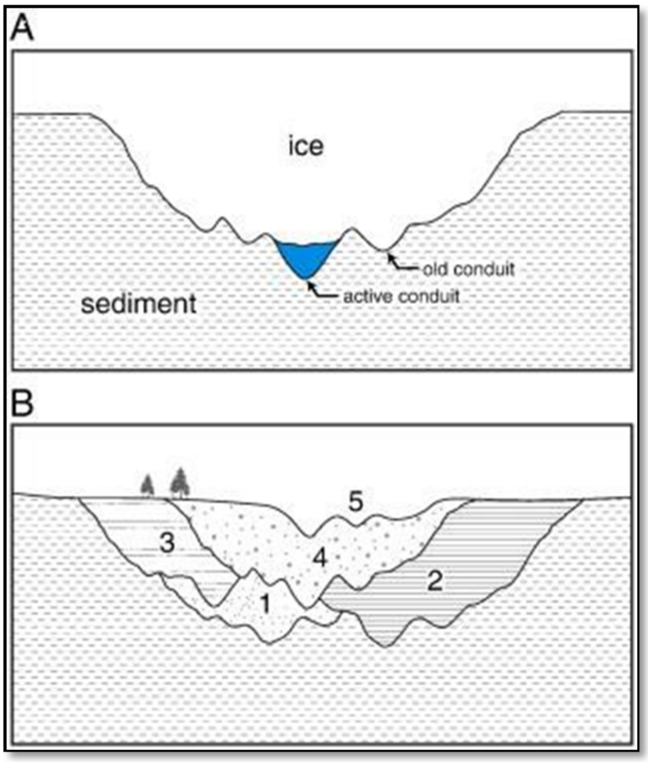


**Figure 26: A) Conceptual sketch of episodic subglacial outburst events. The incision made by each event gets fully or partially closed in by ice after drainage has stopped. As meltwater flow starts again the water tend to choose a path laterally along the base of the ice. Thereby, large tunnel valley complexes as seen in figure 21 can be formed by several minor events. B) If the formation of the valley complex happens within several glacial cycles a number of different minor valleys filled with sediments can form the composite valley (Kehew et al. 2012).**

#### *6.2.1.3 Clinoforms*

The clinoforms at the end of valley V01 seen in figure 21 are quite small compared to clinoforms evaluated by others (e.g. Praeg, 2003; Kristensen et al., 2008). Still they are interpreted to have been formed during retreat of an ice-sheet. As channelized meltwater flowing underneath the ice sheet reaches the ice margin the sediments will get deposited by freeze-on, due to supercooling, along the adverse valley slopes (Kristensen et al., 2008). Some other places clinoforms have been observed at the sides of the valleys, both in first and second interval. These are possibly caused by deposition of sediments in parts of the channels where the water velocity has been lower, for instance inside the bends of the sinuous formed channels.

### 6.2.2 Seismic Velocity effects

Rock velocity depends upon the mineral composition and the granular nature of the rock matrix, cementation, porosity, pore fluid type, and pore pressure (Avseth et al., 2005). Further, depths of burial and geologic age can also affect the seismic velocities present.

Figure 26 and 27 are showing velocity pull ups in the horizons underlying mapped tunnel valleys. These velocity pull ups in time sections are probably caused by sediments of greater velocity inside the valleys compared to the seismic velocity of the surrounding layers. The opposite effect, where shallow features with sediments of relatively low seismic velocity cause a lowering in the underlying reflectors, is referred to as a velocity push-down.

Recently Kristensen and Huuse(2012) published an article on buried tunnel valleys in the Danish sector of the North Sea, close to the Norwegian sector, in which they evaluated seismic velocity anomalies associated with tunnel valleys. In their study both push down- and pull up effects in the horizons beneath tunnel valleys were observed. Considering the proximity to current study area the possibility of detecting both types of velocity anomalies would be present. Yet, no horizons with push down-effects have been detected beneath the mapped valleys.

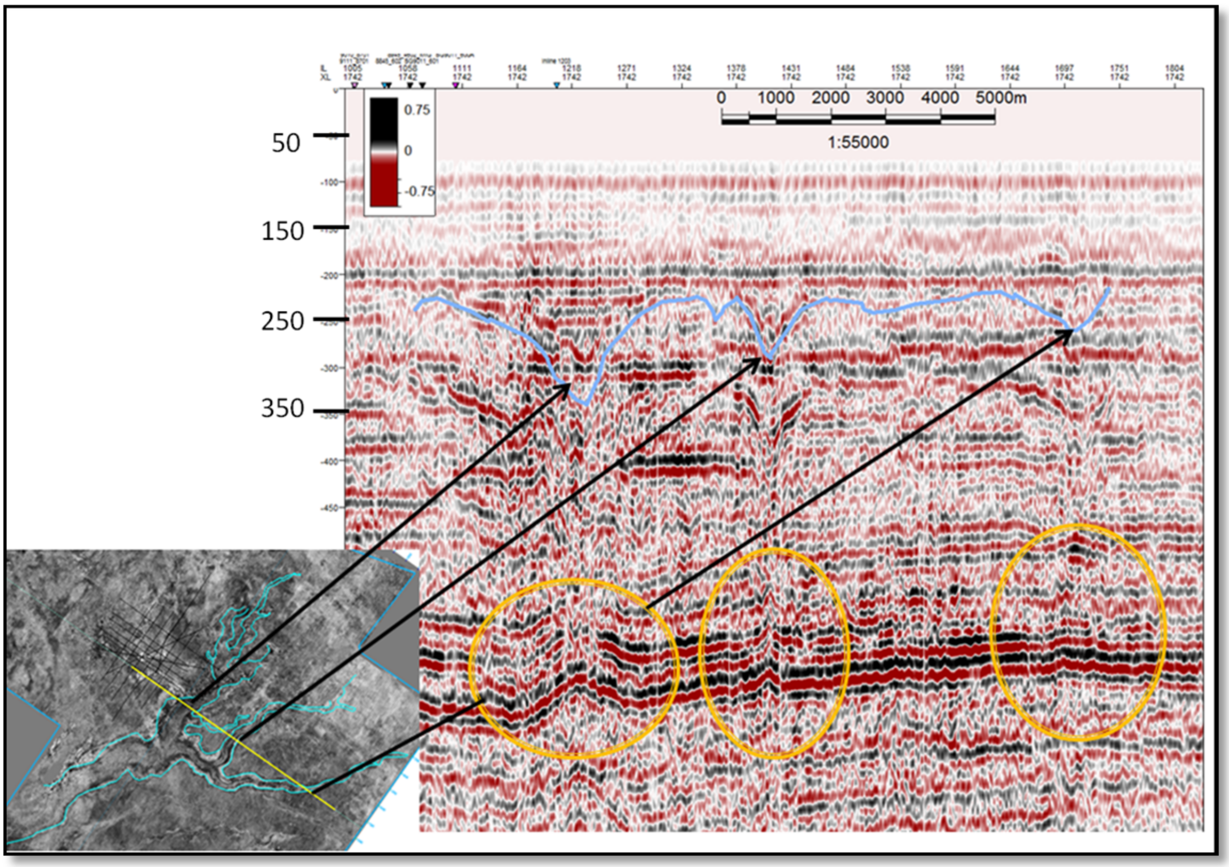


**Figure 27: In Crossline 1742 pull up effects can be observed beneath the mapped tunnel valleys. The yellow line in the small image indicates where seismic line is present in comparison to the mapped valley (V15). It is possible to see amplitude anomalies where the tunnel valley is located down to about 1800ms TWT due to pull ups.**

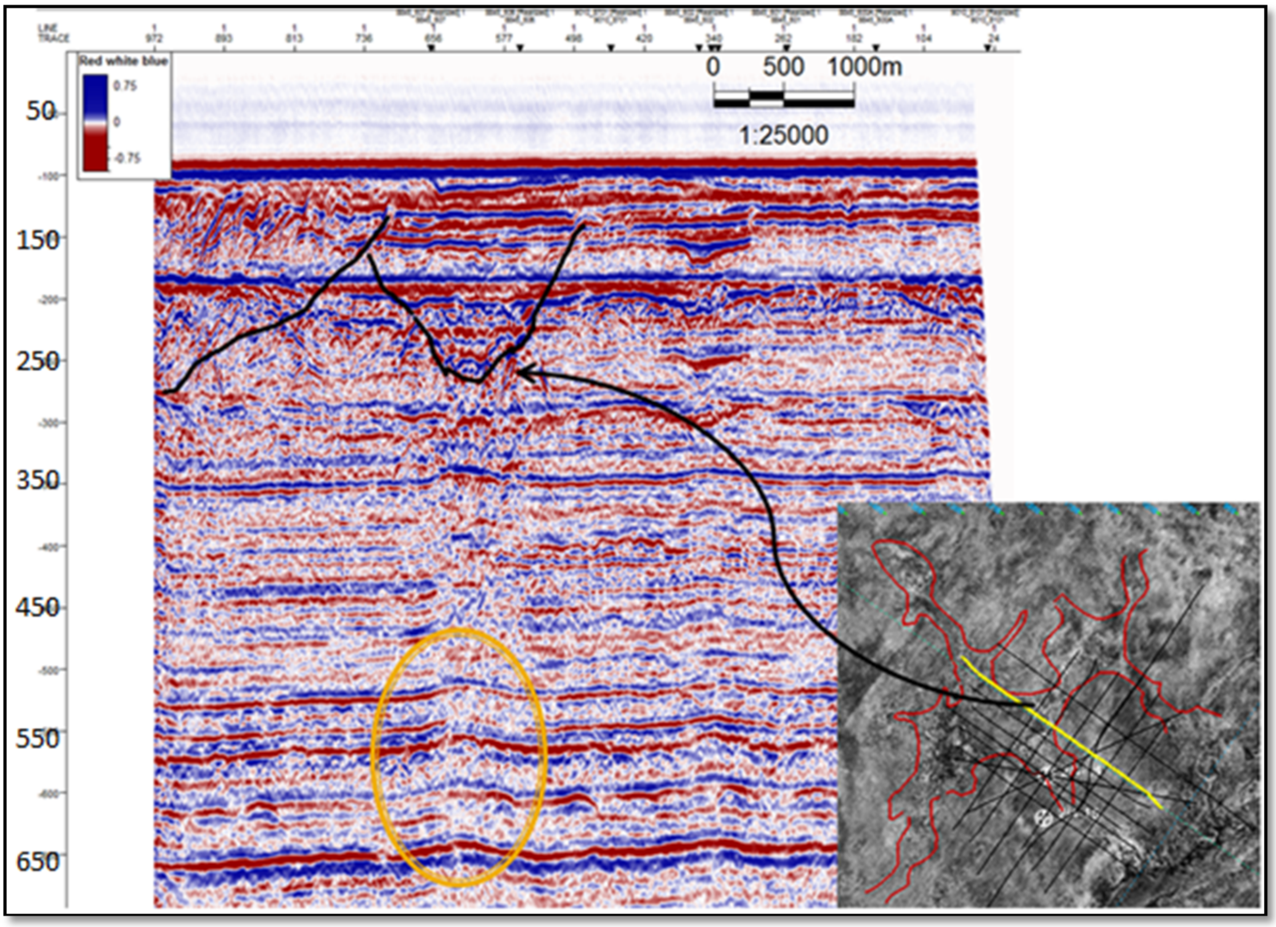


**Figure 28: 2D line 8845_811A pull up effect beneath a mapped tunnel valley. The tunnel valley complex is marked by a red outline in the small image on the right hand side. The orange circle marks where the pull up can be seen.**

Further, Kristensen and Huuse (2012) tried to find a correlation between the seismic infill facies and the velocity anomaly effect recognized. However, they were not able to determine a system. Furthermore, the dissimilar velocity effects seemed to occur randomly throughout the area, and hence, no local geographical relation could be seen.

The velocity anomalies are regardless caused by velocity variations in the valley infill. The mapped valleys are found in the Nordland formation which is dominated by shale. According to Avseth et al. (2001) shales tend to have lower velocities than sands at shallow depths. Thus, the velocity pull ups might indicate sands or gravel present within the valleys. Even so based on studies of buried tunnel valleys onshore Denmark the type of sediment infill has been divided in two different groups; the first including meltwater sands, gravel and glaciolacustrine silt and clay with velocities of 1750±100m/s, and the second including clay tills with velocities of 2150±100m/s (Jørgensen et al., 2003, as cited in Kristensen and Huuse, 2012). This indicates that till would cause velocity pull ups, and sands and gravel velocity push down.

Tills are generally characterized by poorly sorted clayey and sandy grains, fairly compacted and often overconsolidated resulting in a rather poor reservoir potential (Stephenson et al., 1988). Sands and gravels on the other hand are likely to be more permeable with fair to excellent reservoir potential (Stephenson et al., 1988). However, porosity can be significantly reduced by diagenetic processes. In the North Sea mechanical compaction, meaning burial packing and ductile grain deformation, is dominating the diagenetic reduction of porosity in the upper 0 to 2.5 km (Avseth et al., 2001). Further, chemical compaction, especially quartz cementation, could also reduce the porosity significantly. This can occur at shallow burial depths, but it is more common in deeper substratum below 2.5 to 3.0 km. At these depths pressure solution might take place (Avseth et al., 2001). The burial depths of the mapped tunnel valleys in this study are not greater than approximately 300m, but as the area has been covered by ice sheets several times the burial depth of the deepest tunnel valleys has been significantly greater than present. The late Weichselian ice sheet is assumed to have reached a thickness between 700-900m in the North Sea basin (Siegert and Dowdeswell, 2002). This can affect both the mechanical and chemical compaction. Water flow within the sediments will increase by meltwater from the ice cap. Water has a significant impact on cementation processes as it might increase mineral dissolution, and further, has the ability to transport the ions to areas where they might precipitate (Prestvik, 2001). Cemented sandstones will have a high seismic velocity and can cause pull up effects as well.

### 6.2.3 Possible fluid migration

The absence of push down velocity anomalies in the study area does not mean that porous and permeable sands and gravels are not present; though, the velocity contrast between sediments inside the valley and the surrounding layers is too small for such velocity anomaly to appear. Tunnel valleys act as reservoirs for groundwater flow in northern Europe and for hydrocarbons in northern Africa (Kristensen and Huuse, 2012). Thus, it is reason to believe that gas can migrate within these valleys.

The valleys are interconnected vertically and laterally by various cut- and fill-structures. Hence, if the tunnel valleys are filled with permeable material it is possible for gas to migrate great distances through these valleys. In isolated parts of the tunnel valleys the sequence of coarse grained sediments followed by a less permeable clay rich sequence can lead to gas migrating horizontally instead of vertically. The overall system of interconnected tunnel valleys, which in places can be in connection with other permeable formations, can form a massive network for fluid flow. On the other hand, if some of the valleys are filled with impermeable sediments they can function as flow barriers, possibly contributing to gas accumulation at the valley side.

Fluid flow will be controlled by the relative permeability which primarily depends on the interfacial tension between the present fluids, in this case between gas and brine. The relative permeability in combination with capillary forces will cause an amount of fluid to remain in the host rock as the fluid migrates further. Thus, the amount of gas migrating through these networks will decrease as the travel path increases. This intra-formation trapping of gas reduces the possible amount of gas leaking to the surface. As there are several ongoing pilot studies on $CO_2$ injection into the subsurface the pertinence of studying possible migration paths for leaked gas is evident.

When considering the storage potential of the tunnel valley system some simplified calculations can be made. Assuming the extreme case where all the valleys are completely filled by sediments with a porosity of 25%, and further, that the valleys are straight triangular depressions, the storage volume ($V_s$) can be calculated using the following equation:

$$V_s = \left(\frac{width \times depth}{2} \times length\right) \times 0.25$$

Furthermore, this volume can be compared to a plan formed sandstone layer of thickness $Z$ with equivalent porosity, and a lateral extent ($A$) similar to the area covered by the 3D volume.

$$Z = \frac{4V_s}{A}$$

Inserting the measures listed in table 1 and 2 the storage pore volume and comparable thickness of sandstone layer will be about 2,6 $km^3$ and 100m respectively. In these calculations composite valley V13 were assigned a length of 10km and a width of 1km. The amount of gas possible to store in these valleys is thereby considered significant. The presence of shallow gas within the valley can be a potential hazard while drilling wells. Hence, mapping of tunnel valleys can be important for several reasons.

## 6.3 Further Work

To improve the knowledge about the infill sediments in the mapped tunnel valleys petrophysical logs from wells in the area penetrating through valleys can be interpreted. These will indicate present parameters, and hence, physical properties of the sediments. Thereby, if the porosities and permeabilities of the valleys are significant it will strengthen the hypothesis that these valleys may act as pathways for gas migration. Jørgensen and Sandersen (2006) presented resistivity maps of tunnel valleys, and thereby, they could distinguish between infill of coarse meltwater sediments and clays. Thus, such resistivity measurements could also improve the knowledge of the sediments in place.

A new seismic cube has been retrieved recently; inspection of this cube to see if bright spots or other signs of leaked gas are observable in the seismic, within the valleys or truncating the valley sides, can also improve the understanding of how the tunnel valley system impacts gas migration.

Further, as no new interpretations have been made in this thesis in order to improve the understanding of tunnel valley genesis this can be done to provide information about ice sheet mechanisms. Also the tunnel valley dimensions and orientations can contribute to further constrain and date the patter of the ice sheets during the last glaciations. More thorough interpretation and understanding of the infill structure can also be beneficial for this purpose.

## 7 Conclusion

In this study shallow buried tunnel valleys in the central North Sea have been mapped combining multichannel 2D and 3D seismic data. The difference in quality of the dissimilar seismic data is noteworthy. The 2D data is unmigrated and has a high-frequency content. The 3D volume, however, is migrated, has a low-frequency content and a minor fold in the upper sequence. Giving the resulting weak amplitudes in the upper part of the 3D cube, one would assume that only minor details of the valley structures could be retrieved from this part. Nevertheless, the horizontal resolution has proved to be significant, and hence, the subsurface morphology of the valleys could be interpreted in much greater detail than if only vertical profiles were provided. This further enhance Praeg's (2003) conclusion that the low-frequency content of conventional seismic from exploration areas not necessarily is a limiting factor in the analysis of shallow structures.

In total 19 different tunnel valleys were identified. The valleys were presented in two overview maps resulting from mapping of two different time intervals; the first interval from the seabed (~90ms TWT) to first seabed multiple (~180ms TWT), and the second interval below first seabed multiple down to approximately 400ms TWT. The resulting map from the first interval shows laterally connected incisions which are mainly sinuous in planform. The tunnel valleys in the second interval were generally of greater magnitude than the ones in the overlying. Further, the typical seismic character of the infill sediments of these valleys was chaotic and disrupted. This is possibly caused by the lithology, however, some of these valleys are also considered to be composite tunnel valleys of several cut- and fill-structures making them more complex.

The infill sediments of the tunnel valleys have been further discussed. As no direct information about the infill has been available, the interpretations have been tentative. However, the possibility of porous and permeable sediments within the valleys is assumed to be conspicuous. Though, these valleys are presumably forming a network capable of transporting gas great distances as well as storing a significant volume of gas. It has be calculated an extreme case for the storage capacity of the tunnel valleys. The resulting value would be equivalent to a 100m thick sandstone layer, with a porosity of 25%, covering a similar area as the 3D volume (1080km$^2$).

Entrapment of gas inside the tunnel valley network can decrease the possibility of gas leaking to the surface. When evaluating storage of greenhoude gases this can be beneficial as it may contribute to reduce the risk of possible spillage. However, shallow features containing gas might as well be a potential hazard while drilling wells. Hence, there are reasons for the petroleum industry to take interest in tunnel valley mapping.

This study has not evaluated the origin of tunnel valleys based on shape, infill or seismic character. It is obvious that ice sheets have been present in the area more than once as several stacked generations of tunnel valleys have been observed. In the future more work can be done in this area to improve the understanding of tunnel valleys. Additionally, this may contribute to further constrain the pattern of the ice-sheets during the last glaciations. Moreover, to improve the knowledge about the valley infill sedimentoligical and petrophysical logs from the area can be investigated.

# Refrences


Aadnoy, B.S. & Bakoy, P., 1992. Relief well breakthrough in a North Sea problem well. *Journal of Petroleum Science and Engineering 8*, p.133-152.

Aavseth, P., Mukerji, T. & Mavko, G., 2005. *Quantitative Seismic Interpretation- Applying Rock Physics Tools to Reduce Interpretation Risk*. Cambridge University Press, Cambridge, UK.

Avseth, P., Mavko, G., Dvorkin, J. & Mukerji, T., 2001. Rock Physics and Seismic Properties of Sands and Shales as a Function of Burial Depth. *SEG Annual Meeting, September 9-14*, 2001, San Antonio, Texas.

Bennett, M.R. & Glasser, N., 2009. *Glacial Geology: Ice sheets and Landforms.* 2'nd edition. Wiley-Blackwell, United Kingdom.

Cameron, T.D.J., Stoker, M.S. & Long, D., 1987. The history of Quaternary sedimentation in the UK sector of the North Sea Basin. *Journal of the Geological Society, London. 144*(1987), p. 43-58.

Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Jordan, C. & Sejrup, H.P., 2010. Pattern and timing of retreat of the last British-Irish Ice Sheet. *Quaternary Science Reviews 29*(2010), p.1-35.

Ehlers, J., Meyer, K.-D. & Stephan H.-J., 1984. Pre-Weichseelian glaciations of North-West Europe. *Quaternary Science Review 3*(1), p 11-40.

Graham, A.G.C., Lonergan, L. & Stoker, M.S., 2007. Evidence for Late Pleistocene ice stream activity in Witch Ground Basin, central North Sea, from 3D seismic reflection data. *Quaternary Science Reviews 26* (2007), p.627-643.

Huuse, M. & Lykke-Andersen, H., 2000. Overdeepened Quaternary valleys in eastern Danish North Sea: morphology and origin. *Quaternary Science Reviews 19*(2000)*,* p. 1233-1253.

Jørgensen, F. & Sandersen, P.B.E., 2006. Buried and open tunnel valleys in Denmark- erosion beneath multiple ice sheets. *Quaternary Science Reviews 25*(2006), p.1339-1363.

Kehew, A.E., Piotrowski, J.A. & Jørgensen, F., 2012. Tunnel valleys: Concepts and controversies- A review. *Earth-Science Reviews 113*(1-2),p.33-58

Kristensen, T. B., Piotrowski, J.A., Huuse, M., Clausen O. R. & Hamberg, L., 2008. Time-transgressive tunnel valley formation indicated by infill sediment structure, North Sea- the role of glaciohydraulic supercooling. *Earth Surface Processes and Landforms 33*(2008), p. 546-559.

Kristensen, T.B. & Huuse, M., 2012. Multistage erosion and infill of buried Pleistocene tunnel valleys and associated seismic velocity effects. *Geological Society, London, Special publications, 368*(2012).

Kristensen, T.B., Huuse, M., Piotrowski, J.A. & Clausen, O.R., 2007. A morphometric analysis of tunnel valleys in the eastern North Sea based on 3D seismic data. *Journal of Quaternary Science 22*(8), p.801-815.

Leraand, F., Whright, J.W., Zachary, M.B. and Thompson, B.G., 1992. Relief-Well Planning and Drilling for a North Sea Underground Blowout. *Journal of Petroleum Technology 44*(3), p. 266-273.

Lonergan, L., Maidment, S.C.R. & Collier, J.S., 2006. Pleistocene subglacial tunnel valleys in the central North Sea basin: 3D morphology and evolution. *Journal of Quarternary Science 21*(8), p.891-903.

NORLEX. Nordland formation. Retrieved from:
http://nhm2.uio.no/norges/litho/nordland.php

North, F.K., 1985. *Petroleum Geology.* Allen & Unwin, Boston, USA.

NPD fact-pages[1]. Nordland group. Retrieved from
http://factpages.npd.no/ReportServer?/FactPages/PageView/strat_Litho_level1_group_formation&rs:Command=Render&rc:Toolbar=false&rc:Parameters=f&NpdId=113&IpAddress=80.202.23.60&CultureCode=en

NPD fact-pages[2]. Well 2/4-14. Retrieved from
http://www.npd.no/engelsk/cwi/pbl/en/well/all/1343.htm.

Ó Cofaigh, C., 1996. Tunnel valley genesis.(Abstract). *Progress in Physical Geography 20* (1), p. 1-19

Parasnis, D.S., 1997. *Principles of applied geophysics*. 5'th edition. Chapman &Hall, London, UK.

Praeg, D., 2003. Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin-high resolution from low frequencies. *Journal of Applied Geophysics 53* (2003), p. 273-198.

Prestvik, T., 2001. *Petrologi og geokjemi.* Vett og Viten as, Nesbru, Norway.

Schlumberger Oilfield Glossary. Common midpoint. Retrieved from:
http://www.glossary.oilfield.slb.com/Display.cfm?Term=common%20midpoint

Sejrup, H.P., Haflidason, H., Aarseth, I., King, E., Forsberg, F., Long, D. & Rokoegen, K., 1994. Late Weichselian glaciation history of the northern North Sea. *Boreas 23*, p. 1-13.

Sejrup, H.P., Larsen, E., Landvik, J., King, E.L., Halfildason, H. & Nesje, A., 2000. Quaternary glaciations in southern Fennoscandia: evindence from southwestern Norway and the nothern North Sea region. *Quaternary Science Reviews 19*, p.667-685.

Sheriff, R.E., 1989. *Geophysical methods*, Prentice Hall, Englewood cliffs, New Jersey, USA.

Siegert, M.J. & Dowdeswell, 2002. Late Weichselian iceberg, surface-melt and sediment production from the Eurasian Ice Sheet: results from numerical ice-sheet modeling. *Marine Geology 188*(2002), p.109-127.

Stephenson, D.A., Fleming, A.H. & Mickelson, D.M., 1988. Glacial deposits. In *The Geology of North America O-2* , Hydrogelology , p. 301-314. Geologic Society of America, USA.

Wingfield, R., 1990. The origin of major incisions within the Pleistocene Deposits of the North Sea. *Marine Geology 91*(1990), p.31-52.

Yilmaz,O, 2001. *Seismic Data Analysis: Processing, Inversion, and Interpretation of Seismic Data*. Reviewed edition of Seismic Data Processing, 1987, Society of Exploration Geophysicists, Tulsa, USA.