Controls on hydrocarbon column-heights in the Eastern province of Haltenbanken, the Norwegian Sea

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Abstract

Knowledge of controls on hydrocarbon column-heights is highly relevant in hydrocarbon exploration, and important for determination of in-place volumes of prospects. The eastern province of Haltenbanken in the Norwegian Sea constitutes a normally- to hydrostatic pressured region, and is host to several large oil and gas fields as well as minor discoveries. This study aims to investigate the controls on the hydrocarbon column-heights and the distribution of hydrocarbons in the area. Regional seismic interpretation of the main reservoir units in the area, the Fangst and Båt Groups, has been conducted on the basis of 3-D seismic and published well data. Investigation and mapping of fluid contact locations relative to spill points allowed for distinguishing between filled and underfilled structures. Seismic amplitude variations in the overburden above the Jurassic reservoirs were investigated to identify potential areas of leakage.

Results from the 15 investigated structures in the study area can give the following categorization: 1) fluid contacts coinciding with spill point, 2) fluid contacts that do not coincide with spill point and 3) structures where it was not possible to determine the controlling factors. Nine structures have fluid contacts coinciding with spill point, and are suggested to be filled. The location of spill point is suggested to be the controlling factor on the column-height in these structures. One structure is suggested to be underfilled, and in one of the structures the uppermost reservoir level is suggested to be underfilled while deeper reservoir levels are likely filled. The column-heights in the reportedly underfilled reservoirs are suggested to be controlled by vertical leakage. In one of the structures the fluid contact is located deeper than spill point, and the column-height is suggested to be controlled by fault sealing and/or leakage through the seal. The controlling factor on hydrocarbon column-heights in the remaining four structures remains unclear, as it has not been possible to map the fluid contacts relative to spill point. Two additional dry structures in the area were investigated, where lack of migration and lack of structural closure is suggested to be the cause for the lack of hydrocarbons.

Investigation of hydrocarbon distribution and migration routes in the study area indicated three main fill-spill routes, all directed towards the northern areas of Haltenbanken.

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1 Introduction

Haltenbanken is host to some of the largest hydrocarbon discoveries made in the Norwegian Sea. This broad fault terrace, located on the passive Mid-Norwegian continental margin, holds a total of 11 fields and over 30 discoveries (NPD, 2016). The majority of these accumulations are found in Jurassic traps, dominated by major to minor rotated fault blocks (Fig. 1.1 & 1.2). The eastern province of Haltenbanken is generally characterized by the presence of normal to hydrostatic pressure, as opposed to the over-pressured western province.

A large part of the hydrocarbon accumulations on the Norwegian Continental Shelf have presumably been discovered, and the industry is facing new challenges in search for future commercial discoveries. The advancement of technology over the past decades has given improved insight and knowledge in hydrocarbon exploration, and the introduction of 3-D seismic data in more recent years has allowed for more advanced mapping of the subsurface geology. However, drilling of dry traps and non-commercial discoveries is still a major concern. Determination of the hydrocarbon column is thus one of the key uncertainty factors when evaluating the presence of hydrocarbon volumes in un-drilled structures. Improved knowledge of factors controlling the hydrocarbon column-height is therefore of high value and can contribute to improved evaluation of prospects and decision-making in hydrocarbon exploration.

Haltenbanken is separated from the Trøndelag Platform in the east by the Bremstein Fault Complex and from the Frøya High to the south by the Vingleia Fault Complex. In the west the Klakk Fault Complex separates the terrace from the Møre and Rås basins, while in the north-northeast it merges into the Dønna Terrace. Two dominating fault trends in the area; N-S and NNE-SSW, give Haltenbanken its rhombic shape (Blystad et al., 1995). Several oil and gas discoveries, as well as dry traps, have been encountered in Haltenbanken since the Norwegian Sea was first opened for exploration activity in 1980 (Figure 1.3). The first six blocks were opened for licensing in 1979, and the first licenses were awarded the following year. Results from the first two seasons of drilling in 1980 and 1981 supported the possibility of making commercial discoveries on the Mid-Norwegian continental shelf (NPD, 2016). In the early stages, exploration in the Norwegian Sea was mainly restricted to Jurassic targets (Henriksen et al., 2005). Several large discoveries were made within the first few years of exploration. The recent exploration has been more focused on stratigraphic traps in the syn-rift play, whereas the early drilling focused on the pre-rift play (Koch & Heum, 1995). In more recent years, the exploration trend has shown more successful drilling results – with fewer dry wells (Fig. 1.3). Recent discoveries in Haltenbanken include structures such as Pil and Bue in 2014 and Imsa South and Boomerang in 2015. Of the structures studied in this thesis, the Midgard and Tyrihans fields were amongst the first to be discovered – in 1981 and 1983 respectively. Oil was proven in the Draugen Field the year after. In 1985, both the Smørbukk and the Heidrun fields were discovered – both proven to be oil and gas bearing. Oil and gas was discovered in the Njord Field in 1986. Heidrun Nord was found gas bearing in 1990, and several smaller discoveries have been made since - including Sigrid in 2001, Yttergryta in 2007, Natalia in 2008 and Nona in 2009.

Investigation of 3-D seismic data has been conducted in several studies in order to identify controls on the hydrocarbon column-heights and potential causes for reduced volumes in structures on the Norwegian Continental Shelf. Løseth et al. (2009) have given a detailed study of leakage processes taking place above a hydrocarbon-filled trap and how leakage is expressed on seismic data. Kristiansen (2011), Georgescu (2013) and Nylend (2015) all conducted studies on hydrocarbon column restriction and leakage in the Barents Sea. Similar studies have also been conducted by Sollie (2015) in the northern North Sea and Ersland (2014) in the western region of Haltenbanken.

Previous studies on column-height controls in Haltenbanken have largely been focused on the overpressured region. The western part of Haltenbanken is highly over-pressured (> 30MPa), while the eastern and central parts have fluid pressures close to hydrostatic (Skar et al, 1999). The overpressures at Haltenbanken, however, are significantly lower than those found in the North Sea at similar depths. Hermanrud & Bolås (2002) work on analysis of pore pressures in western Haltenbanken suggested that the pore pressures are controlled by vertical leakage through fracturing. Furthermore, they suggested that glacial flexuring resulted in fatal leakage due to formation of high paleo stress during repeated glaciations and deglaciations in the Quaternary. In a study of individual structures in western Haltenbanken, Ersland (2014) investigated leakage zones, potential column-restricting faults as well as amplitude anomalies in the overburden. The main conclusion from this study was that structures that are filled to structural spill point are in pressure communication with shallower, dry structures, while underfilled and dry structures are related to a fluid contact coinciding with fault intersections.

This study, however, was restricted to gas-filled structures in the over-pressured region of Haltenbanken only. A study of controls on hydrocarbon column-heights in the eastern normal pressured region of Haltenbanken has yet to be conducted - and is the area of concern for this thesis.

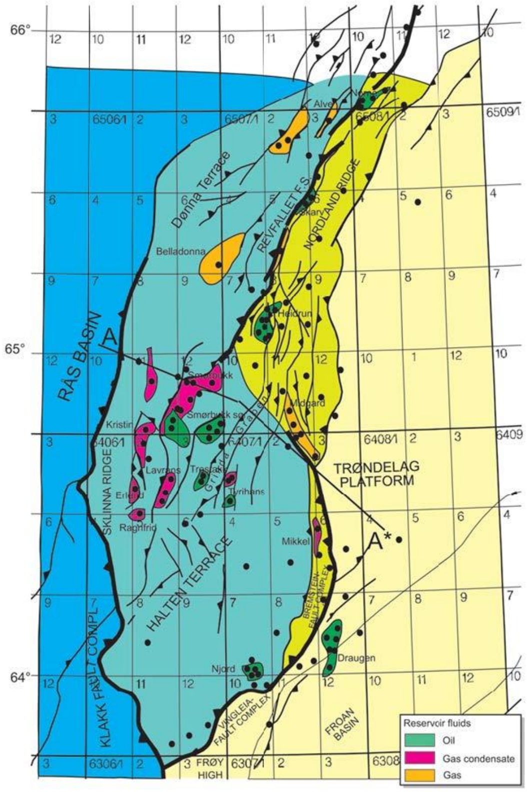


Figure 1.1: Map of structural elements in Haltenbanken and surrounding areas. Main faults and larger developed fields are outlined (From Nysæther, 2006).

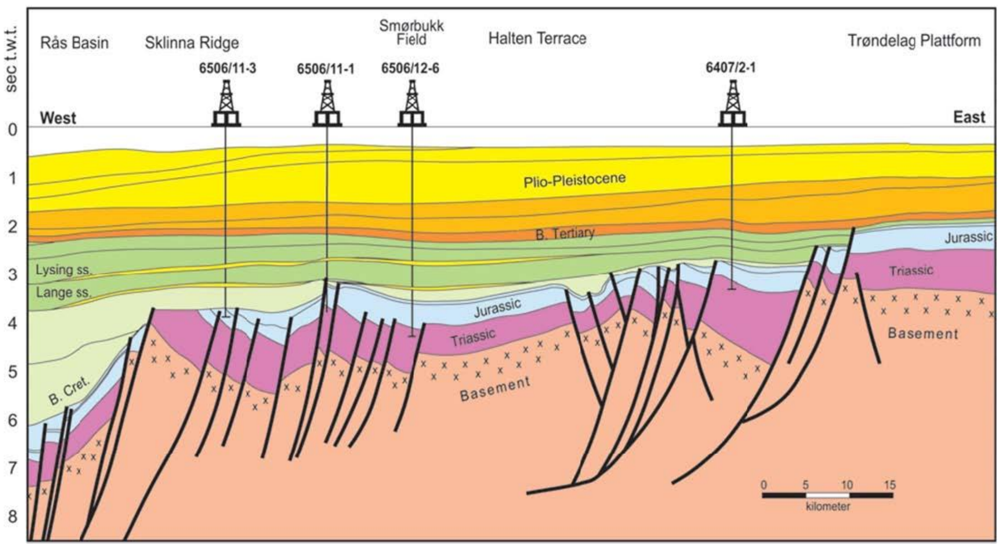


Figure 1.2: Structural profile of Haltenbanken and surrounding areas from W to E (displaying section A-A* in Figure 1.1), illustrating the eastern region dominated by larger tilted fault blocks and the western region dominated by smaller fault blocks. Vertical scale shows two-way travel-time in seconds (From Nysæther, 2006).

Figure 1.3: Overview of the exploration history in Haltenbanken. Wells presented are number of *wildcats* drilled per year (Source: The Norwegian Petroleum Directorate (2016)).

The overall aim of this thesis is to investigate controls on hydrocarbon column-heights in Jurassic reservoirs in the eastern province of Haltenbanken. Investigation of fluid contacts, spill points and seismic characteristics of the reservoirs and overburden has been conducted in order to improve the knowledge of the hydrocarbon distribution in the area and to distinguish filled structures from structures with reduced hydrocarbon columns. This is carried out by interpreting 3-D seismic datasets provided by Statoil (2004 and 2007), as well as well data from the Norwegian Petroleum Directorate and Statoil. Furthermore, the distribution of hydrocarbons and fill-spill routes are studied to get a better understanding of the migration history and present day location of fluid contacts.

This study is focused on the structures in the eastern region of Haltenbanken, within quadrants 6406, 6407, 6506 and 6507. It covers the areas to the east and west of the Grinda Graben, the Høgbraken Horst and the Gimsan Basin. To adequately confine the extent of this study, a selected number of structures have been chosen based on location, available data and previous work.

2 Geological background

The Mid-Norwegian continental margin differs from other margins as it has experienced an unusual long rifting phase along with major tectonic activity continuing after crustal separation (Bukovics & Ziegler, 1985). Collision between the Laurentian and Fennoscandian plates led to the development of the Caledonian orogeny during Ordovicium to Devon. The sedimentary basins of Mid-Norway are superimposed on this Caledonian suture. Wrench movements during Devonian and Early Carboniferous times resulted in a deeply fractured and weakened crust. These fractures later became reactivated during following rifting phases. Regional crustal extension episodes caused subsidence of a complex graben system, culminating with the crustal separation between Greenland and Eurasia in Early Eocene (Bukovics & Ziegler, 1985).

2.1 The Mesozoic

The Mesozoic Era is the most important time period for the occurrence of source and reservoir rocks, as well as the preservation of hydrocarbons in the Norwegian Continental Shelf.

The Triassic period was dominated by a globally dry and arid climate resulting in continental deposition such as evaporates and redbeds. The Triassic evaporites strongly influenced the structural development of the Haltenbanken area by decoupling Triassic and younger strata from the older strata and basement. This led to the formation of extensional forced folds as the Triassic evaporites behaved in a ductile manner. Many of the normal faults in the area are basement-detached, listric, faults that flatten within the evaporites. Older strata below the Triassic evaporites show no signs of this deformation (Withjack et al., 1988).

While crustal extension in the Norwegian-Greenland Sea area accelerated during the Early Triassic, rifting in the Haltenbanken area initiated in the Early Jurassic and reached its climax in the middle Early-Late Jurassic (Bukovics et al., 1985; Marsh et al., 2010). The tectonic extension in the post-evaporite sequence was localized on a few large structures (Marsh et al., 2010).

The Early Jurassic Åre Formation of the Båt Group is one of two main source rocks in Haltenbanken, and is mature for condensate generation in the eastern part of the area (Koch & Heum, 1995). The formation consists of coastal plain to delta plain deposits (Dalland et al., 1988). Sedimentation involved the progradation of the coastlines by sediment influx of sand from the west onto the shelf. The sediment influx originated from the present deep Cretaceous Møre and Vøring Basins, as these basins were subject to uplift and deep erosion in the Middle Jurassic. Hence, the basin areas were sites of thermal domes in that period, creating an erosional unconformity (Brekke et al., 2001). Another important formation deposited in the Early Jurassic is the Tilje Formation. The formation forms both a primary and secondary reservoir unit in several Mid-Norway fields. This shallow-marine, tidally dominated formation marks a change from the fluvial deposition in the Åre Formation (Brekke et al., 2001; Dalland et al., 1988). The sedimentation pattern in the area was strongly controlled by the tectonic activity during the Late Jurassic (Martinsen & Dreyer, 2001). The late Early Jurassic Tofte Formation is only recognized in the western part of Haltenbanken, and wedge out eastwards where it interfingers with the Ror Formation. The sandstones of the Tilje Formation were deposited by eastwards prograding fan deltas - reflecting a tectonic uplift to the west. The Ror Formation was deposited in open shelf environments below wave base. Sand input from the west also indicates the synsedimentary uplift in the west (Dalland et al., 1988).

The Ile Formation of the Fangst group was deposited during the Early- to Middle Jurassic in various tidal influenced delta or coastline settings (Dalland et al., 1988). A semi-regional transgression resulted in the deposition of the Not Formation, and lagoons or sheltered bays were developed. The Middle-Jurassic Garn Formation was deposited by progradations of braided delta lobes. This formation is time equivalent to parts of the Brent Group in the North Sea and the Stø Formation in the Hammerfest Basin (Dalland et al., 1988).

The initial phase of the major extensional tectonic period that caused the break-up of the Central Atlantic started in the end of Middle-Jurassic Epoch in the Norwegian-Greenland Sea. When the North Sea dome deflated in the early-to middle-Late Jurassic, the elevated areas in the central parts of the Møre and Vøring Basins subsided rapidly. These events led to the development of a more complicated system of tectonic highs and basins, and the Vøring and Møre Basins were separated from the basins of East Greenland (Brekke et al., 2001). At the same time, a major sea-level rise flooded most of the topography, and the deposition was entirely dominated by open marine claystone deposition. The Melke Formation of the Viking Group is one of the formations deposited during this time. This period was followed by a regional sea-level fall. This fluctuation in sea level in combination with the tectonic circumstances appears to have been favorable for widespread accumulations of large black shales – with very good source potential (Brekke et al., 2001). The Spekk Formation of Late Jurassic age was deposited under such anoxic bottom water conditions (Dalland et al., 1988). The Spekk Formation is mature for oil in the central part of Haltenbanken and at an early maturation stage in the eastern part of the terrace (Koch & Heum, 1995). High-energy shallow marine sheet sands and bar deposits like the Rogn Formation were later deposited as a result of erosion of the crest of the fault blocks (Brekke et al., 2001).

In the Early Cretaceous a low-stand in the Ryazanian was followed by a renewed sea-level rise in the Barremian. The Norwegian Sea was still dominated by structural highs and platform areas, and the Ryazanian/Berriasian erosional unconformity on top of the carbonaceous marine shales is present across the entire region. Deep basin areas still continued to form by subsidence along the rift axis of the Møre and Vøring Basins. The central platform area of the Norwegian-Greenland Sea, separating the Møre and Vøring Basins from the Jameson Land Basin, is likely to have existed throughout Cretaceous times (Brekke et al., 2001). The platform areas and structural highs became eroded and capped by a condensed sequence of limestone and marl - such as the Lyr Formation. A sudden sea-level drop in the Barremian halted the widespread deposition of shale and marl, giving way for renewed delta progradations. The Lange Formation was then deposited in a shallow marine environment in Haltenbanken, although deep marine in the western basins (Dalland et al., 1988). A new pulse of regional transgression followed, and continued into the Late Cretaceous. This subsequently led to drowning of the intrabasinal highs and surrounding lands (Brekke et al., 2001).

In the Late Cretaceous the Norwegian-Greenland Sea area was subjected to tectonic activity linked to seafloor spreading in the Labrador Sea. This resulted in faulting, accelerated basin subsidence and conjugate uplift, tilting and emergence of the bounding platform areas to the major basins, such as the Møre and Vøring Basins (Brekke et al., 2001). Deep marine mudstones were deposited along with turbudites of considerable thickness in local depo-centres. These sands may have been derived from the emergent axial platform areas to the west and north, or transported from Greenland along regional channels (Brekke et al., 2001). The Lysing Formation, consisting of turbudites, has been interpreted to be submarine fan deposits of Late Cretaceous age (Dalland et al., 1988). As the basins of the Norwegian-Greenland Sea continued to subside rapidly, the formations of the Shetland Group (The Kvitnos-, Nise- and Springar formations) were likely to have been deposited. These are all open marine deposits (Brekke et al., 2001; Dalland et al., 1988).

2.2 The Cenozoic

The widespread Late Cretaceous tectonic episode may be viewed as plate tectonic adjustments and rifting in the North Atlantic leading to the final continental break-up in the Norwegian-Greenland Sea area in the Late Paleocene/Early Eocene (Brekke et al., 2001). This was associated with a large-scale regional uplift. The axial part of the Norwegian-Greenland Sea became highly uplifted due to increased heat flow along the future spreading axis prior to the break-up (Brekke et al., 2001).

The regional uplift is evident from a hiatus and erosional break of late Danian/early Thanetian age across the Møre- and Vøring Basin area. These basins experienced a dramatic shallowing during this time (Brekke et al., 2001). In the Haltenbanken area the deep marine Tang Formation directly overlies the open marine Springar Formation. The Tare Formation was also deposited in the deep marine environment during the Danian to Late Paleocene (Dalland et al., 1988). Marine sedimentation continued in Eocene, and the Brygge Formation claystones were deposited in Haltenbanken (Dalland et al., 1988).

The Oligocene and Miocene of the Norwegian continental margin reflect the sedimentation on a marine, subsiding passive margin overprinted by intermittent regional phases of tectonic movements and uplift (Brekke et al., 2001). Two main phases of compression during the latest Eocene/earliest Oligocene and Middle Miocene are associated with the formation of intrabasinal domes and arches in the Vøring Basin and around the Faeroe Islands. The compressive deformation can be related to the transform movement along the Jan Mayen Fracture Zone, and the subsequent rearrangement in seafloor spreading axes in the Norwegian-Greenland Sea (Brekke et al., 2001; Bukovics & Ziegler, 1985; Doré & Lundin, 1996). This coincides with the regional hiatus on the eastern basin margins across

Haltenbanken, separating the Brygge Formation from the Early Miocene to Late Pliocene Kai Formation (Brekke et al., 2001; Dalland et al., 1988).

Periods of glaciations caused by the climatic deterioration in the Neogene had a significant impact on the sediment supply to the shelf in the Late Pliocene and Pleistocene (Brekke et al., 2001). Huge sediment volumes were deposited as a result of deep mainland erosion due to the onset of major glaciations at approximately 2.7 Ma. A regional hiatus is present in the lower part of the Upper Pliocene along the Norwegian continental margin. In parts of the Vøring Basin, the Upper Pliocene sediments rest on the Middle Miocene unconformity. On the shallow parts of the margin is an erosional unconformity below the glacigenic sediments, formed as a result of large ice sheets extending out to the shelf break (Brekke et al., 2001). The late Pliocene Naust Formation was deposited on top of this unfonformity, in a marine environment with a possible transition to glaciomarine environments in the upper part (Dalland et al., 1988).

During the last 2.7 Ma, large quantities of glacially derived material were transported from the Norwegian mainland areas and inner shelf and deposited as prograding sediment wedges into offshore Mid-Norway. In the Haltenbanken-Trænabanken region the shelf edge migrated 100-150 km westwards (Rise et al., 2005). Four major glacial events occurred during the Pleistocene, the latest Weichselian glaciation (15-30 ka) being the best known (Mangerud, 2004). The largest Weichselian ice sheet covering Scandinavia is argued to have reached a thickness over 2 km (Siegert et al., 2001). The glaciations were followed by postglacial lithospheric bending; causing lateral stress variations on the mid-Norwegian margin (Grollimund & Zoback, 2003). After melting of the last ice sheets, isostatic processes has led to a large-scale uplift of Fennoscandia. The postglacial doming is estimated to have a maximum uplift value of 850-900 m (Fjeldskaar et al., 2000; Gudmundsson , 1999).

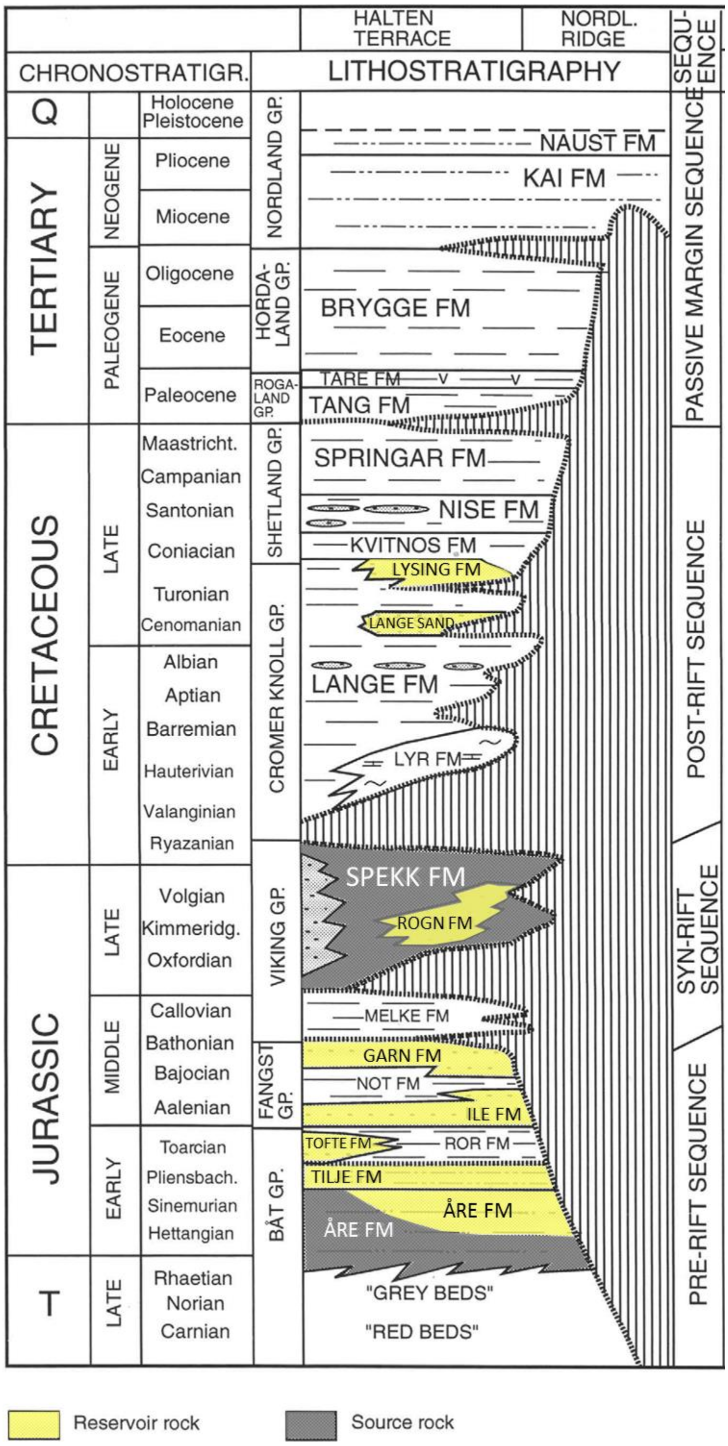


Figure 2.1: Lithostratigraphic column of Haltenbanken. Rifting sequences refer to the main rifting sequences leading to the formation of the terrace (Modified from Dalland et al. (1988) and Koch and Heum (1995)).

3 Background theory

This chapter provides a brief review of definitions and relevant topics for understanding controls on hydrocarbon column-heights as well as accumulation and migration of hydrocarbons.

3.1 Hydrocarbon generation, migration and accumulation

Hydrocarbon generation takes place with deep burial of shale and coal beds with high content of organic matter. The process is time- and temperature controlled. The main source rocks in the Haltenbanken region belong to the Spekk, Melke and Åre formations. The Spekk Fm. is of Upper Jurassic to Lower Cretaceous age, the Melke Fm. of Middle to Upper Jurassic age and the Åre Fm. of Upper Triassic to Lower Jurassic age. The Åre Fm. also acts as a reservoir in some of the structures, usually in the upper sandstone layers of the formation. The Spekk Fm. is a highly favorable source for oil, while the Åre Fm. contains layers of coals and shales that give rise to a mainly mixed oil and gas (Karlsen et al., 2004). Hydrocarbon generation in the area has been assumed to have initiated significantly earlier in the deeper laying Åre Formation than in the shallower Spekk Formation - during Mid- to Late Tertiary. Expulsion from the Spekk and Melke formations may have occurred as late as Neogene, while expulsion from the Åre Formation may have occurred as early as Early Paleogene. When it comes to the maturity of the hydrocarbons in the area, it generally follows a consistent E-W trend, indicating that the lateral migration distances from structure to structure are relatively short.

Transport of hydrocarbons from the source rock to the reservoir is referred to as migration. Hydrocarbons migrate from low permeability source rocks into high permeability reservoir rocks driven by buoyancy. Migration of hydrocarbons can be divided into primary migration and secondary migration (Tissot & Welte, 1984; Bjørlykke, 2010).

3.1.1 Primary migration

Primary migration is described as the flow of petroleum out of the generating source rock into permeable rocks (Fig. 3.1). The breakdown of kerogen into petroleum causes pressure build up in the source rock, as the volume increases. This leads to fracturing of the rock, and the increased permeability lets hydrocarbons escape and migrate towards permeable layers. The hydrocarbons can also escape through the pore network, in the presence of thin sandy or silty layers acting as migration pathways (Bjørlykke, 2010).

3.1.2 Secondary migration

Secondary migration is the movement of hydrocarbons from the source rock to the reservoir rock, or up to the surface (Fig. 3.1). This migration is mainly driven by buoyancy, as well as pressure gradients. Oil and gas will flow upwards along the upper parts of the reservoir layers, and will be accumulated if they reach a trap. Hydrocarbons will migrate upwards until they reach the surface, unless capillary resistant forces of a cap rock, such as impermeable shale, prevent further flow (Bjørlykke, 2010). Juxtaposition of permeable and impermeable layers due to faulting can also restrict migration. This is often the case in highly faulted basins. Cementation or shale gouge/smears along the fault planes can lead to reduced permeability and hinder migration (Lothe et al., 2006; Bjørlykke, 2010).

3.1.3 Spill point

The hydrocarbon column can accumulate to a certain depth in a reservoir. The point of maximum accumulation of a trap is referred to as the spill point (Fig. 3.1). This can be controlled by a structural spill point, or a fault spill point. The structural spill point is the deepest point of an anticline structure. The fault spill point is the point at which the hydrocarbon column can extend down to where juxtaposed reservoir layers are in communication.

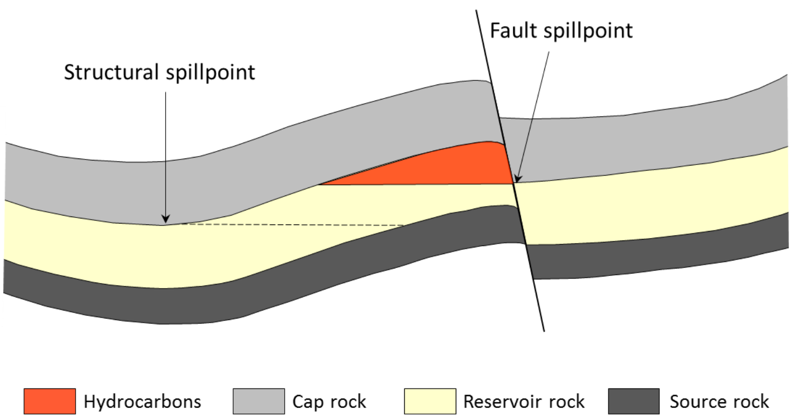


Figure 3.1: Simplified illustration of a petroleum play with structural and fault spill point.

3.2 Pore pressure

Pore pressure, also known as formation pressure, is the pressure of fluids within the pores of a geological formation. Pore pressures are generally compared to the hydrostatic pressure at the same depth – equal to the pressure of a column of formation water from the sea surface. As a formation is increasingly buried, the pressure of water in the formation increases. The hydrostatic pressure increase is close to linear with depth, and is known as the hydrostatic gradient (Osborne & Swarbrick, 1997). Normally pressured formations are in equilibrium with the hydrostatic pressure, if the pore network is interconnected all the way to sea level. These can be described as an open system (Buhrig, 1989). This is the situation in most of the structures found in Eastern Haltenbanken, as further discussed in the next section. Overpressured formations are characterized by pore pressures exceeding the hydrostatic pressure at a given depth. Overpressuring mechanisms include rapid overburden loading (high subsidence rate), aquathermal pressuring, shale dewatering and hydrocarbon generation. Overpressured formations are also referred to as closed systems. Additionally, moderately pressured reservoirs can be described as restricted systems (Buhrig, 1989).

3.2.1 Pore pressure in Haltenbanken

The main hydrocarbon discoveries in Haltenbanken are found in the Jurassic reservoirs in the lower-pressure regimes (Skaar et al., 1999). Pore pressures in the Jurassic formations in the central and eastern province of Haltenbanken are close to normal hydrostatic pressure, while the reservoir pressure increases further in the highly over-pressured western province of Haltenbanken. Major differences are observed in fluid pressures between the two hydrodynamic systems in this area; a 30 MPa pressure difference separates the water-bearing reservoirs in well 6506/11-1 in Western Haltenbanken from the hydrocarbon-bearing reservoirs in Smørbukk and Smørbukk South - wells 6506/12-6 and 6506/12-3 respectively (Koch & Heum, 1995; Skaar et al., 1999).

3.3 Trap integrity and seal failure

Analysis of trap integrity is a critical aspect in hydrocarbon exploration, as it can affect the prediction of hydrocarbon column-heights. Faults and fractures are often associated with seal failure and leakage (Bolås & Hermanrud, 2002; Hermanrud et al., 2005). Three main mechanisms can lead to leakage: shear failure, tensile failure and capillary leakage.

3.3.1 Faults and fault intersections

Faults can serve as main conduits for fluid flow in basins or they can act as sealing barriers (Sibson, 2000; Ligtenberg, 2005). Open faults are only temporary features as they will in time be closed by mechanical deformation of cemented by mineral precipitation (Bjørlykke & Høeg, 1997). Faults zones can also contain interconnected fractures that constitute preferable fluid pathways (Løseth et al., 2009). The sealing capacity of a fault is determined from a number of factors. These include the fault damage zone, the types of juxtaposed rocks across the fault zone, cataclasis, clay smear, cementation, fault complexity and orientation to the maximum horizontal stress (Gabrielsen & Doré, 1995; Harper & Lundin, 1997; Fisher & Knipe, 1998; Gartrell et al., 2004). Hydrocarbon leakage can be related to fault reactivation, controlled by locally elevated pore pressure in the reservoir, fault orientations nearly optimally oriented for fractional slip in the present day stress-field or a recent perturbation of compressional stress caused by post-glacial rebound (Wiprut & Zoback; 2002). Gartrell et al. (2004) further found that fault intersections can play an important role in trap integrity and leakage, as these can represent an effective pathway for fluid leakage. Only a small displacement could significantly reduce the permeability along a fault or fault intersection.

3.3.2 Shear and tensile failure

Fractures and faults can form by tension build up during tectonic deformation or due to glacial and unloading (Bjørlykke & Høeg, 1997). The sealing ability of a trap can be affected by the mode of failure, associated with faulting (shear failure) or fracturing (tensile failure). Faulting and fracturing are initiated when the stress state is such that the failure conditions for a rock are met. The mode of failure can determine which fault orientation is likely to slip and can thus control the hydrocarbon column in structures that have experienced fault reactivation (Hermanrud et al., 2005).

3.3.3 Capillary leakage

Hydrocarbons can leak through the pore network. This occurs when the buoyancy of the hydrocarbon phase overcomes the capillary entry pressure of the cap rock. The capillary entry pressure is determined by the radius of the largest interconnected pore throats of the seal (Berg, 1975).

3.4 Significance of seismic amplitude variations

The seismic reflection method is based on recording and measuring of seismic wave reflections at rock boundaries due to changes in the acoustic impedance. Changes in acoustic impedance are caused by lithology variations and pore fluids, where the acoustic impedance is defined as the product of the density and the compressional wave velocity (Badley, 1985). The presence of hydrocarbons in the subsurface is often recognized on seismic data, as variations in pore fluids can result in changes in acoustic impedance, and is often imaged as amplitude anomalies. This includes bright spots and dim zones, hydrocarbon related diagenetic zones (HRDZ), gas chimneys, seismic pipes, pockmarks and carbonate build up structures (Ligtenberg, 2005; Arntsen et al., 2007; Løseth et al., 2009).

3.4.1 Bright spots and dim zones

Bright spots and dim zones/spots are among the most common direct hydrocarbon indicators on seismic data. Bright spots are defined as high amplitude, negative phase anomalies related to a decrease in density/acoustic velocity (Fig. 3.2). This is caused by changes in the fluids in the subsurface rocks. Bright spots usually appear as localized, high amplitude on the seismic data. These are often observed near leaking faults, above leaking reservoirs, within reservoirs and along gas chimneys (Ligtenberg, 2005).

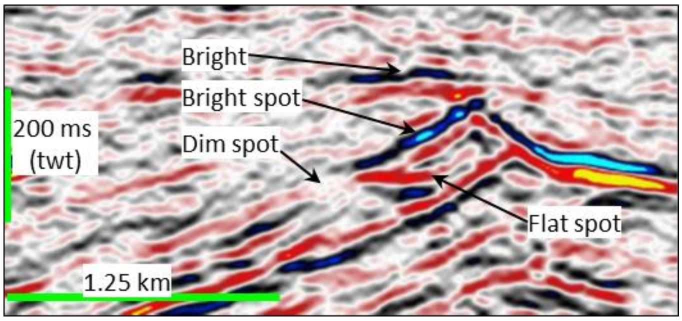


Figure 3.2: Brights, bright spots and dim spots as observed on 3-D seismic data. (Slightly modified from Løseth et al. (2009)).

3.4.2 Hydrocarbon-related diagenetic zones

Hydrocarbon-related diagenetic zones (HRDZ) are defined as high amplitude reflection with positive phase, and form when hydrocarbons leak and migrate upwards into the overburden rocks. These zones are also potential seismic indicators of hydrocarbon migration. A strong seismic response occurs as a result of localized intense carbonate cementation due to biological oxidation of hydrocarbons. These are also often related to hydrocarbon leakage (O'Brien et al., 2002; Ligtenberg, 2005).

Furthermore, seismic chimneys and seismic expressions associated with remobilized sediments are important indicators of hydrocarbon leakage, and can cause significant amplitude anomalies. These are, however, not observed in the study area.

4 Data and methodology

This chapter gives a brief overview of the data, tools, interpretation methods and workflow applied in this study. Uncertainties in relation to this are also described in the following chapter.

4.1 Seismic dataset

The 3-D seismic data set consist of two surveys, ST04M07 (2004) and ST00M01 (2000), which are provided by Statoil (Figure 4.1). The seismic survey ST04M07 is a mega-merge of several surveys and covers an area of approximately 68100 km² across the Norwegian Sea, including the Haltenbanken area. The in-lines are oriented NW-SE, the crosslines are oriented NE-SW and the horizontal interval spacing for both in-lines and crosslines is 25 meters.

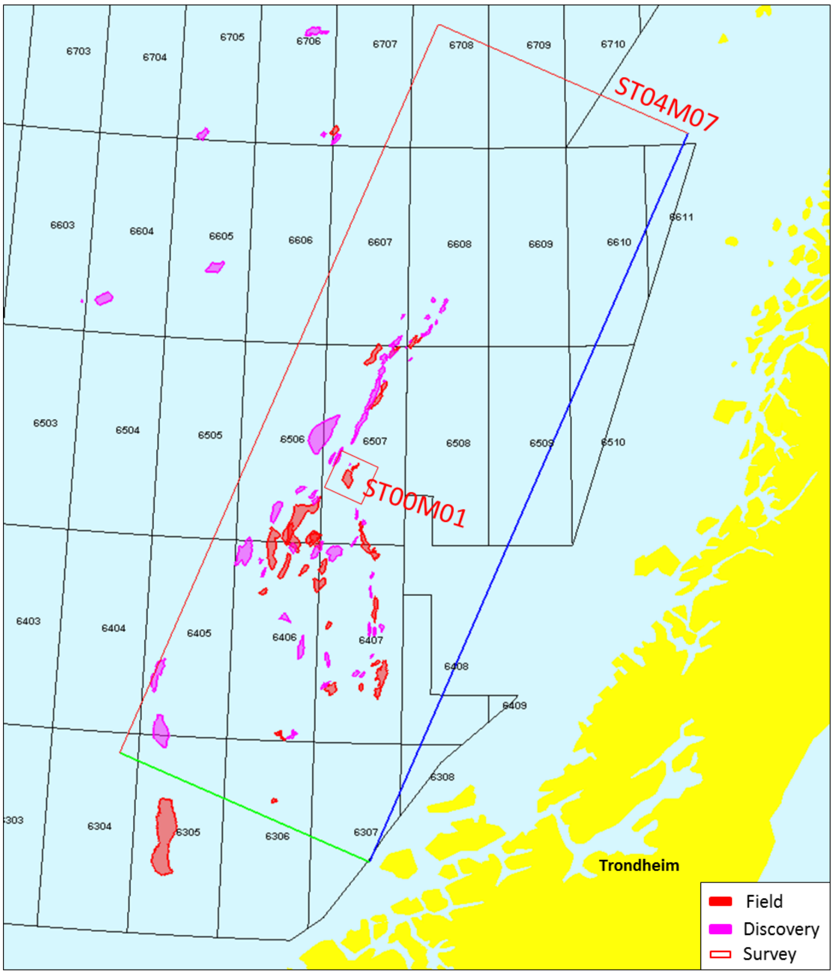


Figure 4.1: The location of the seismic surveys (ST04M07 and ST00M01) in Haltenbanken and surrounding areas in the Norwegian Sea (Retrieved and modified from Petrel and NPD fact maps, 2016).

The seismic survey ST00M01 is part of the more extensive survey Sw7000 and covers an area of approximately 261 km² in the Heidrun area in Haltenbanken, the Norwegian Sea. The in-lines are oriented NW-SE and the crosslines NE-SW. Horizontal interval spacing is 12.5 meters. The outline of the 3-D seismic cube (ST04M07) does not fully show the extent of the area covered by seismic data. The area of seismic coverage is outlined in red in Figure 4.2. All the generated surfaces in this study are positioned within this area.

The datasets are zero-phase processed and have a European standard normal polarity (Figure 4.3). Positive peaks (red reflectors) indicate an increase in acoustic impedance and negative troughs (blue reflectors) indicate a decrease in acoustic impedance.

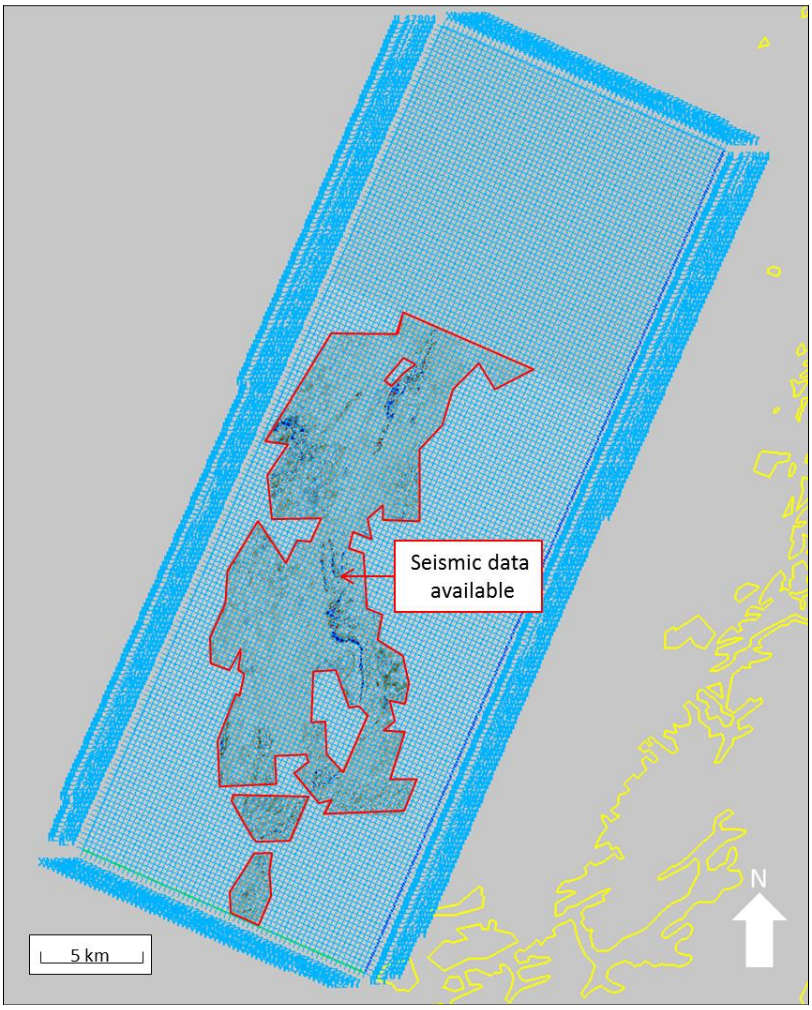


Figure 4.2: Outline of the seismic dataset. Red outline marks the area covered by seismic reflection data, and areas outside do not have seismic coverage.

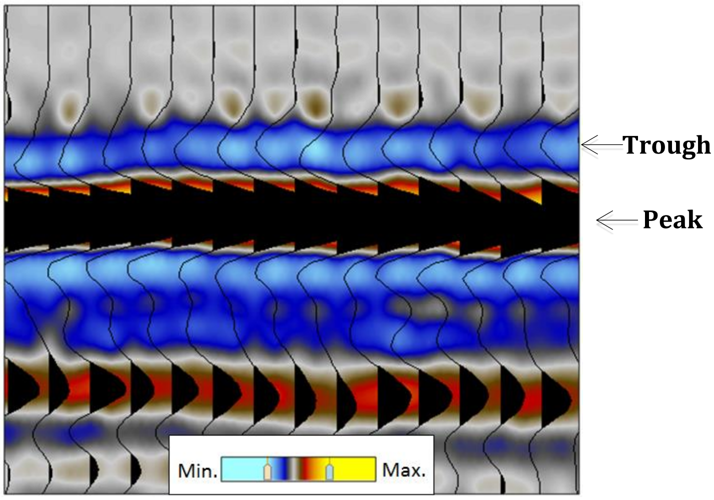


Figure 4.3: Phase and polarity of seismic cube ST04M07 and ST00M01. Amplitude scale shows color legend of reflector amplitude.

4.2 Well data

The well database was provided by Statoil ASA. 90 wells were accessible in total in this study, seven of which are located outside the seismic coverage area (Table 4.1 shows wells used for this study). Four of these wells are production wells. They have therefore not been considered when doing the seismic interpretation, as they do not contain any information about stratigraphic levels and depths. The well data comprises digital conventional well logs (i.e. gamma ray, sonic) and check-shots. Completion reports were made accessible from Statoil and the Norwegian Petroleum Directorate. These were used to obtain information about shows and residual hydrocarbons, and in some cases additional information about fluid contact depths.

Table 4.1: List of wells used in the study area. Certain wells do not give information about fluid contacts.

Wells	Structure	TD (Fm.)	TD (m)	Fluid contacts	Shows
6406/3-2	Trestakk	Åre	4522	ODT	X
6407/1-2	Tyrihans South	Grey Beds	4558	OWC	X
6407/1-3	Tyrihans North	Grey Beds	4467	N/A	X
6407/1-4		Not	3805	OWC	X
6407/2-4	Dry structure	Ile	3000	N/A	X
6407/2-5 S	Nona	Åre	3311	GDT, OWC	
6407/7-1 S	Njord Main Field	Red Beds	3925	OWC	X
6407/7-3		Åre	3716	N/A	X
6407/7-6	Njord West Flank	Åre	3971	GWC	X
6407/7-7 S		Åre	3678	N/A	X
6407/10-1	Dry structure	Grey Beds	3346	N/A	X
6506/12-1	Smørbukk	Åre	4924	OWC	
6506/12-6		Åre	4738	OWC	X
6506/12-7		Tilje	4840	N/A	X
6506/12-11 S		Åre	4843	N/A	
6506/11-2		Åre	4806	N/A	X
6506/12-3	Smørbukk South	Tilje	4359	OWC	
6506/12-5		Åre	4587	OWC	
6507/7-2	Heidrun	Åre	3260	OWC	
6507/7-3		Åre	2850	OWC	
6507/7-4		Tilje	2850	OWC	
6507/7-5		Tilje	2659	OWC	
6507/7-6		Åre	2470	GOC, OWC	X
6507/7-8		Åre	2855	OWC	
6507/7-9		Naust	850	N/A	
6507/8-1		Åre	2600	GOC, OWC	
6507/8-4	Heidrun North	Åre	2559	GOC, OWC	X
6507/11-1	Midgard	Grey Beds	3138	GWC	
6507/11-3		Grey Beds	3250	GOC, OWC	X
6507/11-5 S		Ror	2599	GOC, OWC	
6507/11-6	Sigrid	Åre	3439	GWC	
6507/11-8	Yttergryta	Åre	2772	GDC	
6507/11-9	Natalia	Åre	3058	GDC	X

4.2.1 Check-shots and well tops

Check-shots and digital well logs were used in order to carry out the seismic interpretation in the Petrel software. Well tops were first generated based on formation tops information. These were obtained from the Norwegian Petroleum Directorates (NPD) web pages, where published well reports are accessible from the well section pages. Depths were then converted to time, by the use of digital check-shots in the seismic dataset provided by Statoil. All well tops were added manually to the dataset.

4.3 Methodology

4.3.1 Seismic interpretation

Interpretation of the seismic data was carried out using the software Petrel, version 2013.5, developed by Schlumberger. Figure 4.4 illustrates the seismic interpretation workflow.

Regional interpretation of the Base Cretaceous Unconformity has been carried out, as well as a more detailed interpretation of top reservoir in the relevant structures (Top Fangst Group and Top Båt Group), and the seabed. As a first step, the seismic dataset was cropped into smaller size cubes. This was done in order to better manage the vast amount of data available in the merged dataset, and to make the software work more efficiently.

In general, manual interpretation of the seismic units was carried out by 2-D tracking with an inline interval ranging from 2-32 lines, depending on data quality and complexity of the structure. Interpretation of crosslines was also conducted in some areas to better tie interpretations. Further interpretation of the formation tops was conducted using 2-D paintbrush auto-tracking, while constantly comparing to the manual interpretation.

Surfaces were generated from the interpreted horizons by utilizing the volume attribute function. These surfaces were further used to project the obtained fluid contacts, and to locate the spill points of each structure.

4.3.2. Seismic attributes

Attribute analysis were conducted to extract relevant features from the seismic data. These were obtained by creating RMS (root mean square) and variance maps. The RMS attribute feature can give information and display the extent and intensity of bright and dim zones in a desired interval in seismic sections. This was carried out by interpreting a close continuous horizon to the relevant feature, and then generating a surface grid. The surface grid was then placed at desired level, by elevating or lowering it by a certain ms TWT. The investigated interval ranges in thickness, from +/-10 to +/-50 ms TWT.

Variance cubes were also extracted, in order to visualize the structural configuration of the different depth intervals. These were utilized as a support for the seismic interpretation. This z-depth map also gives information about local signal variation.

4.3.3 Seismic interpretation workflow

Figure 4.4 gives a simple overview of the seismic interpretation workflow, from uploading of seismic data in the Petrel software to seismic interpretation and generation of different surfaces and maps.

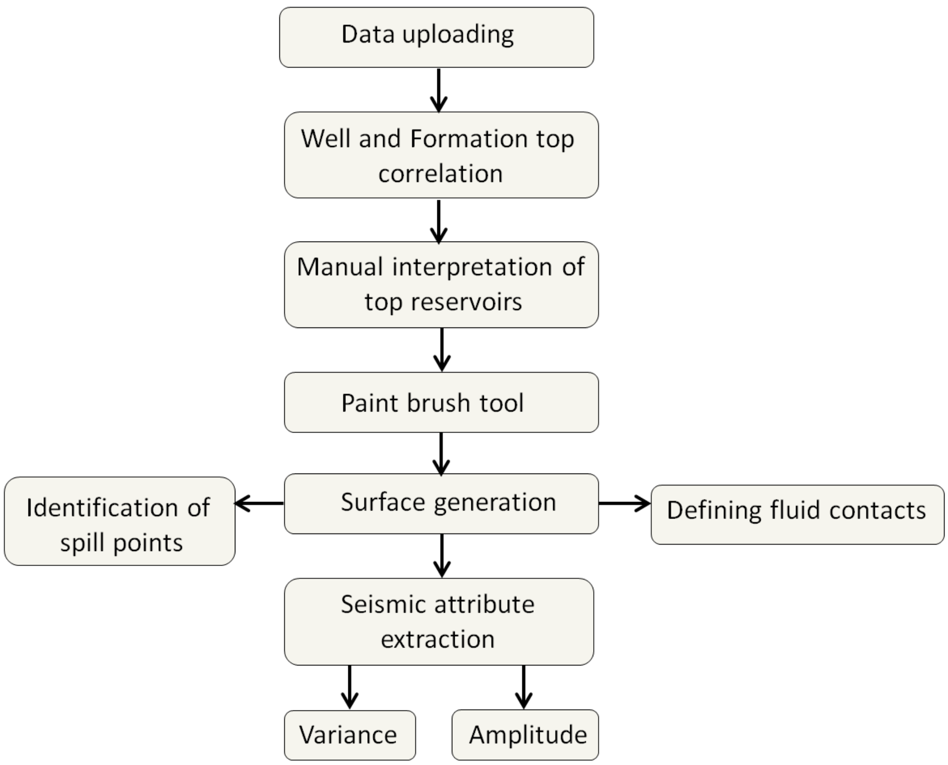


Figure 4.4: Simplified overview of the interpretation workflow.

4.3.4 Visualization of data

The Adobe Illustrator CS6 software has been utilized to create figures and illustrations such as modification of illustrations and interpretations on seismic sections in the following chapters. Seismic surfaces illustrated are displayed in a 2-D view with a vertical exaggeration of 3 and with an artificial light source in order to highlight structural features of the surface.

4.4 Uncertainties

4.4.1 Seismic resolution

Uncertainties related to seismic resolution include poor vertical and lateral resolution in certain areas of the dataset. The data quality in the southern area of the dataset, in the vicinity of the Njord structure, is poorer than in other areas. Reflectors in this area are often seen as dim or discontinuous. In some areas they disappear completely. The interpretation here is therefore associated with more uncertainty. Furthermore, the fact that the main seismic dataset is a mega-merge, consisting of several merged datasets, makes large differences in the quality and resolution. Reflectors can therefore appear at varying strength across the merged areas.

4.4.2 Data coverage

The lack of data coverage in some areas of the dataset has made mapping of the structures challenging. Uncertainties in mapping of spill points and extent of the structures are therefore significant in some areas (Figure 4.2). This has proven to be the case in Yttergryta and Heidrun North.

4.4.3 Depth conversion – check-shots

In order to carry out the seismic interpretation, depth (m) has been correlated with TWT (ms). Uncertainties can be associated with the conversion from depth to TWT – which has been calculated from check-shots in the relevant wells. In structures where additional information of fluid contacts has been given by Statoil ASA, contact depths have been compared to the additional fluid contact tables. This includes the Heidrun and Heidrun North structures. Depth conversion in structures with multiple wells shows large deviations from well to well. This could lead to the structure appearing filled according to one well, but under-filled according to another.

4.4.4 Fluid contacts

Determination of the fluid contact depths have proven to be challenging in certain structures and uncertainties regarding the hydrocarbon column can therefore occur. In some structures, fluid contacts are not established, or information has not been published by the NPD. Several of the structures only have an estimated “gas/oil-down-to” (ODT/GDT) situation proven. This is the best possible estimation of the contact depth in a well. The base of the sandstone formation layer is therefore interpreted as the lithological “gas/oil-down-to” contact. This uncertainty in fluid contact depth makes it challenging to determine whether a structure is filled to structural capacity or under-filled.

4.4.5 Uncertainty of method

As this thesis method largely relies on seismic interpretation, uncertainties regarding the method itself should be mentioned. Seismic interpretation is based on human interpretation of seismic data. In areas where no well data is available, investigation has to be made based on the interpreters understanding of the geology.

Several uncertainties are related to the data and methods utilized in this thesis. It is to be noted that these have all been taken into consideration when conducting the following analysis and interpretation.

5 Results

This chapter will present the observations, descriptions and interpretations of the structures studied in this thesis. The structures have been divided into interpreted migration routes, and are presented in the following sub-chapters (Table 5.1). Each chosen seismic section has been shown to give the best possible representation of the reservoir setting and observations made.

Table 5.1: Overview of areas and corresponding wells present in the seismic data.

Migration route	Structure	Wells			
$A_1/A_2 - A'$	Trestakk	6406/3-2			
	Smørbukk	6506/12-1	6506/12-6	6506/12-7	6506/12-11 S
		6506/11-2			
	Smørbukk South	6506/12-3	6506/12-5		
	Heidrun	6507/7-2	6507/7-3	6507/7-4	6507/7-5
		6507/7-6	6507/7-8	6507/7-9	6507/8-1
	Heidrun North	6507/8-4			
B-B'	Tyrihans South	6407/1-2			
	Tyrihans North	6407/1-3	6407/1-4		
	Sigrid	6507/11-6			
	Natalia	6507/11-9			
C-C'	Nona	6407/2-5 S			
	Midgard	6507/11-1	6507/11-3	6507/11-5 S	
	Yttergryta	6507/11-8			
	Njord	6407/7-1 S	6407/7-3		
	Njord West Flank	6407/7-6	6407/7-7 S		
	Dry structure	6407/2-4			
	Dry structure	6407/10-1			

The following structures presented in this chapter have been investigated in order to further determine the controls on hydrocarbon column-heights in the area. Wells present in each structure are listed in the above table. A number of structures are drilled by more than one well, and/or by wells which are not included in this study. The following analysis however, is based on available well data included in the provided dataset. A display of the study area and location of the structures is presented in Figure 5.1, by a regional Base Cretaceous Unconformity (BCU) surface map. The BCU surface map is displayed in order to give a coherent overview of the study area.

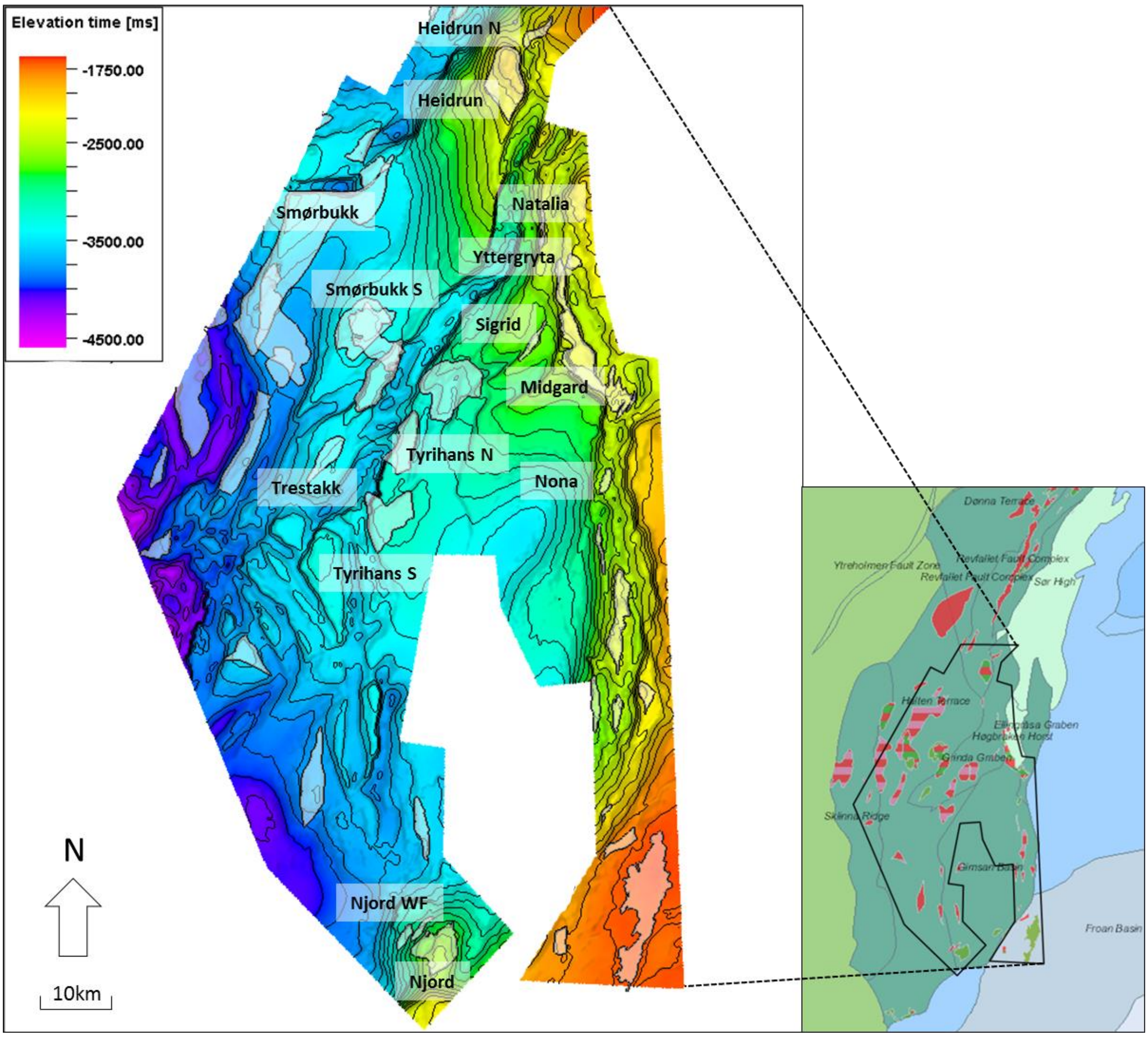


Figure 5.1: Overview of the study area: Base Cretaceous Unconformity surface map with structures outlined in white. Areas cut out of the surface map are areas located outside of the seismic data coverage.

No regional top reservoir surface has been possible to map across this extensive area in the given time frame. This surface map, however, gives a good indication of the N-S to NW-SE trending fault patterns, as well as a general outline of the structural configuration in the area.

The following investigated structures have been chosen to adequately fit the extent of this study. Consequently a number of structures in Eastern Haltenbanken are not included in the following analysis (Figure 5.2). Other structures have not been included due to lack of data coverage or due to newer discoveries which have not yet released well data (e.g. Pil and Bue (6406/12-3 S, 6406/12-3 A), Novus (6507/10-2 S)). Structures in the western part of Haltenbanken, in the over-pressured regime, have previously been studied by Ersland (2014).

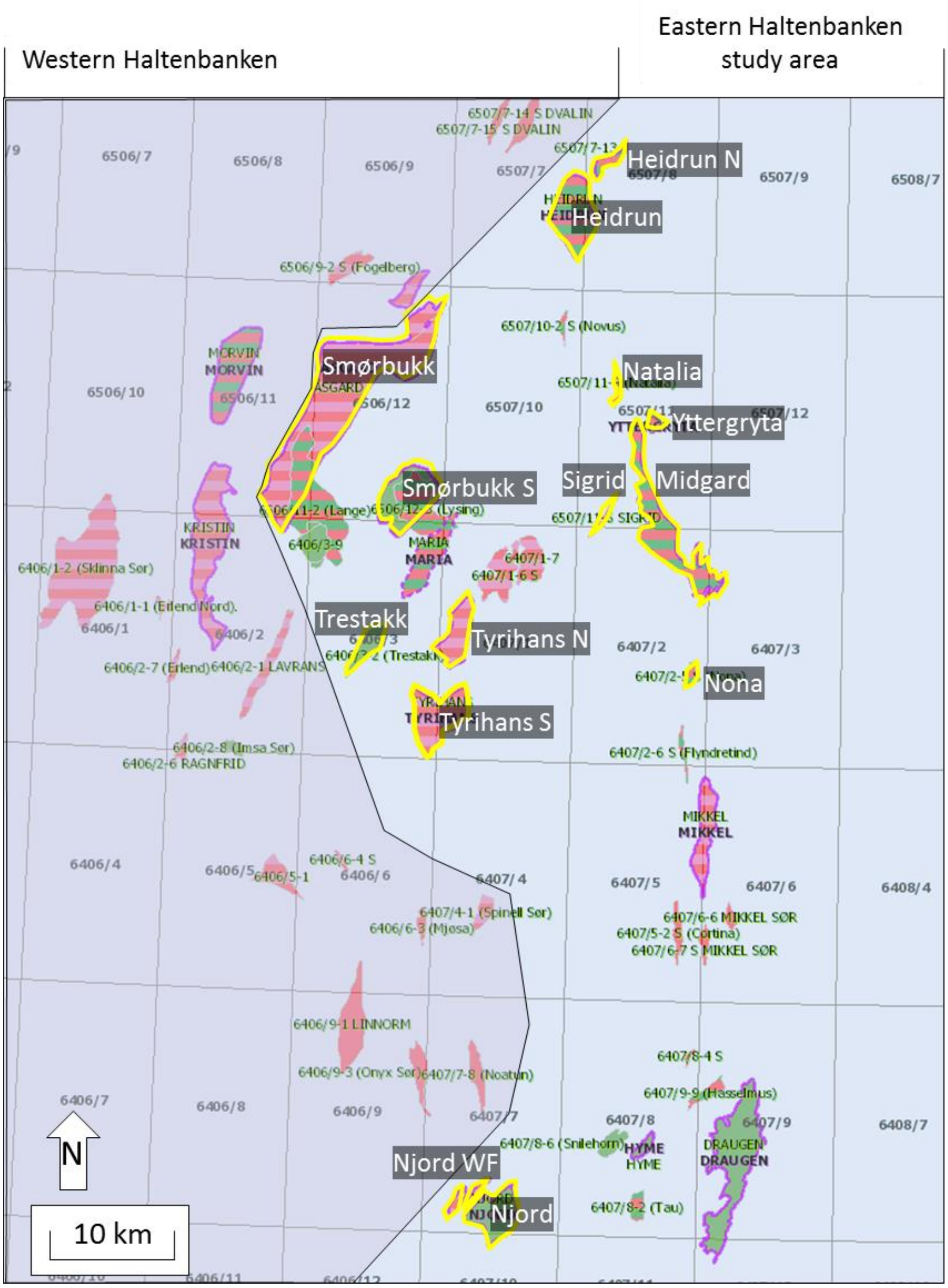


Figure 5.2: Overview map of Haltenbanken showing structures included in this study – outlined in yellow (Retrieved and modified from NPD fact maps, accessed 01.10.2016).

5.1 Smørbukk area - Heidrun

5.1.1 Trestakk - 6406/3-2

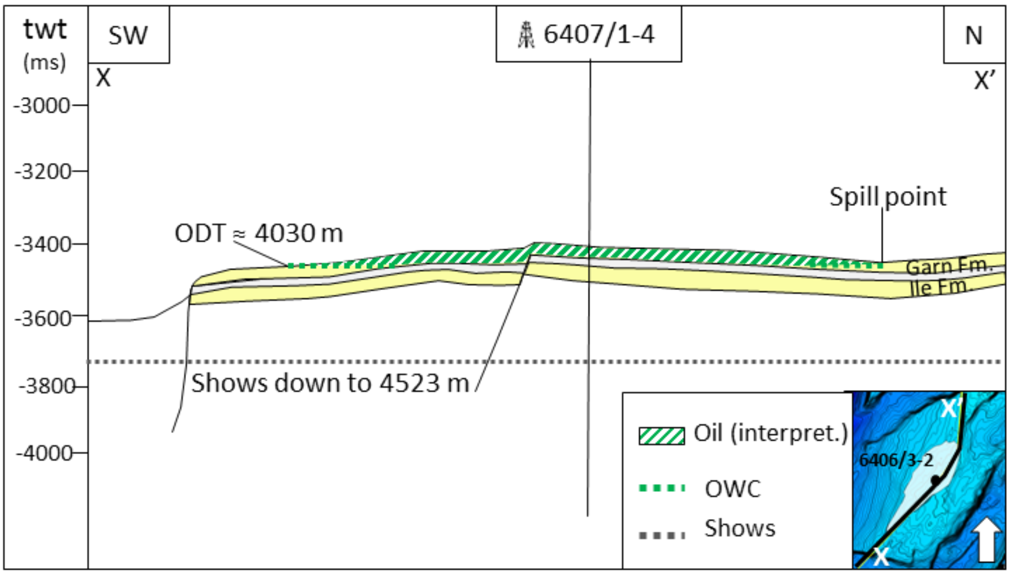


Figure 5.3: Simplified cross section illustration of the Trestakk structure showing the reservoir section in the Garn Fm., along with well, suggested oil-down-to contact depth and noted shows.

The Trestakk discovery is located west of the Tyrihans North field in the middle of block 6406. Middle Jurassic sandstones of the Garn Formation were encountered at 3930 m, and were found oil-bearing. A fluid contact, however, was not clearly established. The Ile and Tilje formations were both found impermeable. The oil-water contact, likely to be an oil-down-to contact, was established by geochemical methods at approximately 4030 m, while logs indicated a much deeper contact - at 4335 m. The well also recorded several intervals of oil shows below this depth throughout the well down to total depth at 4523 m.

Data and check-shots from well 6406/3-2 are not included in the dataset provided in this study and the interpretation of this structure have been conducted based on the interpretation of the surrounding areas. The results from the Trestakk structure are regarded as considerably uncertain based on: the uncertainty in oil-water contact depth (varying from different methods) and the uncertainty in depth conversion. Mapping of the oil-water contact and spill point has been conducted based on data available from nearby wells, such as wells 6407/1-2 and 6407/1-4. Nonetheless, the interpretation of the top Fangst Group shows that Trestakk spills to the north-northeast, towards the Maria discovery (well 6406/3-8). Utilizing check-shots from well 6407/1-2 the depth of the spill point is located at approximately 4031 m, while check-shots from well 6407/1-4 places it at 4070 m. The exact depth of the oil-water contact is also uncertain and varies greatly from geochemical methods to logs, as previously mentioned. This situation is illustrated in Figure 5.4, where the possible oil-water contact location is shown with black arrows.

In the seismic section bright reflectors are observed in the western part of the structure (Figure 5.4). However, the extent of these brights also coincide with the zone where 3-D seismic datasets have been merged, and are thus not clearly related to amplitude anomalies in the overburden. No other significant anomalies are observed in the seismic section.

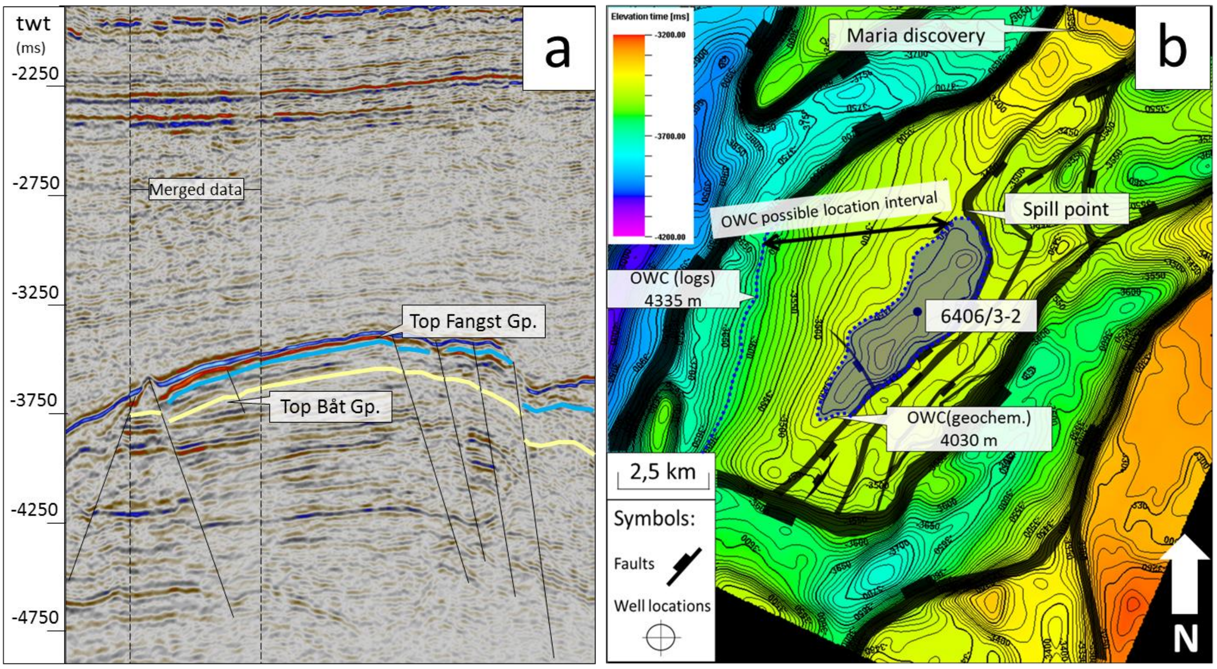


Figure 5.4: Interpretation of the Trestakk structure. Seismic section from NW to SE showing (**a**) uninterpreted cross section along with well tops (**b**) and interpreted cross section along with possible brights. (**c**) shows Top Garn Fm. surface map along with structural elements, wells, fluid contact (from completion log of well 6406/3-2) and outlined cross section (yellow line). Contour line spacing is 10 ms.

5.1.2 Smørbukk - 6506/12-1

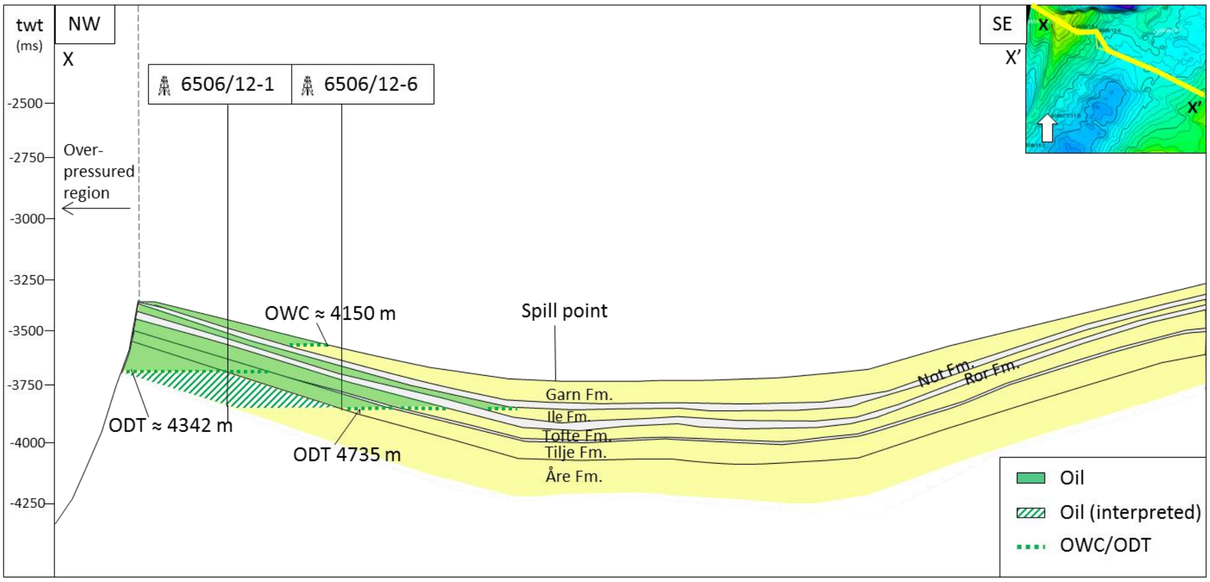


Figure 5.5: Simplified cross section illustration of the Smørbukk structure showing the reservoir sections in the Fangst Gp., along with wells, fluid contact depths and noted shows.

The Smørbukk Field is located in the western part of Haltenbanken, separated from the overpressured region by a large sealing fault zone acting as a pressure barrier. The Jurassic sandstones making up the reservoir in this major trap makes up an antiform structure. The structure was first drilled by well 6506/12-1, and was set out to prove hydrocarbons in both Jurassic, Triassic as well as Cretaceous targets. The well proved gas/condensate in the Fangst- and Båt groups; however, no fluid contact was established from logs or cores. Nevertheless, top reservoir time maps from the well completion report shows a fluid contact at approximately 3600 milliseconds, corresponding to approximately 4342 m from check-shots in the well. Well 6506/12-6 proved hydrocarbons in the same reservoir levels, in the Ile and Tilje formations. An oil-water contact was indicated outside well position, in the interval between 4117 and 4150 m. Furthermore the Tilje Formation consisted of several interbedded sandstones, appearing to have different pressure regimes. Well 6506/12-7 found oil shows in the Garn and Ile formations, while the Tilje Formation only contained small traces of oil. No fluid contact was established in the Tilje Formation, but shows were found in the Garn and Ile formations down to approximately 4538 m. In addition to this, well 6506/12-11 S found the upper parts of the Åre Formation to be hydrocarbon bearing. The Smørbukk structure is a highly complex and compartmentalized structure, with hydrocarbons in different reservoir levels. This strong compartmentalization is likely to be caused by lithological heterogeneities and diagenetic processes. The varying well results and fluid contacts in the structure emphasize this (Table 5.2). In summary, it appears that the Ile Formation is almost completely hydrocarbon filled in the structure, while the fluid contact in the Tilje Formation varies throughout the field. The shallowest sand of the Fangst Group, the Garn Formation, is in several areas found to be drained of hydrocarbons, containing residual hydrocarbons only. Hydrocarbons in the deeper laying Åre Formation are restricted to the upper parts of the formation alone - also called Åre 2 reservoir zone. According to published well data, no clear fluid contact has been established for the structure as a whole. In addition to the Jurassic reservoirs, oil has been proven in sands of the Cretaceous Lange and Lysing formations. These are overlaying the Jurassic reservoirs to the southeast of the structure. Dim zones are observed above the reservoir in the seismic section. In the northernmost part of the structure the seismic data is largely disturbed and it is not possible to observe any seismic features here. Some brights are also observed in the Shetland Group – in the Nise and Kvitnos formations. Sections of the overburden also appear to be displaced above the Jurassic reservoirs (Fig 5.6). The lateral extent of the seismic amplitude anomalies are displayed in the RMS amplitude map of the Top Kvitnos Formation reflector (Shetland Group) (Fig. 5.6). Concentrated dimming is evident in the northwestern part, located around the fault intersection near the apex of the structure.

Table 5.2: Overview of information from available exploration wells and hydrocarbons distribution in Jurassic reservoirs in the Smørbukk structure.

Well	**Content**	**Formation**			
		Garn Fm.	Ile Fm.	Tilje Fm.	Åre Fm.
6506/12-1	Gas/cond.			ODT≈4342 m	
6506/12-6	Gas/cond.	OWC=4117-4150 m (outside well position)		ODT 4735 m	
6506/12-7	Gas/cond.	Shows	Shows down to 4538 m	Shows	
6506/12-11 S	Oil & gas				ODT 4843 m
6506/11-2	Oil & gas	Shows		ODT 4705 m	

(shaded) = hydrocarbons proven in well (shaded cells: 6506/12-1 Ile, Tilje; 6506/12-6 Ile, Tilje; 6506/12-11 S Tilje, Åre; 6506/11-2 Ile, Tilje)

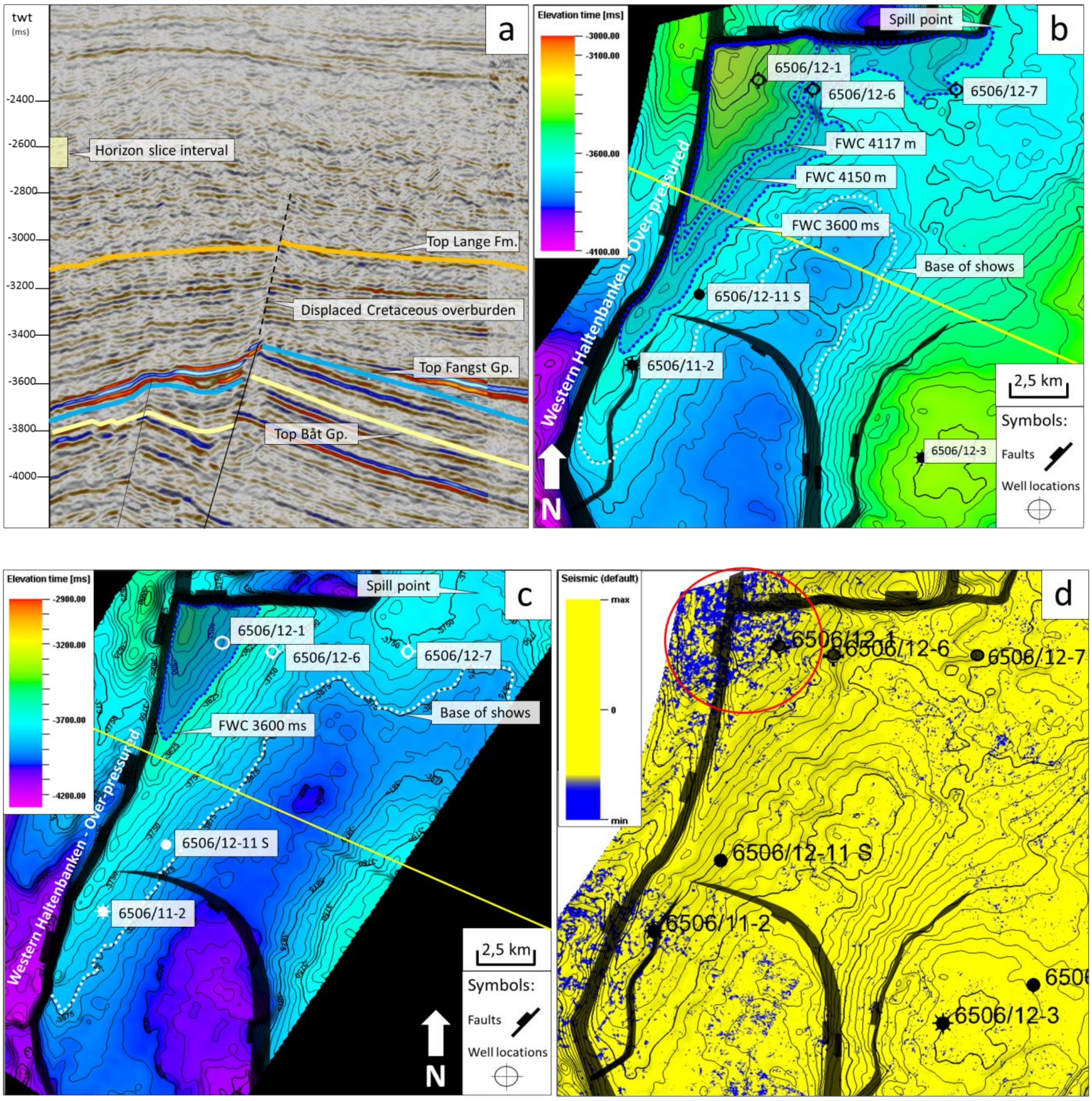


Figure 5.6: Interpretation of the Smørbukk structure. Seismic section from NW to SE showing (**a**) interpreted cross section along with horizons, displaced overburden and brights (**b**) Top Fangst Group surface map displaying wells, structural elements, fluid contacts and outlined cross section (yellow line), (**c**) Top Tilje Fm. surface map and (**d**) RMS amplitude map of the Top Kvitnos Fm. showing concentration of dims (red circle) . Contour line spacing is 25 ms.

5.1.3 Smørbukk South - 6506/12-3

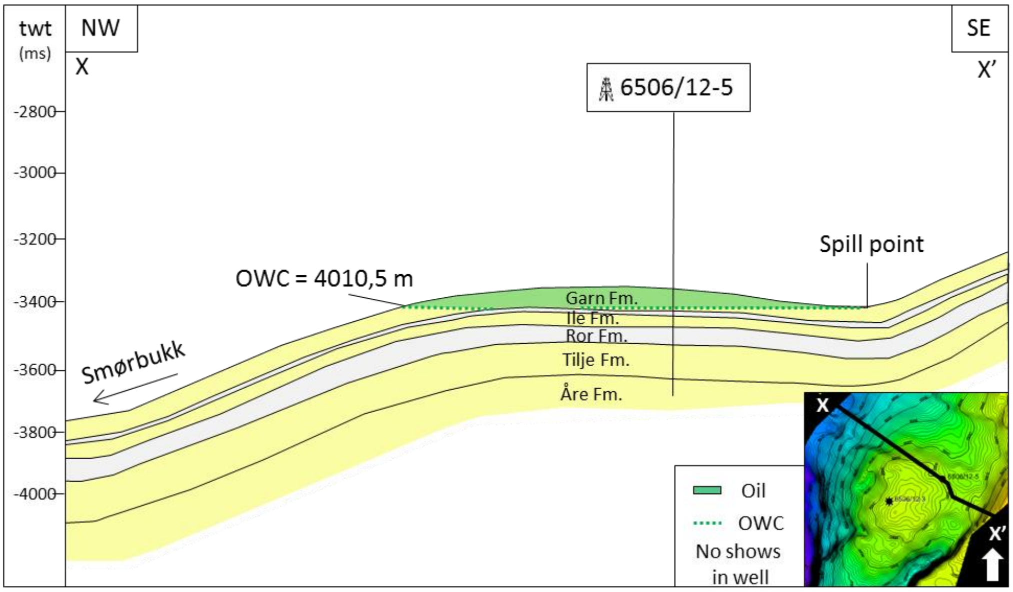


Figure 5.7: Simplified cross section illustration of the Smørbukk South structure showing the reservoir section in the Garn Fm. from well 6506/12-5 along with oil-water contact.

Southeast of the Smørbukk Main Field is the Smørbukk South structure. Smørbukk South is situated at an antiform structure, in the southeastern part of block 6506. It was drilled by well 6506/12-3, set out to prove hydrocarbons in the Middle and Early Jurassic sandstones. The well proved oil and gas/condensate in Jurassic as well as Cretaceous reservoirs (Table 5.3). Hydrocarbons were encountered in the Garn and Tilje formations, with an oil-water contact in the Tilje Formation at 4216 m. Along with the hydrocarbons encountered in the Late Cretaceous Lysing Formation., a total of 242 m of hydrocarbons was proven in the well. Well 6506/12-5 was later drilled in the northeastern margin of the structure, and gave further information about the Jurassic reservoir sections. Hydrocarbons were proven in the Garn Formation only, with an oil-water contact at 4010.5 m. The Garn and Not formations were found sealing in the well. Furthermore, well 6406/3-3 (not included in dataset) drilled in the southern part of the structure found only hydrocarbon shows, in the Garn Formation down to 3955 m, and poor shows in the Tilje Formation from 4210 m to 4262 m.

Table 5.3: Overview of information from exploration wells in the Jurassic reservoirs of the Smørbukk structure

Well	Content	HC level (formation)	OWC	Additional info
6506/12-3	Oil/Gas	Garn, Ile & Tilje Fm.	4216 m in Tilje Fm.	No shows
6506/12-5	Oil	Garn Fm.	4010,5 m in Garn Fm.	OWC at 3410 ms from completion report
6406/3-3	Shows	Garn & Tilje Fm.	3955 m in Garn Fm.	Weak shows in Tilje Fm. 4210-4262 m

The spill point of the structure is located in the eastern region, where the structure borders the Grinda Graben (Figure 5.7). Completion reports from wells 6506/12-3 and 6506/12-5 have been available from the Norwegian Petroleum Directorate. These show that the fluid contact coincides with spill point in the southeast, and the following interpretation is based on this information.

No strong amplitude anomalies are observed in the seismic section, although some questionable brights are observed in the Shetland Group. RMS amplitude maps generated from the overburden show no clear indication of zones of concentrated brights (Figure 5.8).

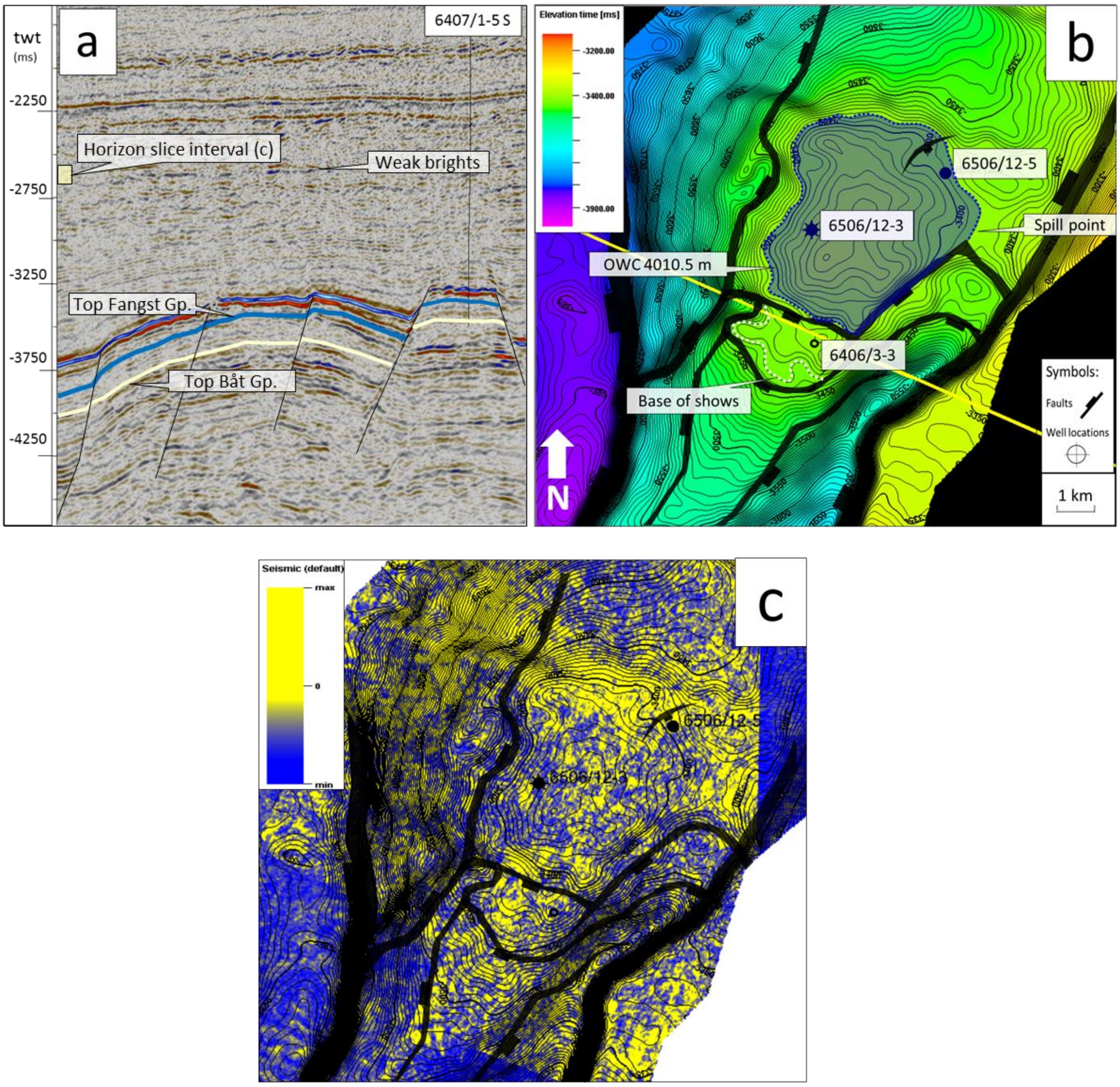


Figure 5.8: Interpretation of the Smørbukk South structure. Seismic section from NW to SE showing (**a**) interpreted cross section (**b**) shows Top Fangst Group surface map along with structural elements, fluid contacts, wells and outlined cross section (yellow line) and (**c**) RMS amplitude map from the intra Shetland Group. Contour line spacing is 10 ms.

5.1.4 Heidrun - 6507/7-2

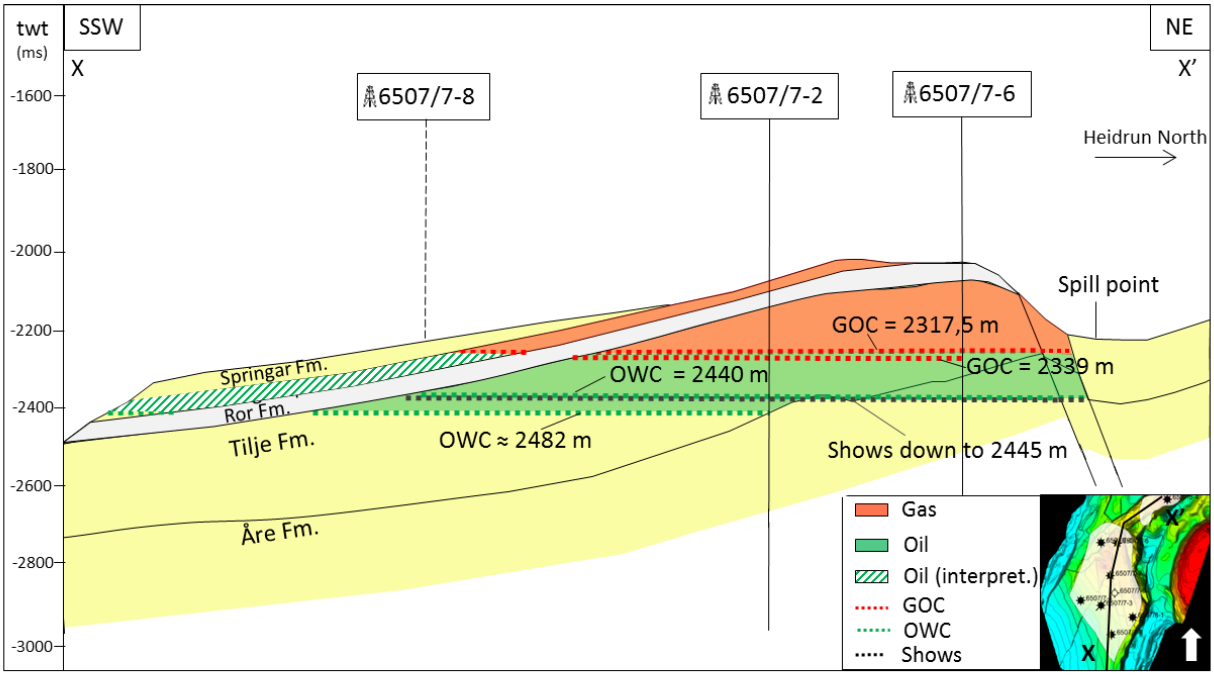


Figure 5.9: Simplified cross section illustration of the Heidrun structure showing the reservoir sections in the Fangst Group, along with wells, fluid contact depths and noted shows. Fluid contacts displayed are from wells 6507/7-2 and 6507/7-6.

The Heidrun Main Field is located in the intensely faulted zone at the intersection of the Nordland Ridge in the northeast and Haltenbanken in the south. This structure is a southward plunging horst block formed by a Late Jurassic fault system. It is bound by major faults trending NE-SW and NW-SE. Wildcat well 6507/7-2 proved oil and gas in the Fangst and Båt groups. Shetland Group sediments were found directly on top of the Fangst Group, indicating heavy erosion at the crest of the structure. Gradients established from electric logs, RFT data and fluid analysis estimated a gas-oil contact at 2317.5 m. The oil-water contact, however, was not as well-defined. Logs placed it at 2455 m, while RFT data indicated a contact in the interval 2476 to 2482 m. More recent data provided by Statoil shows a more complicated situation, with contact depths varying locally in different segments or compartments of the structure. Heidrun is a highly faulted and complex structure with several local channels and lobes, especially in the Åre Formation.

Well 6507/7-6 proved oil and gas in the Fangst and Båt groups. Shetland Group sediments were found directly on top of the Fangst Group, indicating heavy erosion at the crest of the structure (Fig. 5.9). A gas-oil contact was established at 2339 m in the Tilje Formation and the oil-water contact at 2440 m in the Åre Formation. Shows were recorded down to 2445 m below the contact, as well as in a thin sandstone sequence at 2096 m in the Cretaceous.

A saddle point situated in the northeastern part of the structure defines the structural spill point where Heidrun spills to the north-northeast towards the Heidrun North structure, at approximately 2400 m. Mapping of the fluid contacts show that the oil-water contact depth is located below the spill point to the northeast.

The central- to eastern segment of the structure holds an area in which the seismic data is largely disturbed by a prominent dome shaped anomalous feature. This is suggested to be a Triassic salt diapir or a vent complex of Paleogene age, related to reactivation of deep-seated Triassic faults (Svensen et al., 2008). A few dim zones are observed above the dome in the Pliocene section. Stacked and continuous brights are also observed in the overburden in the vicinity of this dome shaped anomaly. RMS amplitude map of the top Shetland Group has been generated to further investigate the extent of the observed amplitude anomalies (Fig. 5.10). The map shows a concentrated zone of brights located above the area where the dome is observed.

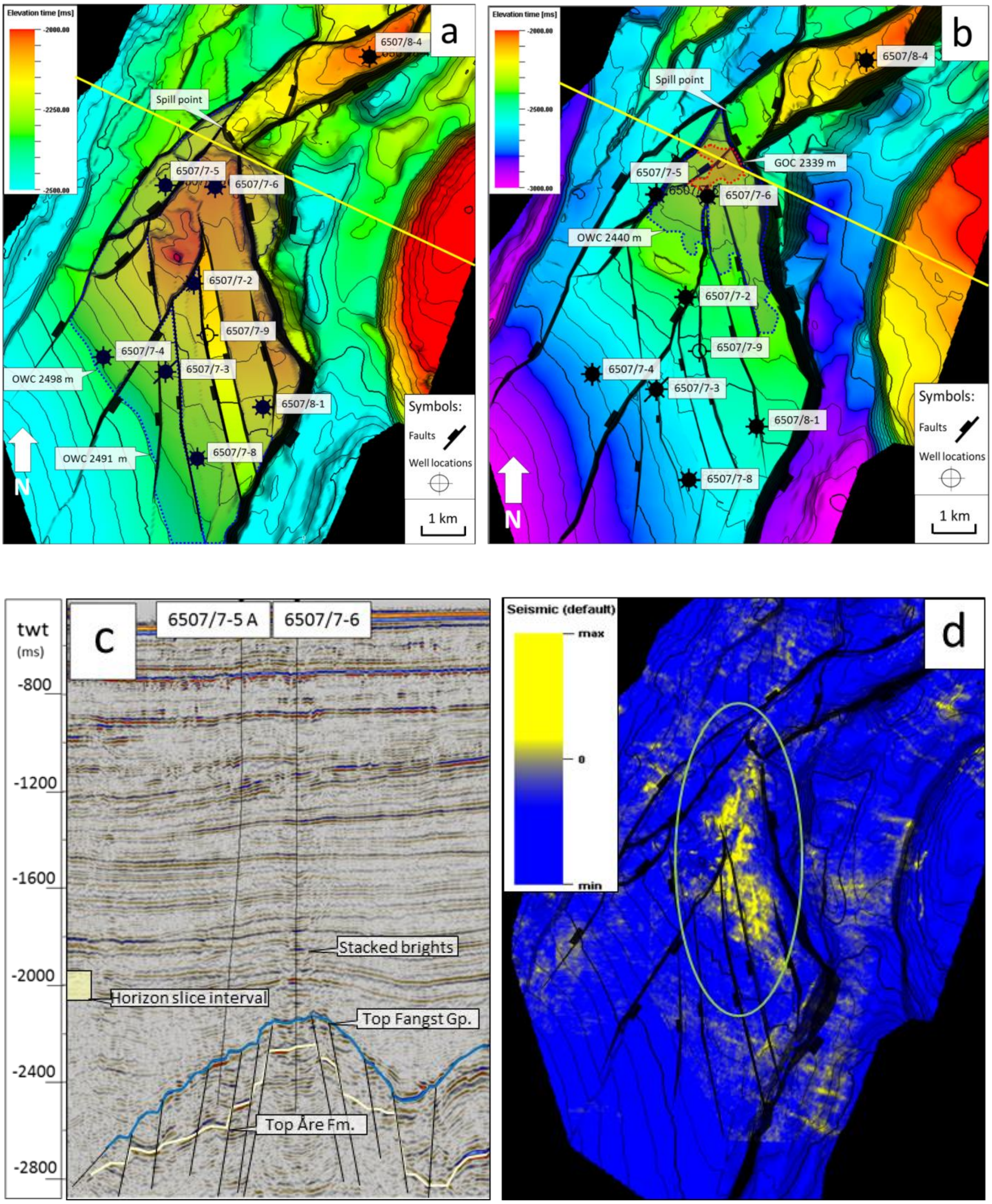


Figure 5.10: Interpretation of the Heidrun main field showing (**a**) Top Tilje Fm. seismic surface map and (**b**) Top Åre Fm. seismic surface map, displaying interpreted segments along with structural elements, different fluid contacts, wells and outlined cross section (yellow line), (**c**) interpreted cross section from the NW to SE and (**d**) RMS amplitude map of the top Shetland Gp showing concentrated strong amplitudes (green circle). Contour line spacing is 50 ms.

5.1.5 Heidrun North - 6507/8-4

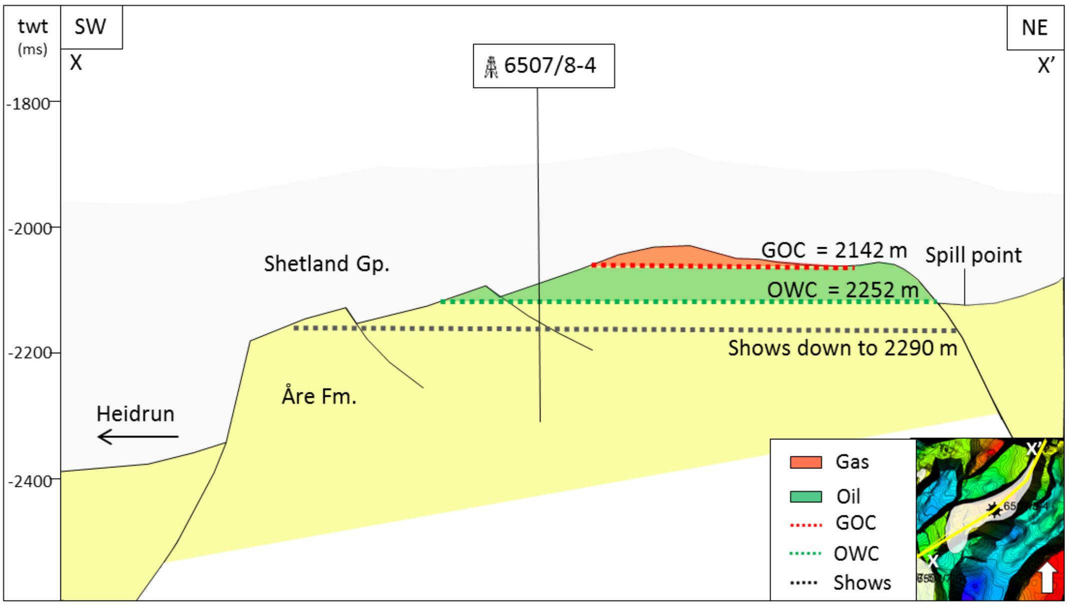


Figure 5.11: Simplified cross section illustration of the Heidrun North structure showing the reservoir sections in the Åre Fm., along with wells, fluid contact depths and noted shows.

Northeast of the Heidrun Field lies the Heidrun North structure. The elongated horst block is situated in the transition zone between the Nordland Ridge to the north and Haltenbanken to the south. Heidrun North is bound by two large NE-SW trending normal faults dipping to the NW and SE and a N-S trending normal fault dipping east.

Gas and oil was proven by well 6507/8-4 in the Åre Formation of the Båt Group. The reservoir was encountered directly under the Late Cretaceous sediments at 2124 m. The gas-oil contact was established at 2142 m and the oil-water contact at 2252 m. Shows were also found down to a depth of 2290 m (Fig. 5.11).

The spill point is located in the northernmost part of the structure, indicating a spill-route continuing further northwards towards the Nordland Ridge. However, it should be noted that the seismic data coverage ends in the area immediately to the north of Heidrun North.

The oil-water contact in Heidrun North is located approximately 5 meters deeper than the mapped spill point. This observation indicates, within the given uncertainties, that the structure is filled to its capacity. However, shows are found below the fluid contact. If Heidrun North is in fact over-filled, hydrocarbons will spill northwards towards the Nordland Ridge area – an area where the regional top seal has been eroded. A few wells have been drilled in this area, but no discoveries have been made. Well 6507/8-6 drilled right northeast of Heidrun North was found dry, and well 6507/8-3 and 6507/7-12, drilled northeast and northwest of Heidrun North respectively; both proved shows in the Fangst Group only.

In the seismic section, several vertical dim zones or discontinuity zones are observed above the reservoir (Fig. 5.12). Intervals of the Paleogene Hordaland Group above the Jurassic reservoir appear to be slightly displaced - particularly evident in the northern leg of the structure. Some weak brights are observed in the overburden.

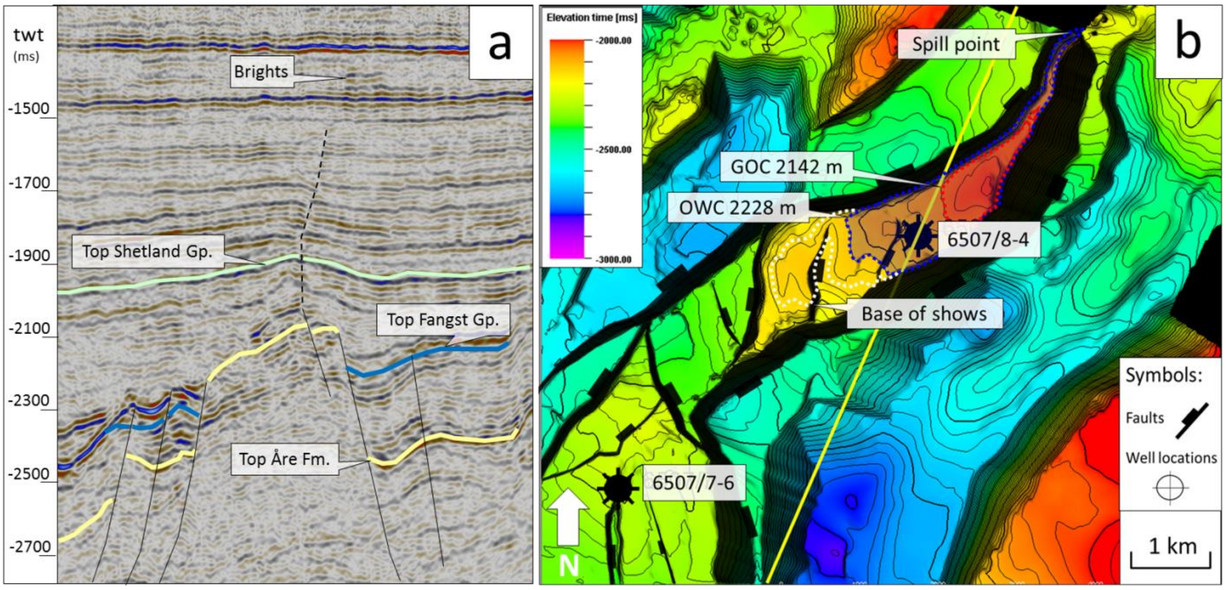


Figure 5.12: Interpretation of the Heidrun North structure. Seismic section from SE to NW showing (**a**) interpreted seismic cross section along with weak brights and (**b**) Top Åre Fm. surface map along with structural elements, fluid contacts, wells and outlined cross section (yellow line). Contour line spacing is 20 ms.

5.2 Tyrihans - Natalia

5.2.1 Tyrihans South - 6407/1-2

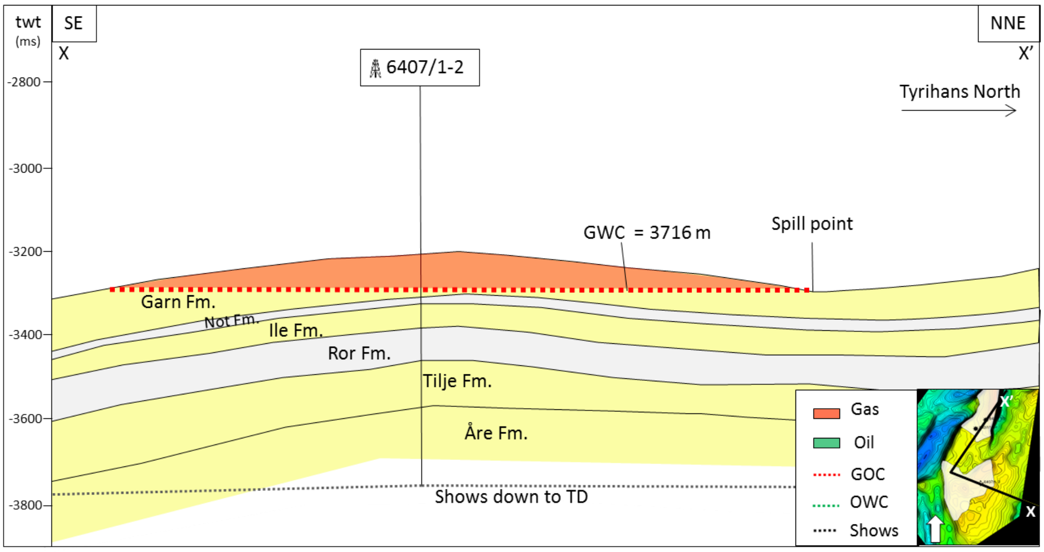


Figure 5.13: Simplified cross section illustration of the Tyrihans South structure showing the reservoir section in the Garn Fm., along with wells, fluid contact depth and noted shows.

The Tyrihans South structure is located on the eastern flank of the Grinda Graben, in the central parts of Haltenbanken. The structure is bound and intersected by normal faults trending NW-SE, NE-SW and ENE-WSW. Middle Jurassic sand horizons were the primary target, and the well 6407/1-2 proved hydrocarbons in sandstones of the Garn Formation from 3659 m down to a well-defined gas-water contact at 3716 m (Fig. 5.13). The secondary objective, Early Jurassic sands, was found to be dry but with shows in the Tilje and Åre formations. These gas shows were recorded to become stronger below 4300 m and downwards. Increasing gas shows was recorded down to total depth drilled.

Tyrihans South spills to the N-NW towards the Tyrihans Nord Field, along the eastern margin of the Grinda graben. This stratigraphic saddle-point between the two structures is located at approximately 3726 m, 10 m deeper than the determined gas-water contact. Within the uncertainty margins this could indicate that the structure is filled to its structural spill point. Weak dim zones are observed in the seismic data in the southern areas of the structure (Fig. 5.14). No other anomalies are observed.

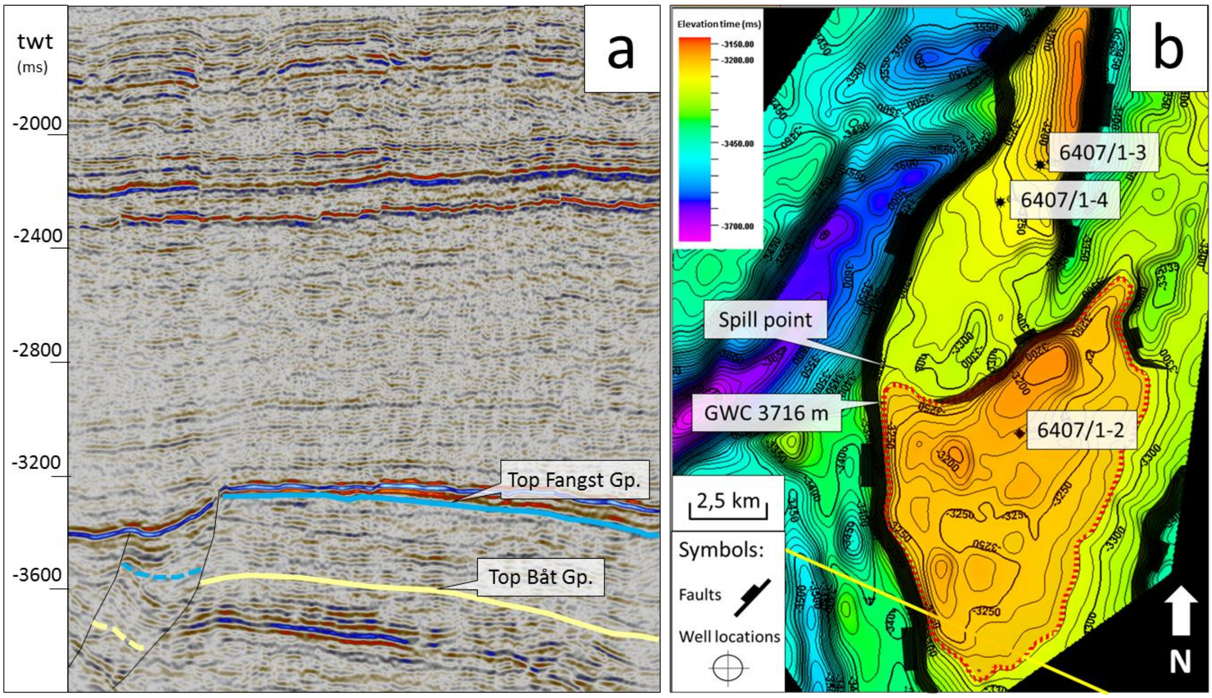


Figure 5.14: Interpretation of the Tyrihans South structure. Seismic section from NW to SE showing (**a**) interpreted cross section and (**b**) Top Fangst Gp. surface map along with structural elements, wells and outlined cross section (yellow line). Contour line spacing is 10 ms.

5.2.2 Tyrihans North - 6407/1-3

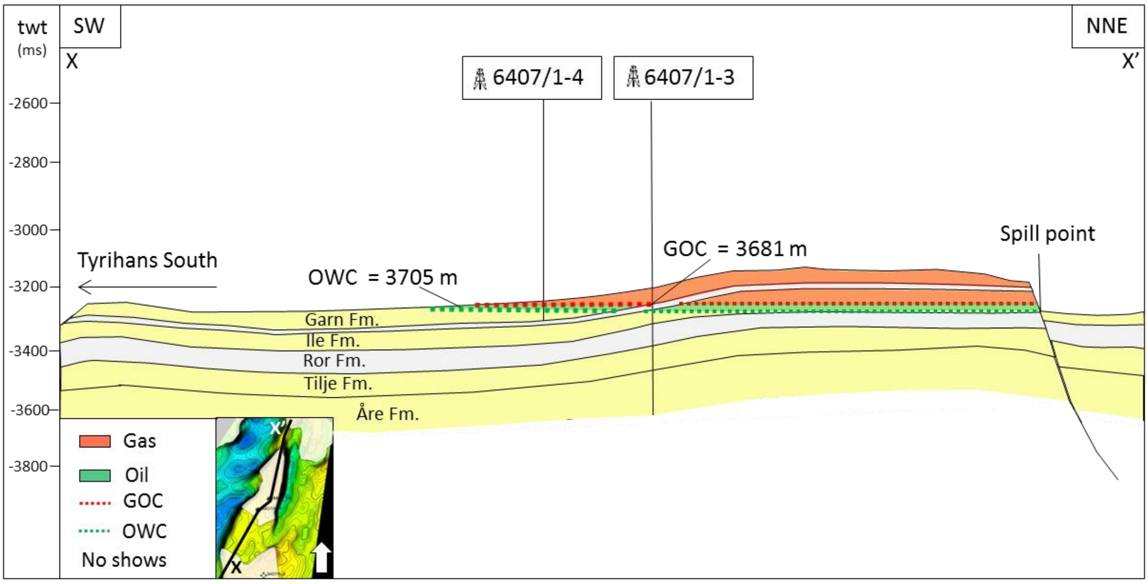


Figure 5.15: Simplified cross section illustration of the Tyrihans North structure showing the reservoir section in the Garn Fm., along with wells and fluid contact depths.

The Tyrihans North structure is located north of Tyrihans South, on a separate but related structure. It is confined by two major faults trending NE-SW and NNE-SSW. The structure is slightly shallower than its southern neighbor. The Garn Formation was encountered at 3600 m, and was found hydrocarbon bearing. The reservoir was found to be more cemented than originally expected. A gas cap extended to 3687.5 m, followed by an oil zone down to 3709 m, where it grades into the underlying silty and clayey Not Fm. A gas-oil contact was established at 3681 m, and the oil-water contact at 3705 m (from well 6407/1-4) (Fig. 5.15). Good gas shows were recorded in the Upper Cretaceous Nise Formation. A possible light oil accumulation (with associated gas), and an oil-water contact at approximately 2560 m. Shows were also recorded in the Early Cretaceous unit. The structure spills towards the northeast, along the ridge on the eastern flank of the Grinda Graben. From the Tyrihans North Field, this ridge continues northeast towards the Late Cretaceous discovery made by well 6407/1-6 S and 6407/1-7. Like in Tyrihans South, the fluid contact closely coincides with the structural spill point by only. Based on these observations the Tyrihans North structure appears to be filled to its structural capacity. A few brights are observed in the overburden (Fig. 5.16). However, brights are also apparent throughout the entire seismic section, down to the basement. These are therefore not considered relevant for further investigation.

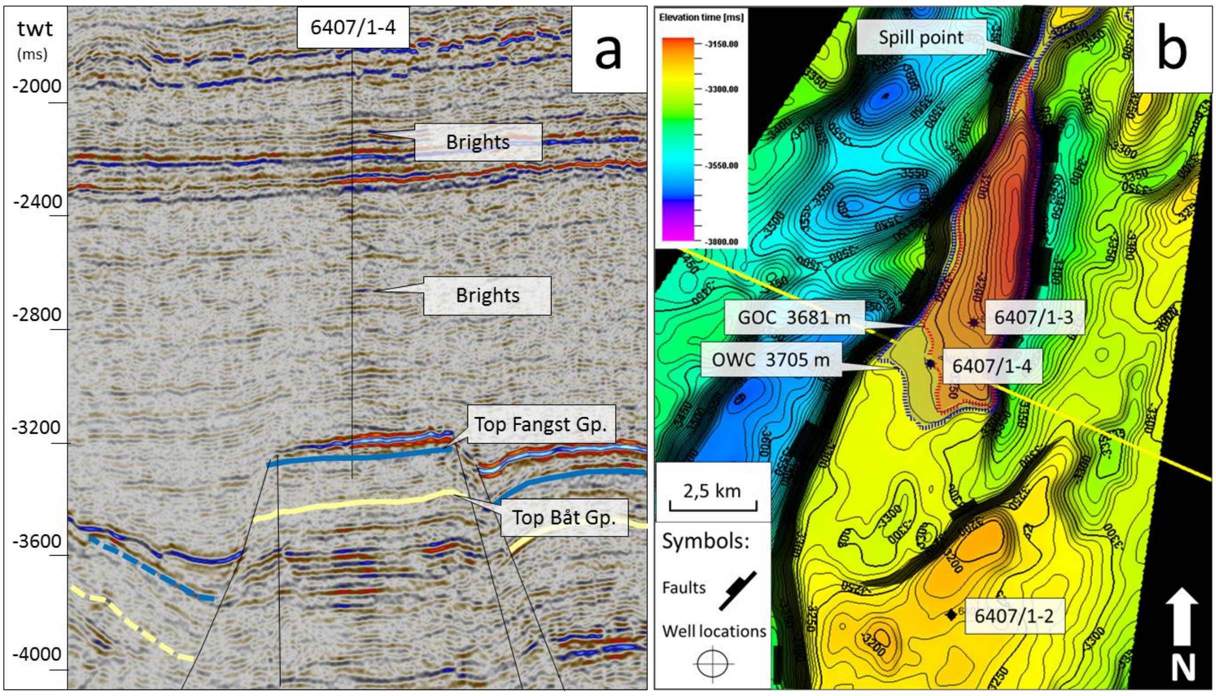


Figure 5.16: Interpretation of the Tyrihans North structure. Seismic section from NW to SE showing (**a**) interpreted cross section along with stacked brights and dim zones and (**b**) Top Fangst Gp. surface map along with structural elements, wells and outlined cross section (yellow line). Contour line spacing is 10 ms.

5.2.3 Sigrid - 6507/11-6

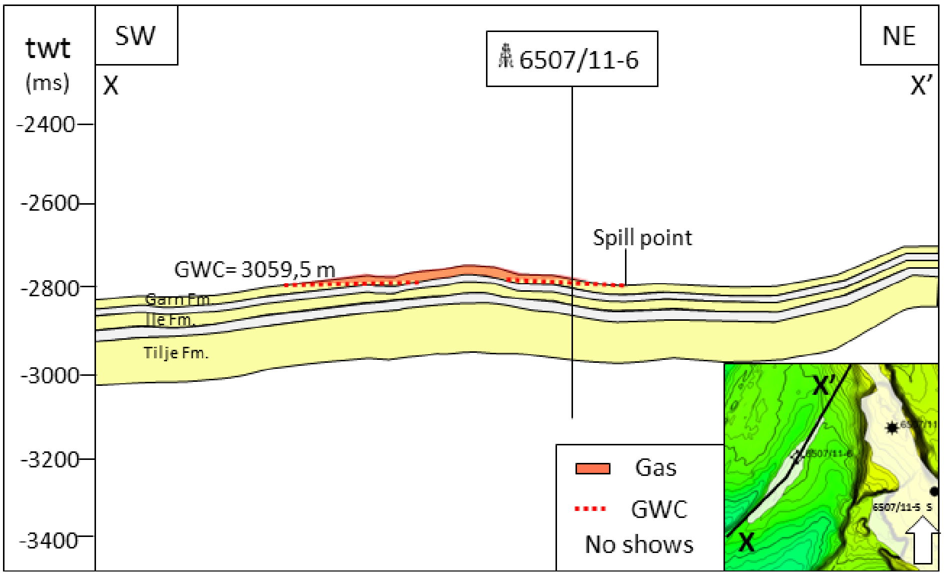


Figure 5.17: Simplified cross section illustration of the Sigrid structure showing the Garn Formation making up the reservoir, along with well, gas-water contact depth and noted shows.

The Sigrid discovery is located approximately 3 km west of the Midgard field. The downfaulted structure is bound by a large NW-dipping NE-SW trending normal fault, extending northwards towards the much larger Midgard Field. A 30 m gas column was discovered by well 6507/11-6, from the top of the Middle Jurassic Garn Formation at 3030 m. A gas-water contact was interpreted at 3059.5 m (Fig. 5.17). Pressure data indicated small pressure barriers between the Garn, Ile, and Tilje Formations although sandstones in the lower part of the Garn Formation as well as in the Ile, Tilje and Åre Formations were all water bearing. No shows have been recorded in well data. Sigrid spills to the northeast at approximately 3063, along the eastern side of the Grinda Graben. This spill point is located at a stratigraphic low point between the two structures. Aside from sporadic bright spots in the Naust Formation of the Nordland Group, no significant observations were made in the overburden in the seismic section. However, reflectors above the reservoir in the Cretaceous section (Lange Fm.) appear to be much stronger over the northern part of the structure. Whether this is related to differences in lithology or other factors is unclear. Noticeably the depth of the interpreted gas-water contact coincides with the depth of structural spill point, indicating that the Sigrid structure may be filled to its structural capacity. No amplitude anomalies are observed in the overburden (Fig. 5.18).

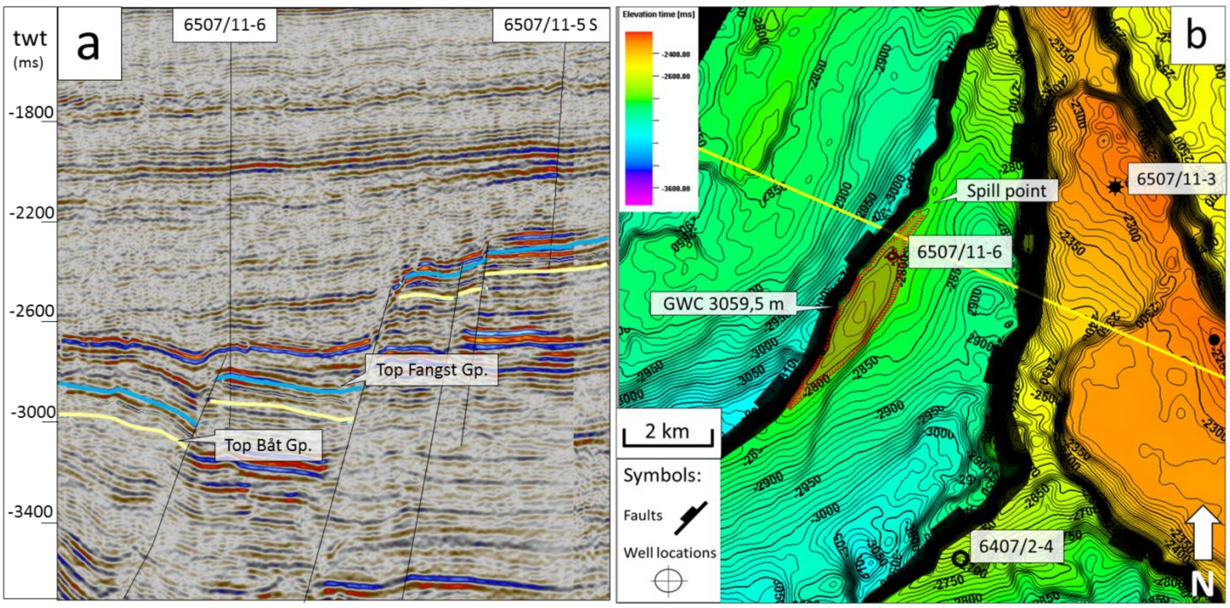


Figure 5.18: Interpretation of the Sigrid structure. Seismic section from NW to SE showing (**a**) interpreted cross section and (**b**) shows Top Fangst surface map along with structural elements, wells and outlined cross section (yellow line). Contour line spacing is 10 ms.

5.2.4 Natalia - 6507/11-9

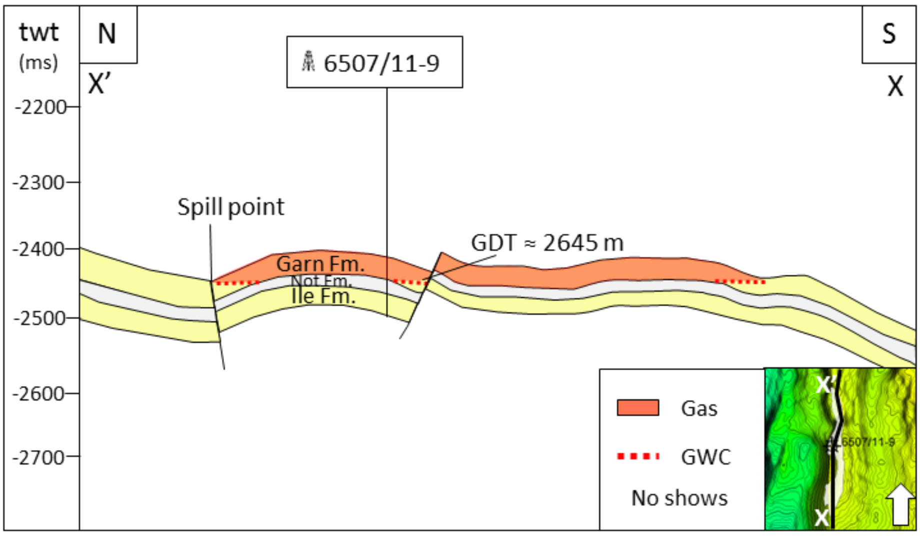


Figure 5.19: Simplified cross section illustration of the Natalia structure showing the Garn Formation making up the reservoir along with well and gas-water contact depth.

The Natalia discovery resides on the edge of the northern Grinda Graben, 5 km north of the Midgard Field. This relatively small rotated fault block is bound by a W-dipping NE-SW trending normal fault, on the western margin of the graben. Well 6507/11-9 was drilled up-dip from the previously drilled 6507/11-4 well, and proved a 40 m gas column in the Garn Formation. A gas-down-to top Not Formation at 2637.8 m was proven, and the first water bearing sand to be penetrated below the hydrocarbon column was at 2645 m. The GWC for the structure is therefore interpreted to be between 2637.8 and 2645 m, given the same pressure regime and hydrocarbon system up-dip. The apex of the structure is mapped at 2575 m - giving a corresponding column-height for the entire structure of 60 m.

The Natalia structure spills to the north at approximately 2645 m, which is in accordance with the gas-down-to contact (Figure 5.19). This suggests that the structure might be filled to its structural capacity. Shows were also recorded below the reservoir level in the Ile Formation down to 2658 m. Furthermore, a gas peak was recorded at 2240 m in the Nise Formation. In the seismic section, a few bright spots are observed in the Nise Formation (Figure 5.20). Aside from this, no significant seismic anomalies are observed.

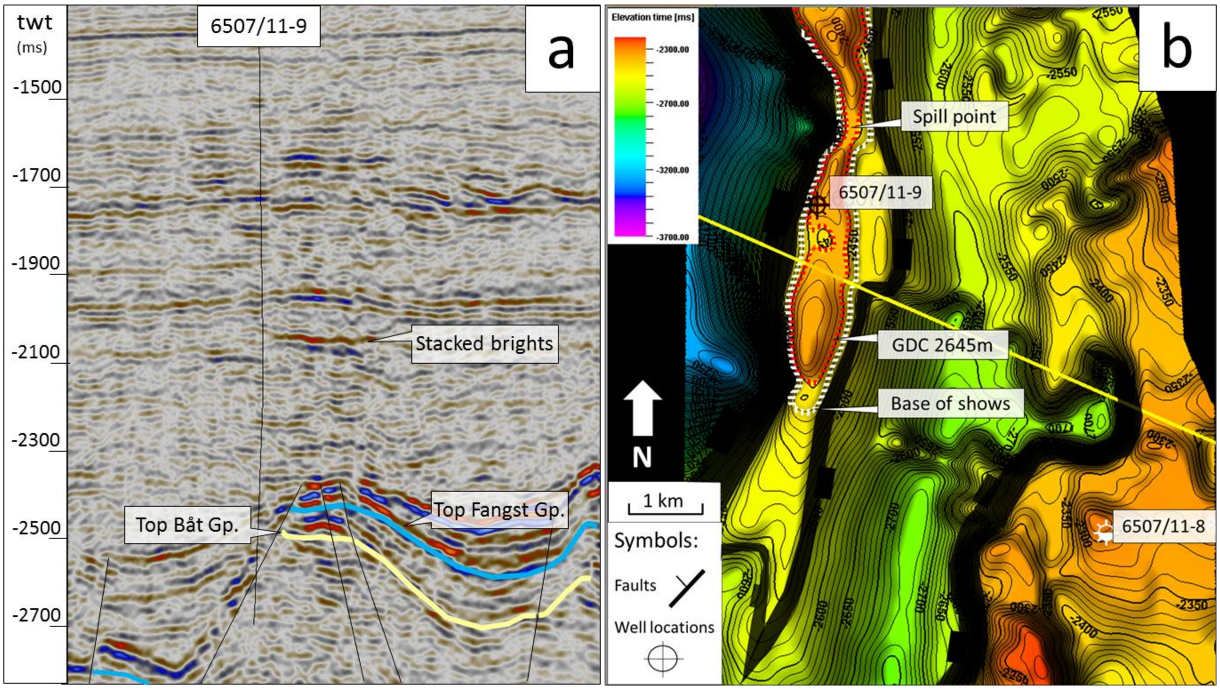


Figure 5.20: Interpretation of the Natalia structure. Seismic section from NW to SE showing (**a**) uninterpreted cross section along with well tops (**b**) and interpreted cross section along with stacked brights. (**c**) shows Top Fangst Group surface map along with structural elements, wells and outlined cross section (yellow line). Contour line spacing is 10 ms.

5.3 Nona - Midgard

5.3.1 Nona - 6407/2-5 S

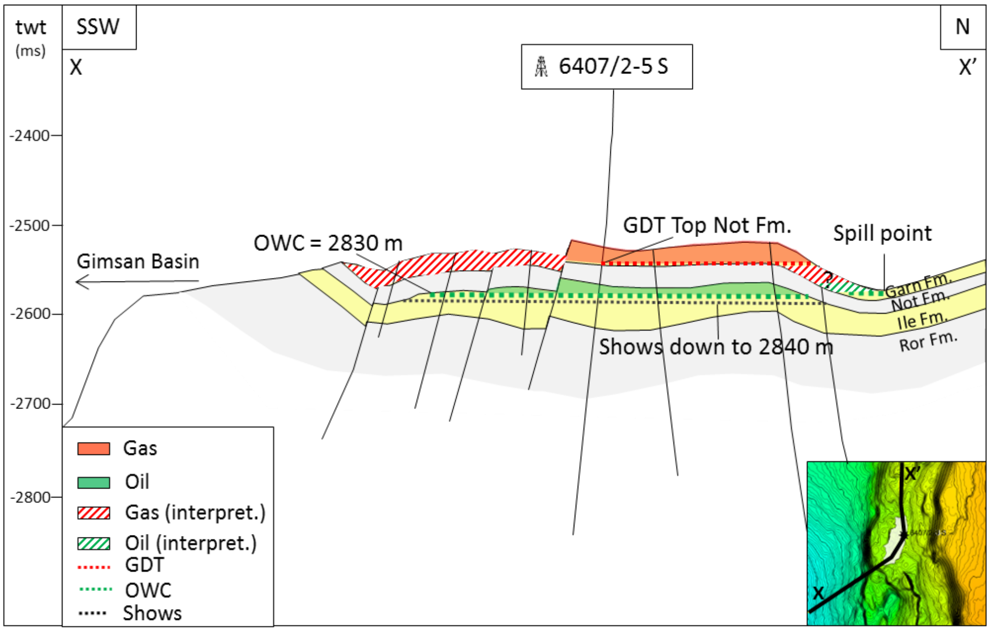


Figure 5.21: Simplified cross section illustration of the Nona structure showing the Garn and Ile reservoirs, along with well, fluid contact depths and noted shows.

The Nona discovery is located within the Bremstein Monocline, 10 km south of Midgard and 15 km north of Mikkel. It is bound by N-S trending normal faults as well as several smaller faults with a more E-W orientation. Well 6407/2-5 S proved both oil and gas in two reservoir units. A gas column of 39 m was encountered from the top reservoir in the Garn Formation down to the deepest sand in the Not Formation. In the Ile Formation, a 34 m oil column was proven, from the shallowest sand down to the oil-water contact at 2830 m (Fig. 5.21). In addition to this, residual oil was found in the reservoir from the oil-water contact down to 2840 m. Pressure data indicated pressure depletion from the Mikkel and/or Midgard fields, and suggested non-communication between the Garn and Ile reservoirs.

Nona spills to the north at approximately 2800 m at the Garn reservoir level and at 2884 m in the Ile reservoir. A clear oil-water contact was established in the Ile reservoir, but in the Garn reservoir only a gas-down-to contact was proved. A noteworthy observation from the seismic section is the brightening and increased continuity of the lower part of the Late Pliocene succession in the section above the reservoir. RMS amplitude maps show no areas of concentrated amplitude anomalies (Fig. 5.22).

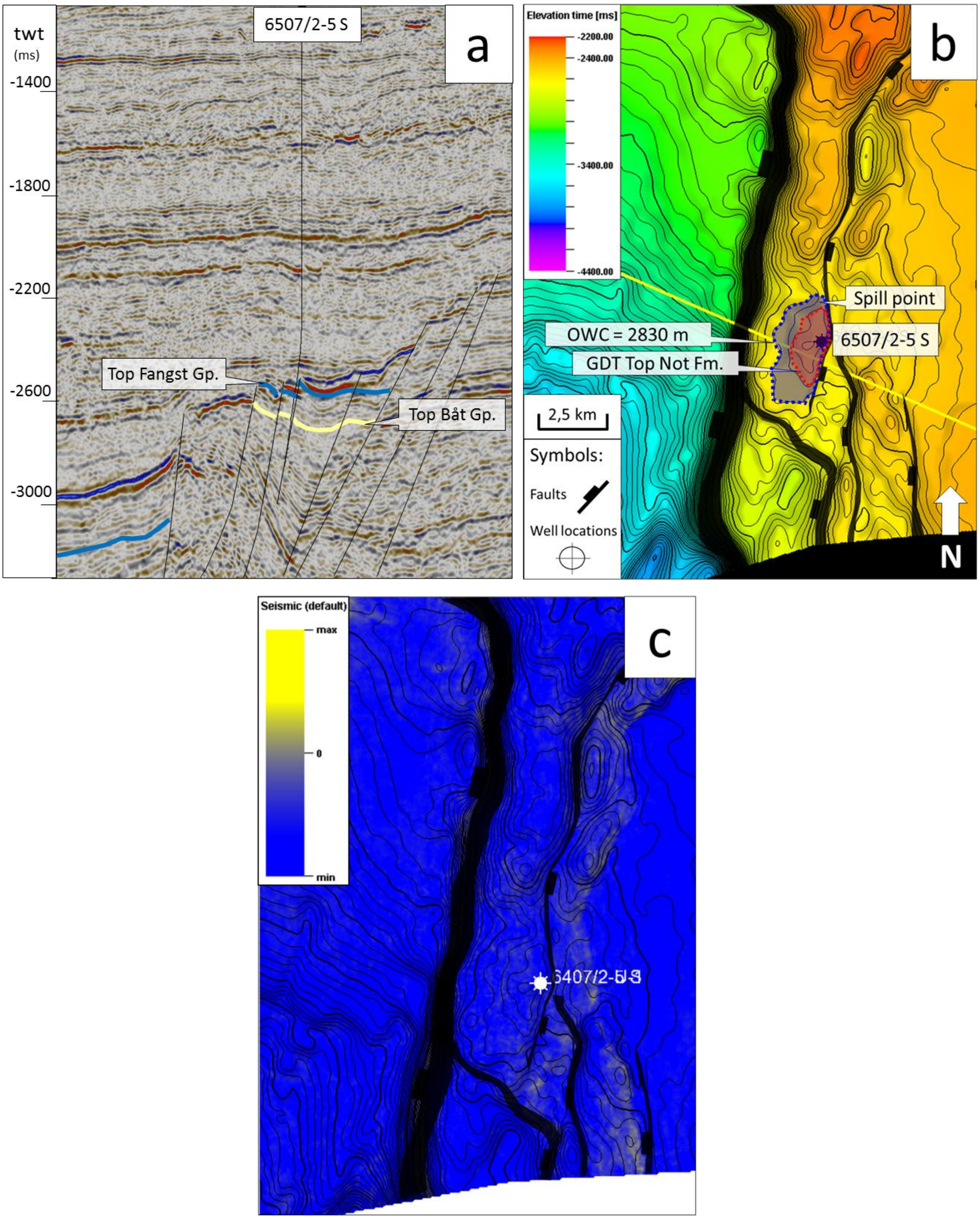


Figure 5.22: Interpretation of the Nona structure. Seismic section from NW to SE showing (**a**) interpreted cross section. (**b**) Top Fangst Gp. surface map and (**c**) RMS amplitude map, showing no concentrated areas of amplitude anomalies. Contour line spacing is 20 ms.

5.3.2 Midgard - 6507/11-1

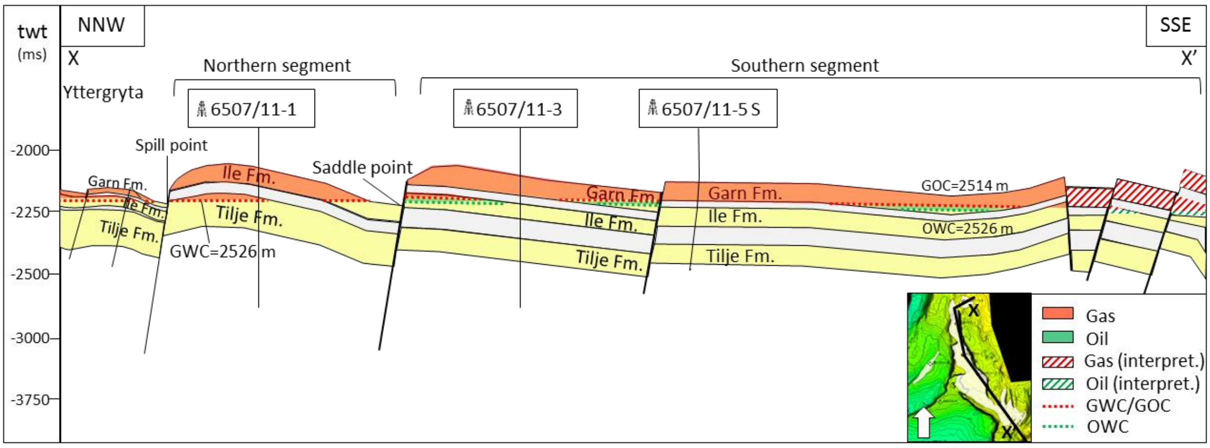


Figure 5.23: Simplified cross section illustration of the Midgard structure showing the Garn, Ile and Tilje Formations making up the reservoirs, along with wells, fluid contact depths and noted shows.

The Midgard structure is located in the eastern part of Haltenbanken, between the Trøndelag Platform in the east and the Grinda Graben in the west. This horst structure is bound by large N-S to NW-SE trending faults (Figure 5.23). Several smaller N-S trending normal faults also intersect the structure in the southeastern region. Well 6507/11-1 proved gas/condensate in two reservoir sandstone sections with a common pressure system. Both the Ile and the Tilje formations were gas/condensate-bearing with a gas/water contact at 2526 m. The Garn Fm. was not encountered in the well. High gas readings were recorded in a fault zone in the Rogaland Gp. in the interval 2097 m to 2120 m. Wells 6507/11-3 and 6507/11-5 S proved gas above a thin oil zone in the Fangst Gp. in the Garn and Ile formations. The gas/oil contact was encountered at 2514 m, and the oil/water contact at 2525.5 m. Two intervals at 2170 m and 2197 m in the Shetland Group had oil shows, as well as oil shows in the Melke Formation at 2393 m.

The Midgard shows can be divided into two segments with a saddle point between the northern and southern segment. The northern segment is penetrated by well 6507/11-1, and the southern segment by wells 6507/11-3 and 6507/11-5 S. Midgard spills to the north towards the Yttergryta structure at approximately 2652 m, while the saddle point between the northern and southern segment is located at approximately 2520 m. Investigation of the contacts versus spill points suggest that the structure is filled, as the fluid contact depth coincides very closely to the mapped structural spill point.

In the northern segment, as well as the northernmost part of the southern segment, a fault is observed displacing the Tang and Tare formations as well as the lower parts of the Brygge Formation (Rogaland Group). Stacked brights are observed in association with this, above the reservoir level (Fig. 5.24). This is especially apparent in the northern part of the structure. These observations are corresponding with the recorded high gas readings in this fault zone from the well data.

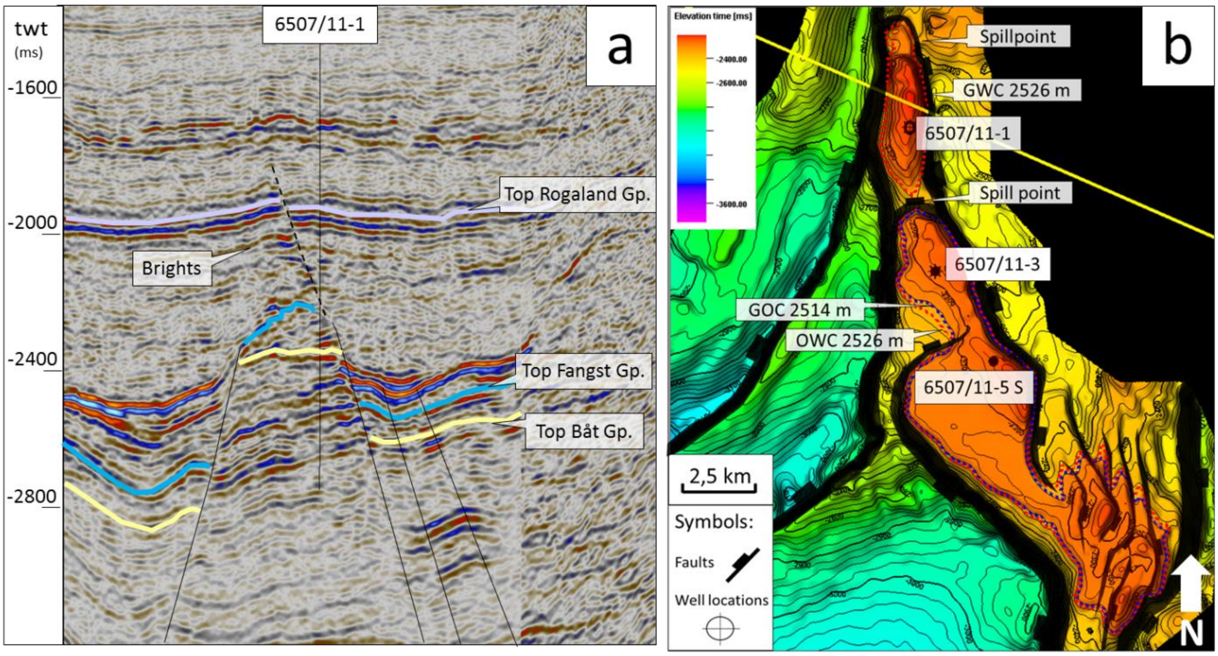


Figure 5.24: Interpretation of the Midgard structure. Seismic section from NW to SE showing (**a**) interpreted cross section along with fractured Rogaland Gp. and stacked brights. (**b**) shows Top Fangst surface map along with structural elements, wells and outlined cross section (yellow line). Contour line spacing is 20 ms.

5.3.3 Yttergryta - 6507/11-8

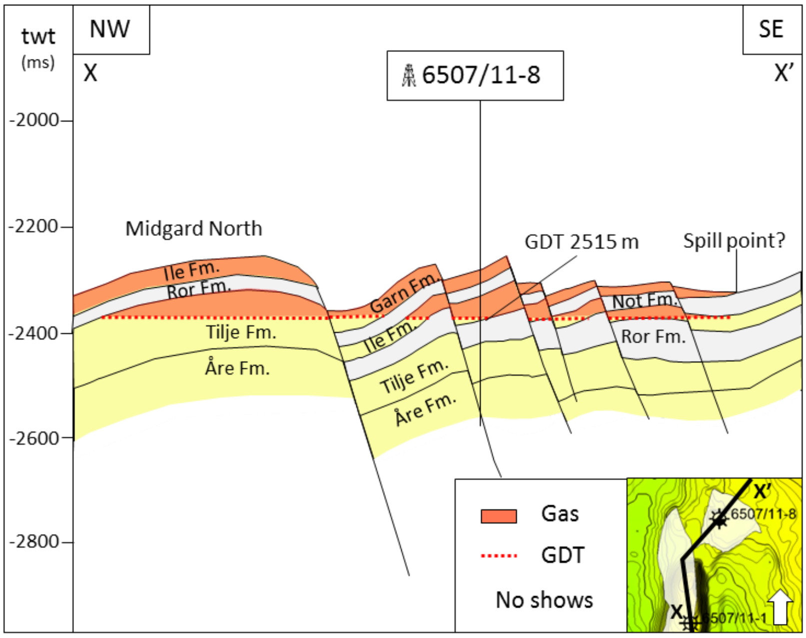


Figure 5.25: Simplified cross section illustration of the Yttergryta structure showing the Garn and Ile Formations making up the reservoirs, along with wells and a gas-down-to contact depth (GDT).

Yttergryta is situated northeast of Midgard on the Høgbraken Horst. The structure is bound by a large W-dipping N-S trending normal fault and a several smaller NE- and SW-dipping normal faults. Well 6507/11-8 encountered the Garn Formation at 2416 m and found both the Garn and the Ile formations to be gas-bearing. MDT pressure data revealed that the reservoir was in a dynamic stage of depletion due to production from the Midgard Field, and a gas-down-to situation was proven. The original pre-production contact was assumed to have been common with the Midgard Field contact at 2515 m, in the Ile Formation (Fig. 5.25). No hydrocarbon shows were recorded in the well apart from in the target reservoir.

The extent of the seismic data in the given dataset does not allow for full investigation of structural spill point as the seismic data coverage ends in the east-northeastern part of the structure. As no clear GWC was established, only an assumed gas-down-to contact, the exact location of the fluid contact is therefore uncertain as well. No faults extending through the Base Cretaceous Unconformity are observed in the structure.

Reflectors in the Rogaland Group appear strong above the reservoir, but this is also the case throughout the areas nearby. Aside from these strong reflectors, no significant amplitude variations are observed (Fig. 5.26).

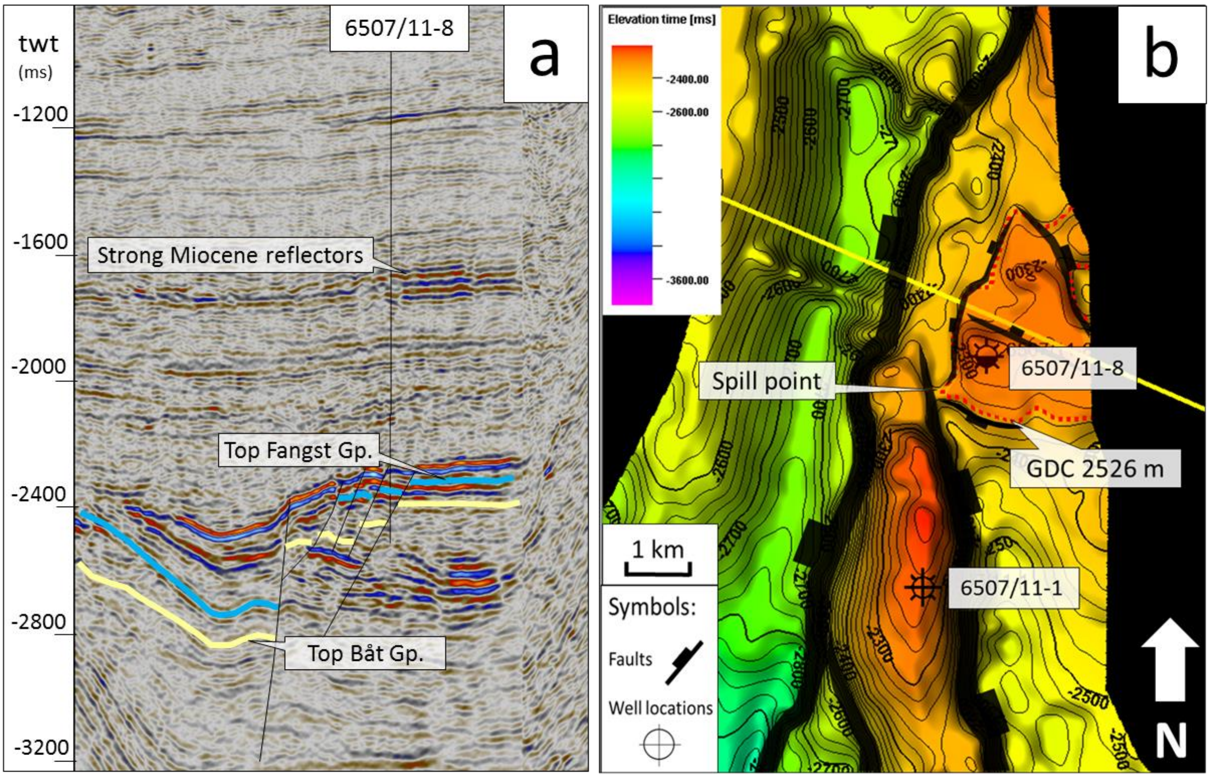


Figure 5.26: Interpretation of the Yttergryta structure. Seismic section from NW to SE showing (**a**) interpreted cross section along with strong reflectors in the Rogaland Gp. (**b**) Top Fangst surface map along with structural elements, wells and outlined cross section (yellow line). Contour line spacing is 15 ms.

5.3.4 Dry structure 6407/2-4

Well 6407/2-4 proved a dry Fangst Group with a questionable show on cuttings at 2891 m in the Garn Formation could be due to the oil based mud, otherwise no fluorescence or oil stain was seen from the cuttings. Apart from gas peaks caused by low mud weight gas readings were very low throughout the reservoir section.

From the interpreted seismic surface maps, the structure does not appear to have a structural closure (Figure 5.27). This observation is in conformance with the lack of hydrocarbons found in the structure. A few dim zones are observed in the overburden, however these also appear sporadically throughout the overburden in the vicinity of the structure (Figure 5.x).

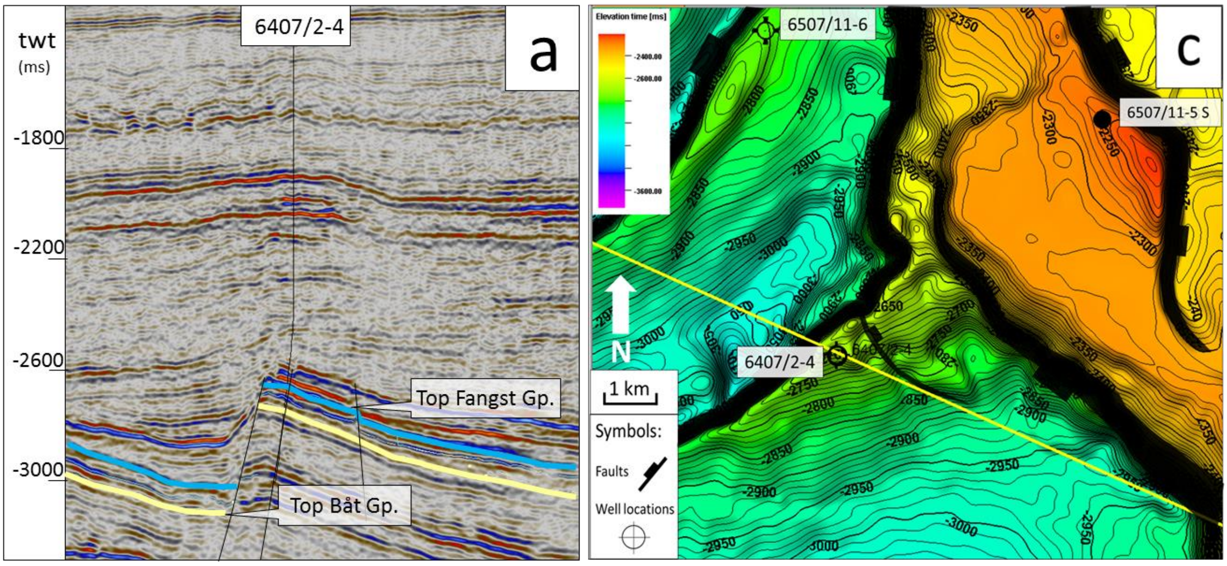


Figure 5.27: Interpretation of dry structure 6407/2-4. Seismic section from NW to SE showing (**a**) interpreted cross section along with brights and dim zones and (**b**) Top Fangst surface map along with structural elements, wells and outlined cross section (yellow line). Contour line spacing is 10 ms.

5.4 Njord area

5.4.1 Njord Main Field - 6407/7-1 S

The Njord oil field is located 30 km west of Draugen in the southern part of Haltenbanken. The structure is situated in a horst block at the southern boundary of Haltenbanken, where the Vingleia Fault Zone separates the terrace from the Frøya High in the south. It has a complex geology, with complicated fault patterns of N-S and NE-SW trending faults. The central parts of the structure are characterized by ramp-flat-ramp faults as well as roll-over folding. Folds are especially prominent in the eastern part of the structure adjacent to the basement in the southeast. Exploration well 6407/7-1 S encountered the top reservoir at 2759 m, and found oil in three separate reservoir units. The results of the well are summarized in table 5.4..

Table 5.4: Summary of results from well 6407/7-1 S in three reservoir units.

	Reservoir	Interval (-m)	Lithostratigraphic Unit	Relative Pressure (g/cc)	OWC depths (-m)
1.	Upper reservoir	2759 - 2783.5	Fangst Gp., Ror Fm.	1.35	N/A
2.	Main reservoir	2839 - 2988	Tilje Fm.	1.40	N/A
3.	Lower reservoir	3017 - 3038	Åre Fm.	No info	3016 - 3045

Njord consists of differentially pressured reservoir units; 70 bar above hydrostatic in the south-east to approximately 120 bar in the north-west. Varying contact depths were suggested from logs and RFT pressure data. The contact was defined from logs to be between 3003 and 3082.5 m. RFT data, however, defined a contact between 3016 and 3045 m. Shows were also recorded in several intervals throughout the well; in the Shetland Group, the Viking Group, as well as in the Fangst Group. Poor shows were also recorded in the Åre Formation at 3047 to 3082 m. Well 6407/7-3, drilled on the western edge of the Njord structure, found light oil in two differently pressured reservoir zones; a 10.8 m column in the Ile Formation, and a 50.4 m column in the Tilje-into the Åre Formation. This well, however, only proved an oil-down-to situation. Shows were recorded below the reservoirs, down to 3205 m. Other shows were also recorded in the Nise-, Kvitnos- and Lange formations.

Because of the complex fault pattern of the Njord structure, seismic interpretation in this area is especially challenging with only a few available wells. According to interpretation made in this study, the Njord structure spills to the south at approximately 2959 m, significantly shallower than the suggested fluid contacts. This indicates that the structure is underfilled. In addition to this, the seismic signal is largely disturbed in parts of this area to the south of the structure near well 6407/10-1 (further described in chapter 5.4.3).

The major NE-SW trending faults appear to divide the structure into compartments (Fig. 5.27). Furthermore well 6407/7-1 S is drilled on the northeastern margin of the structure, where only the Garn Fm. is recorded present in the Fangst Gp. The apparent absence of the Ile Fm. in this segment can explain why the upper reservoir zone continues into the Ror Formation – an uncommon reservoir in Haltenbanken. Well 6407/7-3 is drilled on the western downfaulted block, where only the Not- and Ile formations are recorded in the Fangst Group. It appears that this fault block constitutes a separate segment in the Njord structure, separated by the NE-SW trending fault (Fig. 5.28).

In the seismic section continuous strong reflectors are observed in the Rogaland Group, in the Tang Formation and Tare Formation, as well as in the lowest parts of the Shetland Group (Fig. 5.28). Several dim zones are also observed throughout the structure.

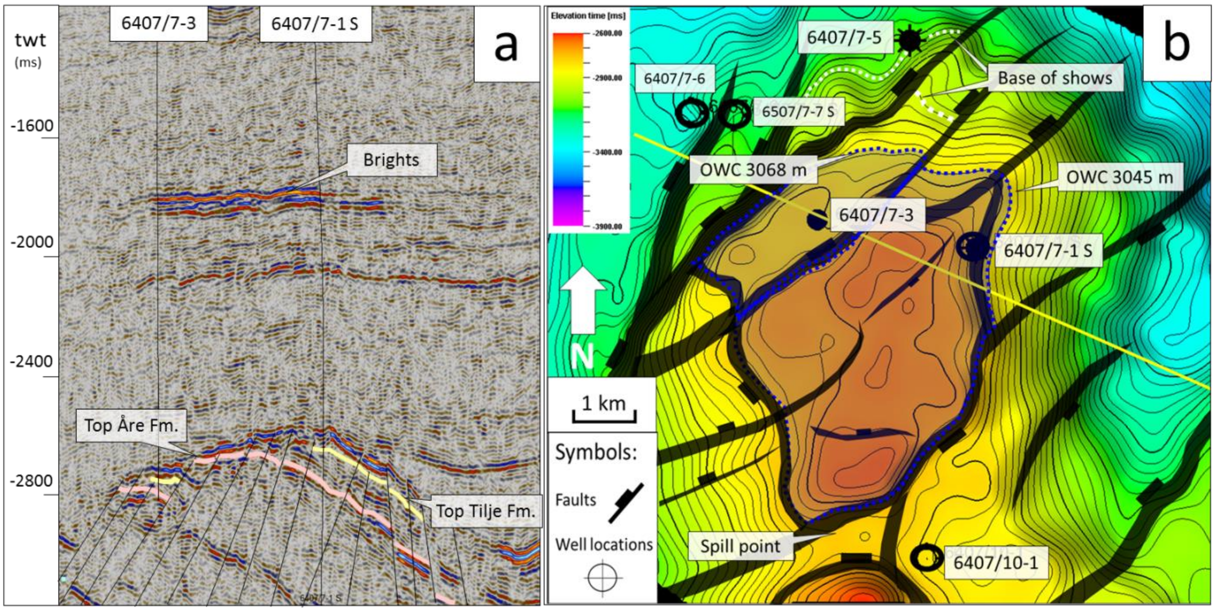


Figure 5.28: Interpretation of the Njord structure. Seismic section from NW to SE showing (**a**) interpreted cross section along with stacked brights and dim zones and (**b**) Top Båt Gp. surface map of the Njord main field, along with structural elements, fluid contacts in interpreted compartments wells and outlined cross section (yellow line). Contour line spacing is 20 ms.

5.4.2 Njord Northwest Flank - 6407/7-7 S and 6407/7-6

The Njord Northwest Flank, located northwest of the Njord Field, consists of several fault blocks (Fig. 5.29). These are defined by faults trending southwest and northeast and dipping towards the west. Exploration wells 6407/7-7 S and 6407/7-6 were drilled in two main fault blocks – the A structure and the B-main structure respectively. Both wells proved a rich gas condensate in the Middle- to Early Jurassic Fangst Group. Well 6407/7-6 was drilled in the B-segment of the northwest flank. It proved a heavy gas condensate in the Tilje Formation along with hydrocarbon shows in the Lange Formation sandstone. A gas-water contact was established at 3777 m. Pressure measurements from The Ile and Tilje formations indicated an overpressure of approximately 160-170 bar in the B-main structure compared to Njord. The A structure was drilled by well 6407/7-7 S, closer to the Njord Main Field. Like in the B-segment, the well proved the presence of gas condensate. However, hydrocarbons were discovered in the Ile-, Tilje- and Åre formations. Indications of hydrocarbons were also found in the Lower Cretaceous Lange Formation. According to MDT pressure points, the Tilje-Åre reservoir was approximately 26 bar over-pressured compared to the Ile reservoir. No contact was established in the structure. It appears that the fault displacing the two fault blocks controls the spill point, and acts as a sealing fault. This further explains the pressure differences between the A and B structures and the Njord Main Field.

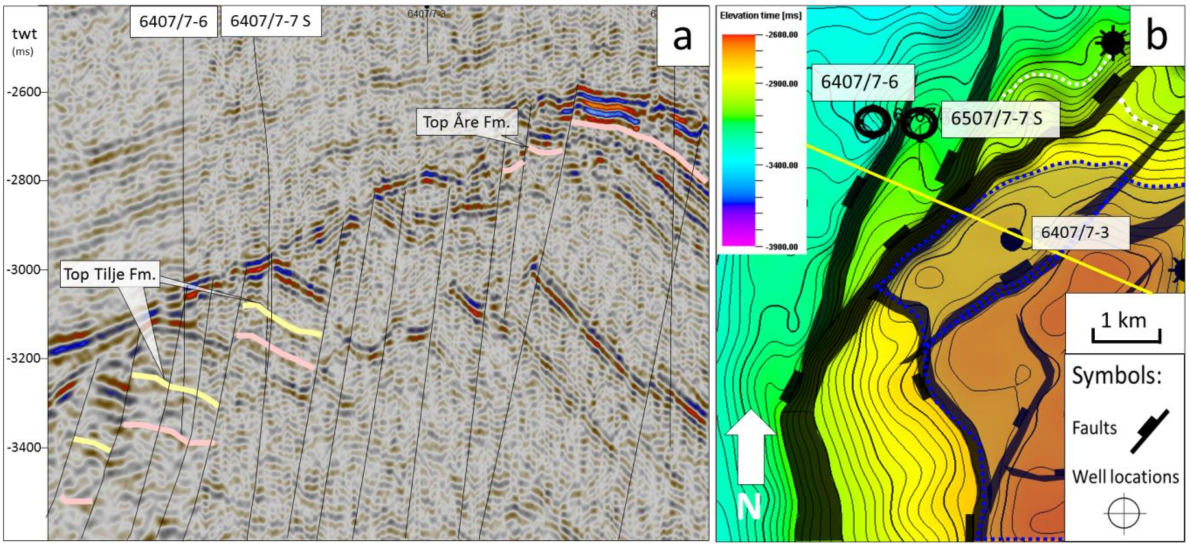


Figure 5.29: Interpretation of the Njord west flank structure showing (**a**) interpreted cross section and (**b**) top Båt Gp. surface map along with structural elements, fluid contacts, and outlined cross section (yellow line). Contour line spacing is 20 ms.

5.4.3 Dry structure 6407/10-1

Well 6407/10-1 is located immediately south of the Njord Main Field on the B-structure. The structure is downfaulted relative to the Frøya High in the southeast and the A-structure to the west. Set out to test hydrocarbon potential in the Fangst Group, the well was found to be dry with shows. A possible small amount of gas was found in the upper part of the Tilje- and Ile formations. Formation pressures also clarified that the A and B compartments of the Njord Field are not in communication.

In the seismic section, a disturbance of the seismic signal is observed in the southeastern part of the structure (Fig 5.28). This chaotic disturbance gradually becomes more evident further south in the section, and is only evident from below the BCU down to the Triassic sequence (Fig. 5.30).

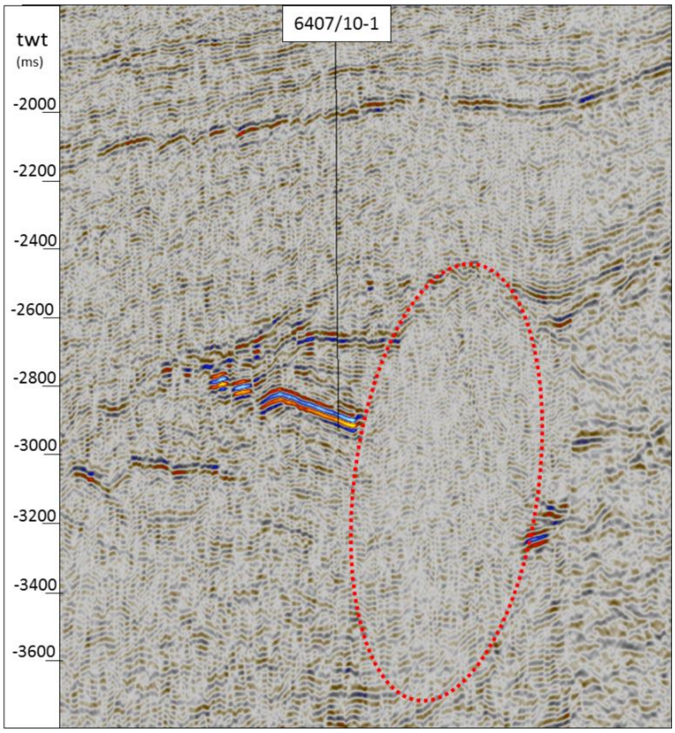


Figure 5.30: Seismic image of dry structure, well 6407/10-1 south of the Njord Field, showing disturbance on seismic data.

6 Discussion

The purpose of this study has been to investigate the controls on hydrocarbon column-heights in the Eastern province of Haltenbanken. Analysis of a variety of traps has been carried out, all with different fluid contacts and hydrocarbon content. This chapter is divided into six sections, where the findings in this study will be further discussed. Firstly a discussion on migration routes and fluid contacts are presented in terms of a fill-spill history for the study area. Further on, the hydrocarbon distribution in the study area is addressed. Thereafter, the observations and findings in this study are further discussed in terms of controlling factors on the hydrocarbon column. In summary, the results from this study can give the following categorization: fluid contacts coinciding with spill point, fluid contacts that do not coincide with spill point and columns where it is not possible to determine the controlling factors.

Investigation of the fluid contact relative to the mapped spill points in the following structures has made it possible to gain an overview of the hydrocarbon distribution within the respective traps throughout the study area. The analysis shows that out of the 15 hydrocarbon filled structures, at least nine are filled to their structural capacities. Furthermore, one of the filled structures appears to be filled below spill point. One of the structures appears to be underfilled, and in one of the structures the uppermost reservoir level appears to be underfilled while deeper reservoir formations are suggested to be filled. In four structures, the results are still unknown, as it has not been possible to map the column-heights relative to the spill points. Two dry traps have also been investigated, where residual hydrocarbons have been recorded in the Jurassic reservoir. Table 6.1 gives a summary of these findings.

Table 6.1: Summary of observations in this study (in Jurassic reservoirs).

Structure	Well	Type of structure	HC type	Reservoir (Fm.)
Heidrun	6507/7-2	Filled	Oil/Gas	Garn, Ile, Tilje & Åre
Heidrun North	6507/8-4	Filled	Oil/Gas	Åre
Natalia	6507/11-9	Filled	Gas	Garn
Yttergryta	6507/11-8	N/A	Gas	Garn & Ile
Midgard "North"	6507/11-1	Filled	Gas/Cond.	Ile & Tilje
Midgard "South"	6507/11-3	Filled	Oil/Gas	Garn & Ile
Sigrid	6507/11-6	Filled	Gas/Cond.	Garn
Nona	6407/2-5 S	Filled	Oil/Gas	Garn & Ile
Smørbukk	6506/12-1	Filled in deeper Fm., underfilled in Garn Fm.	Oil/Gas	Garn, Ile, Tilje & Åre
Smørbukk South	6506/12-3	Filled	Oil/Gas	Garn, Ile & Tilje
Tyrihans South	6407/1-2	Filled	Oil/Gas	Garn
Tyrihans North	6407/1-3	Filled	Oil/Gas	Garn
Trestakk	6406/3-2	N/A	Oil	Garn
Njord Main Field	6407/7-1 S	Underfilled	Oil/Gas	Garn, Ile, Tilje & Åre
Njord West Flank	6407/7-6	N/A	Gas/Cond.	Tilje
Njord West Flank	6407/7-7 S	N/A	Gas/Cond.	Ile, Tilje & Åre
Dry structure	6407/10-1	Dry w/shows	Gas shows	Tilje
Dry structure	6407/2-4	Dry w/shows	Questionable shows	Garn

6.1 Spill routes and migration history

Analysis of fill-spill routes among the investigated structures are carried out in the following section in order to better understand and explain the location of the present day fluid contacts. The migration history in the study area can be discussed in terms of three main fill-spill routes. These routes are suggested based on the regional surface maps of top reservoirs combined with fluid contact information in the various structures. Figure 6.1 illustrates these proposed routes, marked in white dotted lines. Additional charging directions are also shown with black arrows. Figures 6.2, 6.3 and 6.4 further present interpreted cross-sections of the routes along with the interpreted top reservoir surface map for the respective section.

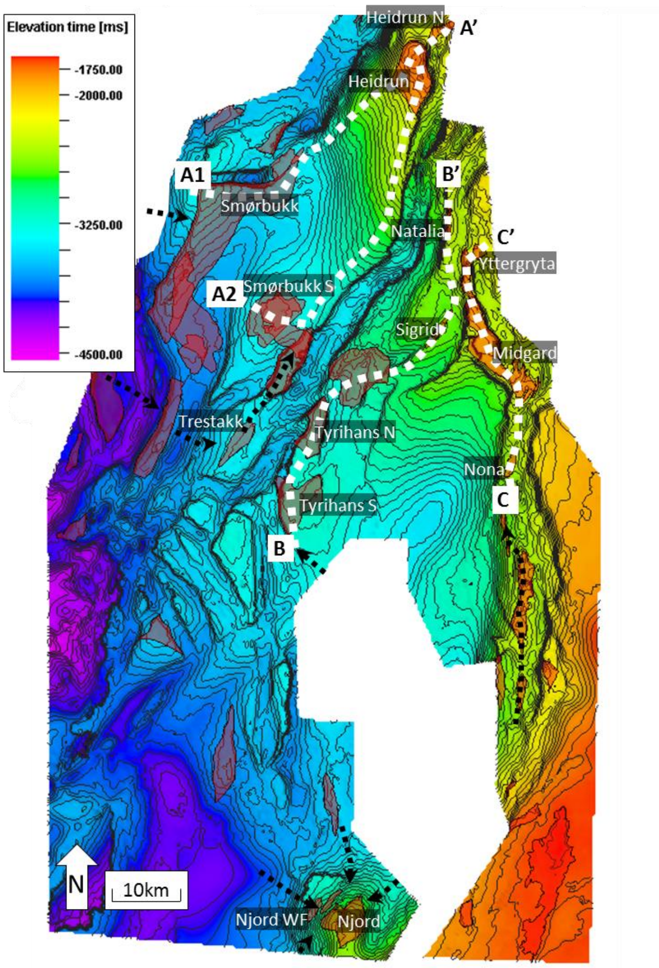


Figure 6.1: Regional Base Cretaceous surface map of the study area with suggested migration routes between the investigated structures - shown in white dotted lines (migration routes A, B and C). Additional hydrocarbon charging directions are shown by black dotted arrows. Interpreted cross-sections from these fill-spill routes are illustrated in figures 6.2, 6.3 and 6.4.

6.1.1 Fill-spill route A

The two cross sections (Fig. 6.2) depict suggested fill-spill routes from W-NE and SW-NE from the Smørbukk and Smørbukk South fields towards Heidrun and Heidrun North. The Trestakk structure south of Smørbukk South is included in this migration route as it is suggested to spill towards the Maria discovery and possibly further north towards the Smørbukk and Heidrun areas. Geochemical data indicates the same marine source rock for all these structures (Karlsen et al., 2004).

The Trestakk field is the deepest located structure in the study area, boarding the over-pressured western Haltenbanken, and is believed to be charged with oil migrated from the stratigraphically overlying Spekk Formation from the Lavrans area to the west (Koch & Heum, 1995). This area is today separated from the down-faulted over-pressured region by the extensive Klakk Fault Complex. It contains oil in the Garn Formation only. The exact depth of the oil-water contact has not been established from wells, and varies greatly from different methods as previously mentioned. Still, mapping of the suggested contact depths relative to spill point indicates that the structure is be filled, and thus that supply of oil to the Garn Formation has been sufficient. Oil shows are, however, recorded in several intervals below the contact. These shows are recorded throughout the Båt Group below the fluid contact down to total drilled depth in the Åre Formation. At these depths of above 4 km the reservoir quality decreases significantly due to quartz cementation. The presence of these deeper shows indicates that the reservoir could be underfilled and that some process has caused a reduction of the hydrocarbon column. However, it is possible that these have arrived from short-distance lateral migration. The amplitude anomalies observed in the overburden on the seismic data is likely to be a result of merging datasets and no further anomalies in the overburden has been observed to support the theory of leakage. Trestakk is likely spilling towards the Maria discovery to the north.

The Smørbukk field is located in the westernmost part of the study area, separated from the over-pressured Western Haltenbanken by the Klakk Fault Complex – currently acting as a pressure barrier. The structure is highly compartmentalized and comprises oil and gas in different structural and stratigraphic levels; in the Early- to Middle Jurassic Fangst Group and the Late Triassic to Early Jurassic Båt Group. Although the structure contains segments and compartments on several levels, only a few fluid contacts are available from the well data. This situation is often encountered in tilted rotated fault blocks with repetitive lithologies of sandstones, shales and coals, such as in the Smørbukk structure. This causes an abundance of hydrocarbon-down-to contacts, and the true fluid contact is rarely proven in the well (Karlsen et al., 2004). Geochemical analyses by Olstad et al. (1997) and Karlsen et al. (2004) suggest that oil first migrated into Smørbukk in the Early Tertiary across the now sealing main fault zone, as this would require migration from areas to the west where the Spekk Formation source rock was mature at the time. This indicates that the fault zone was once open for migration from the west, but has later become sealed during progressively deeper burial and subsequent quartz cementation. In the more recent filling episode Smørbukk likely experienced later filling from the local kitchen between Smørbukk and Smørbukk South - when the fault zone to the west was sealed. These filling scenarios indicate less long-distance migration.

It is possible that the deeper formations are filled to spill, while shallower formations are underfilled. Hydrocarbons spilling from the Smørbukk structure will likely migrate up towards the Heidrun structure in the northern part of Haltenbanken as suggested in Fig. 6.2. Shows are recorded in several intervals below the fluid contacts throughout the Fangst and Båt groups. This might indicate that the structure previously contained a larger hydrocarbon column than what is present today, and that leakage could have occurred. The Garn Formation usually constitutes the reservoir in most of the studied structures in Haltenbanken, however, only residual hydrocarbons are found in some of the Garn units in the Smørbukk structure. This further supports the theory of hydrocarbon loss through leakage from shallower reservoir units. In addition to this, oil is found in the Cretaceous Lange and Lysing sands above the Jurassic reservoir section. Geochemical analysis of these oils proves to be similar in composition to the oil encountered in the Jurassic reservoirs (Karlsen et al., 2004). Vertical leakage of oil from the shallowest Jurassic reservoir could explain these accumulations in the Cretaceous section. Amplitude maps from the overburden above the reservoir show reduced reflectivity over the northwestern part of the structure at the fault intersection bordering the overpressured area. This might indicate that leakage has occurred in through this fault at some point in time and that the hydrocarbon column-height in the shallow reservoir is controlled by vertical leakage through this intersection.

Smørbukk South, like the neighboring Smørbukk, received hydrocarbons from the local deep basin to the west of the structure during the later filling event starting approximately 10 Ma bp (Karlsen et al., 2004). The structure is located west of the Grinda Graben and contains oil and gas in the Fangst Group down to the Tilje Formation of the Båt Group. Well completion reports give a fluid contact coinciding with the spill point – suggesting that the structure is filled.

Spill from both Smørbukk and Smørbukk South is directed towards the Heidrun area - the shallowest of the investigated structures in the study area. Heidrun contains reservoirs throughout the Fangst and Båt groups, with laterally sealed compartments and a large variation in fluid contacts within the structure. It borders the Nordland Ridge area to the north, and has received oil and gas from mature source rocks in the large drainage area to the southwest. It is suggested to have received major quantities of spill from the Smørbukk structures (Heum et al., 1986). Heidrun is a highly complex structure, and investigating the fluid contact versus spill point as one whole structure does not give a realistic image of what controls the hydrocarbon column in the structure. This is especially evident from the fact that the structure holds such a large oil column – which would not normally be expected in normal fill-spill conditions. Further discussion on possible explanations for the present day hydrocarbon distribution in the Heidrun Field is included in subchapter 6.4. Heidrun is suggested to spill further towards Heidrun North. Heidrun North is possibly filled to spill point, and further migration is directed to the north – towards the Nordland Ridge area where a regional seal is lacking. This area is not included in the provided dataset.

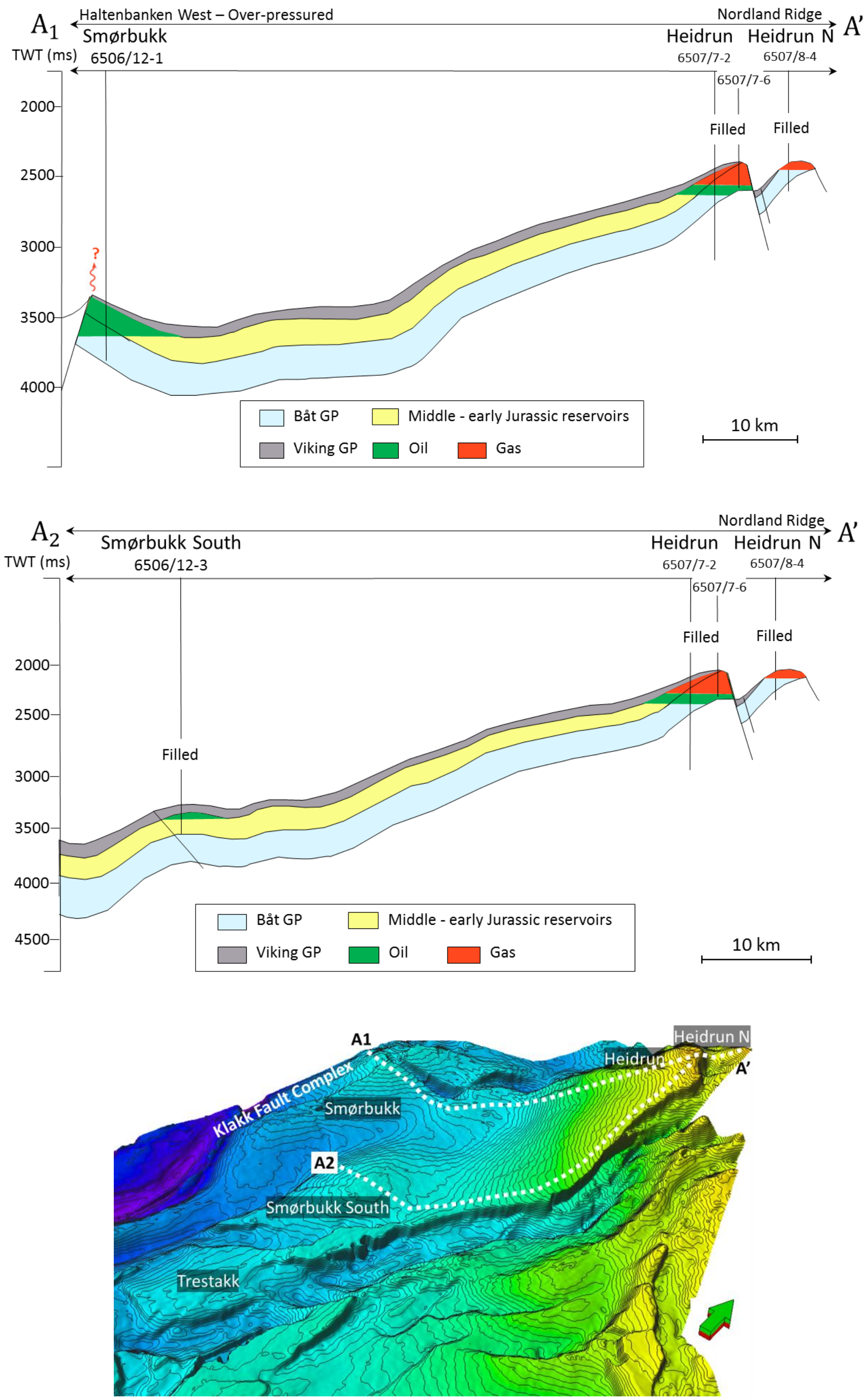


Figure 6.2: Migration route from W-NE through Smørbukk, Smørbukk South, Heidrun and Heidrun North in interpreted cross section and in surface map view. Cross sections are vertically exaggerated. Green arrow is North.

6.1.2 Fill-spill route B

The cross section B-B' (Fig.6.3) shows a suggested SSW-NNE migration route along the eastern flank of the Grinda Graben, through Tyrihans South and Tyrihans North in the south towards the Natalia discovery in the northeastern Haltenbanken. This migration route stretches from depths of more than 4 km to approximately 2.5 km in the shallowest part in the north.

The Tyrihans South structure is a gas accumulation in the Garn Formation. It is likely charged with heavy gas condensate from the underlying Åre Formation coal sequence, from the southern areas of the Gimsan Basin. Heum et al. (1986) suggest that the hydrocarbon accumulation in Tyrihans South is in a state near the critical point where small changes in pressure, temperature or composition can lead to considerable changes in phase condition. The gas-water contact coincides relatively closely with the mapped structural spill point, indicating a filled structure. However, shows have been recorded in the deeper lying Tilje and Åre formations.

Further spill from Tyrihans South is directed towards Tyrihans North. The structure is also filled to the fault spill point in the northwest. The structure is gas-filled with a thin oil leg, as opposed to the purely gas-filled Tyrihans South. This situation is typical when a moderately small fault defines the spill point, and the reservoir formation is in contact across the fault (Heum et al., 1986). In this scenario, oil and gas can spill simultaneously. The change in hydrocarbon content in the two structures is likely due to the difference in the drainage area. Geochemical analysis by Heum et al. (1986) suggest that Tyrihans South has a drainage area covering all maturity levels, while Tyrihans North has a drainage area with discontinuous maturity levels – causing a slight preference of the end components and a lack of intermediate components.

Spill from Tyrihans North is further directed towards the Natalia structure. This is a small gas discovery in the northern part of the study area. As in the previously mentioned structures, Natalia appears to be filled to spill. Natalia further spills to the northeastern margins of Haltenbanken where it meets the Nordland Ridge. This area is not covered by the seismic dataset in this study. The Sigrid small gas discovery is included in this migration route, as spill from Tyrihans North is likely directed towards the Sigrid and Natalia structures. The gas-water contact in the Garn Formation very closely coincides with spill point, and the structure is thus interpreted as filled. Further spill from Sigrid could be directed either towards Natalia or the northern segment of Midgard.

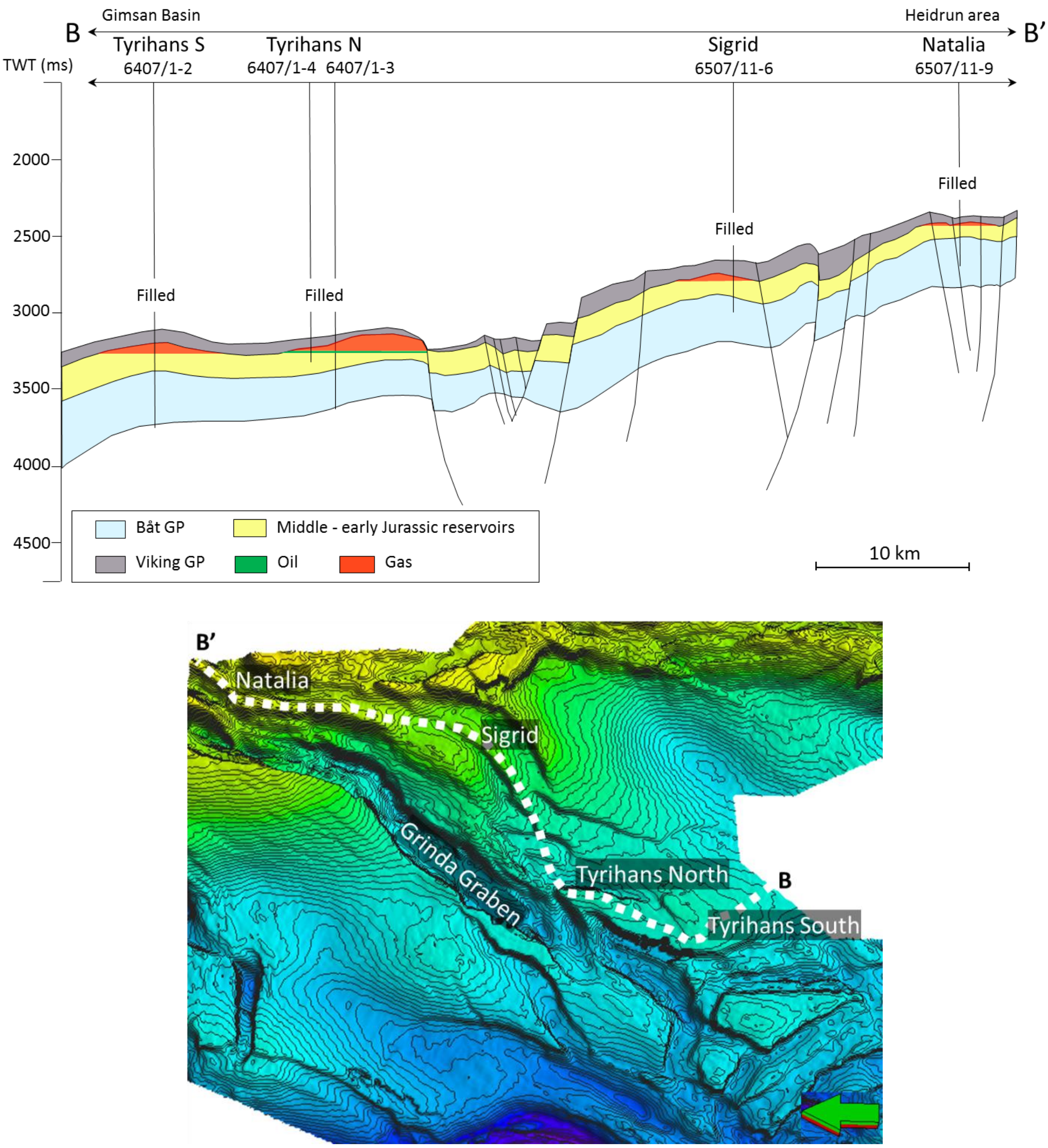


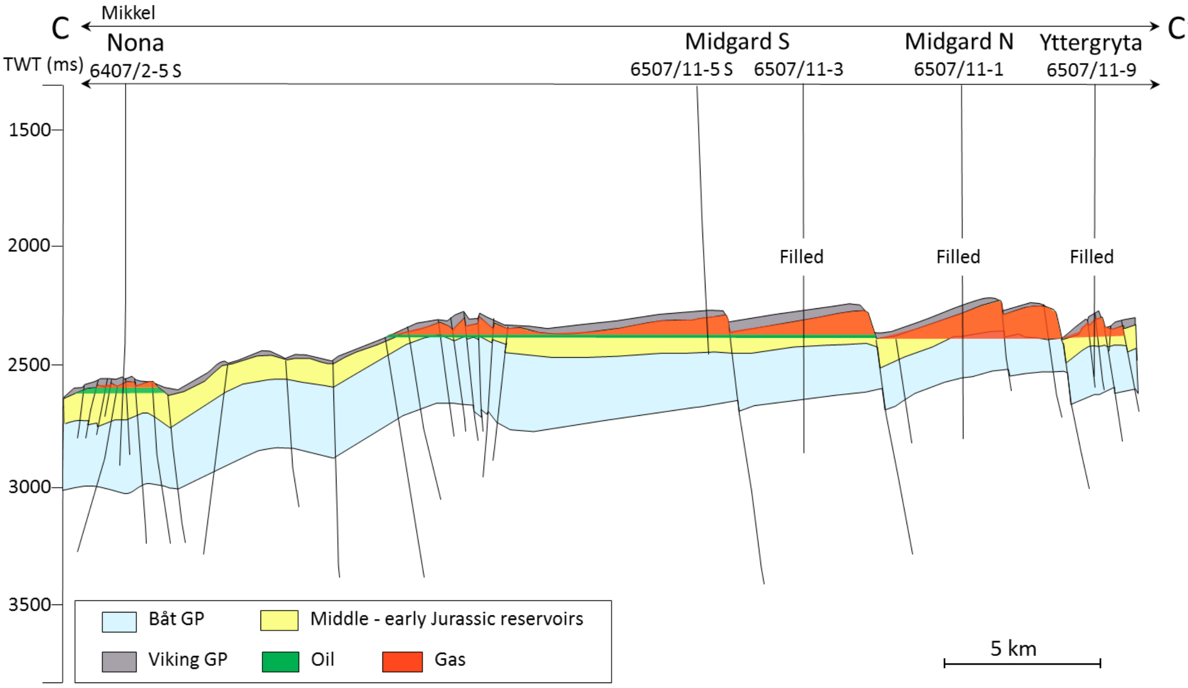
Figure 6.3: Migration route from SSW-N through Tyrihans South, Tyrihans North, Sigrid and Natalia in interpreted cross section and surface map view. Cross section B-B’ is vertically exaggerated. Green arrow shows North.

6.1.3 Fill spill route C

Of the investigated structures only Midgard, Yttergryta and Nona have migration distances of more than 15-20 km (Karlsen et al., 2004). These structures are located in the easternmost region of the study area, bordering the Trøndelag Platform to the east. Section C-C' (Fig. 6.4) presents a N-S migration route from the Nona structure by the Bremstein Fault Complex through Midgard to Yttergryta.

The Nona discovery comprises oil and gas in the Garn and Ile formations. Oil was encountered in the Ile Formation with a proven contact, while gas was found in the Garn Formation, with only a gas-down-to situation proven. The Mikkel structure south of Nona is possibly located along the same fill-spill route, but is not included in this study. Well information from the Norwegian Petroleum Directorate suggested non-communication between the two reservoir formations. However, in this study it is suggested that the formations could in fact be in communication. It is possible that production from nearby fields such as Mikkel and/or Midgard has affected the pressure measurements. Nonetheless, if there is communication, a gas-oil contact would most likely exist outside well position between the recorded gas-down-to contact and the oil-water contact. It is possible that oil has migrated into the reservoir at an early stage, and that later migration of gas has flushed oil out. For this situation to occur, the reservoir formations would have had to be in communication at this time. As the oil-water contact is coinciding with the spill point in the top reservoir, the structure is suggested to be filled. Hydrocarbon shows are, however, recorded below the oil-water contact in the Ile Formation. These shows extend down to approximately the depth of the spill point in the Ile Formation. This observation could suggest a possible paleo-fluid contact which is deeper than the estimated spill point. A possible explanation for this is that the fault to the north of the structure was sealing in the past, allowing for a deeper accumulation of hydrocarbons. If seal-breach through the fault occurred, lateral leakage could have followed. No strong indications of vertical leakage have been observed on the seismic data, or on amplitude maps.

Further spill is most likely oriented towards the shallow Midgard oil and gas field, located in the transition zone between Haltenbanken and the Trøndelag Platform. This structure contains mainly gas with a thin oil leg. According to well data from the structure, oil is only reported in the southern segment. However, as the nature of the hydrocarbons near the water contact in the northern segment was not clearly defined, due to a shaly lithology at the critical level, the northern segment probably contains a similar oil leg (Heum et al., 1986). A fault to the north of the structure defines the saddle point between the segments. Midgard is suggested to be filled to spill as the fluid contact closely coincides with the spill point towards the Yttergryta structure. However, Midgard and Yttergryta is likely sharing a common contact, across the spill point in the north. This observation indicates that the true spill point of the Midgard (and Yttergryta) structure is located at another point. As previously mentioned, the seismic data coverage ends at the Yttergryta structure, so no further mapping to the northwest of the structure has been possible. It is possible, however, that the true spill point is located in the southeastern part of Midgard, where the structure borders the Ellingråsa Graben. Based on this, it is unclear if the system as a whole is truly filled to spill. Midgard shows a migration history similar to that of the Heidrun structure. It can be divided into two phases: with oil migration starting in Early Tertiary from the early mature coal sequence in the deep parts of the drainage area, until Late Tertiary, when gas was generated in large amounts from the late mature coal sequence in the basin and the hydrocarbons in the structure changed phase from oil to gas (Heum et al., 1986).



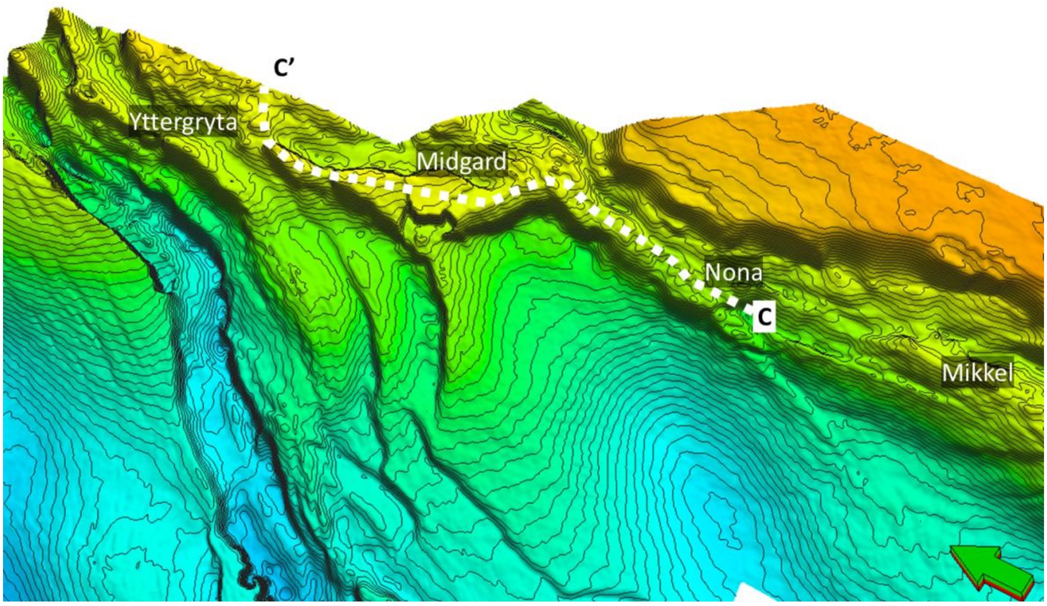


Figure 6.4: Migration route from S to N NE through Nona, Midgard and Yttergryta illustrated in interpreted cross section and in surface map view. Cross section C-C' is vertically exaggerated. Green arrow shows North.

6.1.4 Summary of fill-spill routes

Based on the three main fill-spill routes in the study area and fluid contacts within the structures, a large number of the structures are found to be filled down to the spill point. Observations based on the interpretation in this study from Sigrid, Natalia, Tyrihans South and Tyrihans North show clear indications that the structures are filled to spill point. Observations from Smørbukk South, Heidrun, Heidrun North, Nona and Midgard also show indications of the structures being filled to spill, but should be regarded as less certain. This is due to uncertainties in regards to location of spill point, compartmentalization and large fluid contact variations within the structures. Compartmentalized structures, where the fluid flow and distribution is controlled by sealing faults forming lateral barriers will be further discussed in following subchapters.

The Njord structure has not been included in any of the main fill-spill routes discussed in this chapter. Njord is located far south of majority of the investigated structures, where Haltenbanken transitions to the Frøya High. Based on the interpretation in this study, it is not filled to its structural capacity. It is suggested to have received hydrocarbon charge from a local drainage area in the deep parts of the basin surrounding the structure to the north and northwest. Geochemical analysis by Lilleng & Gundesø (1997) suggests that the Njord oils derive from a mature source corresponding to the Spekk Formation at depths indicating long distance secondary migration. Furthermore the analysis of oil from the dry 6407/10-1 structure shows a composition of a much lower maturity than oils from the Njord Field. This could indicate that lack of migration across the faults defining the compartments in Njord is the reason for the lack of hydrocarbons in this present day dry structure.

6.2 Fluid contacts coinciding with spill point

Based on the interpretation conducted in this study several of the investigated structures share an important common observation: the depth of the spill point closely coincides with the recorded hydrocarbon-water-contact depth. This suggests that the structures are filled to their structural capacities. Furthermore, it suggests that the depth of the spill point is the controlling factor on the hydrocarbon column-heights in the respective structures. Table 6.2 gives an overview of the structures in which this situation is observed.

Table 6.2: Overview of structures where column-heights are controlled by spill point location.

Structure	Content	Reservoir level (Fm.)	Shows below contact
Midgard North	Gas/Cond.	Ile (& uppermost Tilje)	-
Midgard South	Oil/Gas	Garn (& uppermost Ile)	-
Sigrid	Gas/Cond.	Garn	-
Natalia	Gas	Garn	13 m below GDT
Tyrihans North	Oil/Gas	Garn	-
Tyrihans South	Oil/Gas	Garn	In Tilje & Åre Fm. down to 4548 m
Smørbukk (deep reservoir levels)	Oil/Gas	Ile, Tilje & Åre	-
Smørbukk South	Oil/Gas	Garn, Ile & Tilje	-
Heidrun North	Oil/Gas	Åre	38 m below OWC
Nona	Oil/Gas	Garn & Ile	Down to spill point in Ile Fm.

The Midgard structure, wells 6507/11-1, 6507/11-3 and 6507/11-5 S, is separated into two segments by a saddle point located north of well 6507/11-3. Both the saddle point depth and the mapped spill point depth in the north towards the Yttergryta structure coincides closely with the recorded oil-water-contact depth, suggesting that Midgard is filled to its structural capacity. The Garn (and uppermost Ile) Formation constitute the reservoir in the southern segment. In the northern segment, however, the shallowest layer in the Fangst Group, the Garn Formation, is eroded. The reservoir in this segment is thus comprised of the Ile (and uppermost Tilje) Formation. An exact fluid contact was not recorded in Yttergryta, however, the suggested gas-down-to contact depth coincides closely with the mapped spill point from Midgard to Yttergryta, suggesting communication between the structures. As the spill point of

Yttergryta has not been possible to map, it is unclear if Yttergryta is filled to spill as well. The structure most likely spills towards the N or NW at the Høgbraken Horst.

The smaller gas discoveries Sigrid and Natalia also share similar observations. The main observations from the analysis of the structures indicate that these are filled to structural capacity and thus that the hydrocarbon columns are controlled by the spill point. This is also observed in the Tyrihans North and Tyrihans South structures. While investigation of the mentioned structures shows a clear coinciding of spill point depth with contact depth, the observations in Natalia are more unclear. As only a gas-down-to situation has been proven, determination of controls on the hydrocarbon column in the structure is more uncertain.

Another element that characterized the spill point controlled columns is the reservoir formation level. Majority of the investigated structures with spill point controlled columns have reservoir levels in the uppermost part of the Jurassic Fangst Group, with the exception of Smørbukk and Heidrun North. The northern segment in Midgard contains hydrocarbons in the Ile and uppermost Tilje formations as the Garn formation is eroded in this location. Figure 6.5 illustrates this scenario exemplified by the Midgard and Yttergryta structures. Although this observation is to be expected as the Garn Formation is one of the most common reservoir rocks in the Haltenbanken area, it differs from the structures discussed in the next subchapter, where structures contain reservoirs throughout the Fangst and Båt groups.

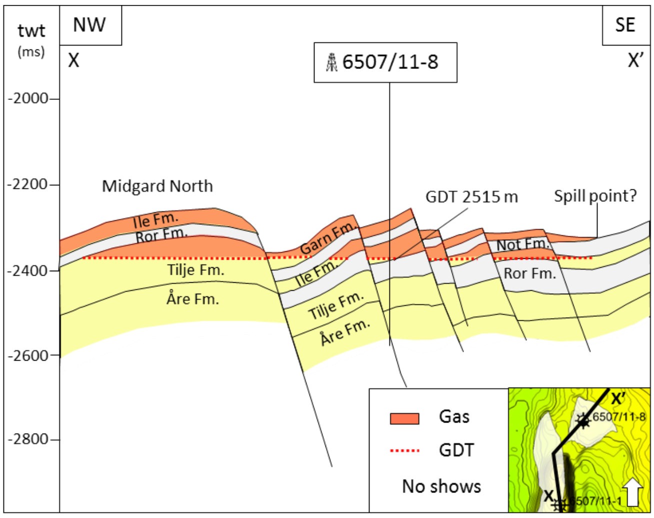


Figure 6.5: Simplified illustration of the accumulation of hydrocarbons in the shallower formation of the Fangst Group, as observed in the Midgard and Yttergryta structures.

6.3 Fluid contacts that do not coincide with spill point

In a number of the investigated structures the hydrocarbon column appear to be controlled by other factors than the depth of the spill point - as this does not coincide with the fluid contact depth (Table 6.3). This subchapter will give a presentation of these structures, as well as a discussion of various alternatives to explain the observations made. These suggested alternatives are based on the interpretation and results from the analysis carried out in this study.

Table 6.3: Overview of structures where column-heights are not controlled by spill point depth

Structure	Content	Reservoir level (Fm.)	Shows	From well
Smørbukk (Garn reservoir)	Oil/Gas	Garn	Throughout Garn Fm.	6506/12-7
Heidrun	Oil/Gas	Garn, Ile, Tilje & Åre	~ 45 m below spill point	6507/7-6
Njord	Oil/Gas	Garn, Ile, Tilje & Åre	~ 120 m below spill point	6407/7-1 S

6.3.1 Fault sealing

Faults can act as both conduits and barriers for fluid flow in the subsurface. Observations from the above mentioned structures suggest that supply of hydrocarbons into the reservoirs has been sufficient. However, observations from the Heidrun structure gives an oil-water contact located deeper than the mapped spill point – giving the impression of an over-filled reservoir. An approximately 40 m vertical difference from the mapped spill point to the deeper oil-water contact is observed. However, fluid contact depths vary greatly within the structure, as it is highly faulted and compartmentalized. Additionally, several local channels and lobes are present in the shallow marine to deltaic sands constituting the reservoir formations. Especially the deltaic Åre Formation contains several sand lobes. If these are not in contact with each other it is possible that the fluid contact can be located at a deeper level than the spill point. Lateral fault sealing is another possible explanation for the deep oil-water contact. The normal fault in the northern segment of the structure makes the spill point towards Heidrun North (Figure 6.6). If this is partially sealing, the oil column could extend to a greater depth than the spill point. If lateral fault sealing is controlling the position of the fluid contacts in Heidrun, it is likely that either quartz cementation or clay smear along the fault plane is restricting the fluid flow across the faults. However, sandstones buried to less than 2.5-3 km usually have very little quartz cementation (Bjørlykke & Egeberg, 1993). Clay smear is therefore a more likely explanation. The Åre Formation has a higher content of clay as the depositional environment was dominated by delta plains with swamps and channels.

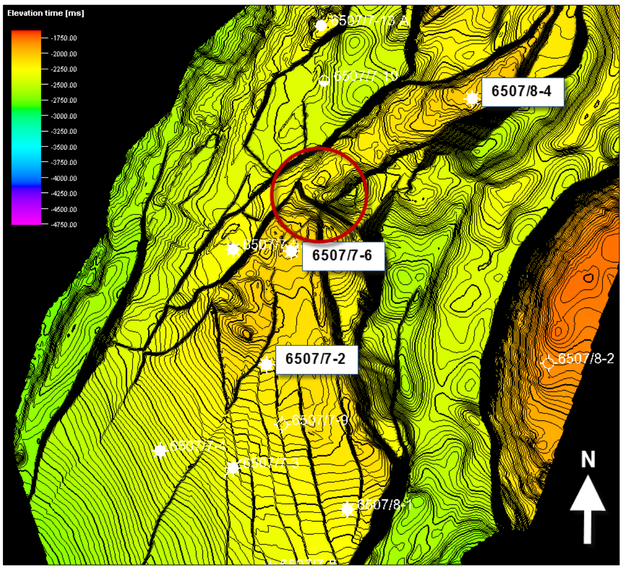


Figure 6.6: Seismic surface map of the top Tilje Formation surface in the Heidrun structure. The red circle marks the fault spill point from Heidrun to Heidrun North.

6.3.2 Leakage

The analysis in this study has shown that the majority of the structures in the eastern part of Haltenbanken appear to be filled, with the exception of the shallow reservoir level in the Smørbukk and in Njord. The presence of underfilled reservoirs is often ascribed to vertical leakage, usually associated with fractures and faults – due to tensile failure and shear failure. Vertical leakage can also occur through capillary leakage, through the pore network of the cap rocks (Bolås & Hermanrud, 2003). As majority of the structures in Eastern Haltenbanken are normally pressured, they are not as prone to induce failure as the overpressured structures in the west. Still, amplitude maps from the Smørbukk structure show dim zones in the overburden in the Shetland Group, concentrated around the fault intersection in the west near the apex. Additionally, the Garn Formation contains only residual hydrocarbons in this area, and oil of similar composition and geochemical character is found in the Cretaceous Lange and Lysing formations above the structure (Karlsen et al., 2004). These observations suggest that the formation most likely contained hydrocarbons at an earlier time, and could have been lost through vertical leakage at the crest of the structure. Further discussion on the occurrence of dim zones above Smørbukk is included in subchapter 6.6.

As previously mentioned, the oil column in the Heidrun structure appears to extend far below the spill point. It is worth mentioning that this unusual observation could also be explained by leakage. Amplitude maps from the overburden show bright amplitudes concentrated above the top of the reservoir. These are however, coinciding with the location of the salt diapir/vent structure, and can therefore not automatically be defined as leakage-related. However, it is a possible that the thin and eroded cap rock in the structure is partly leaking gas through capillary leakage. This situation could allow for the preservation of such a large oil column in the structure.

Although no firm oil-water contact was established in Njord, the suggested fluid contact depth is located significantly shallower than the mapped spill point to the south. This suggests that the structure, or at least the southeastern compartment, is underfilled. No amplitude maps were generated from this structure, however, the structure differs from other structures in the study as it contains overpressured compartments in different stratigraphic levels. Furthermore the presence of residual hydrocarbons and shows in the overburden indicates that vertical leakage has likely occurred in the Njord structure.

In addition to fault sealing and leakage, lack of migration into the reservoirs could control the hydrocarbon column in structures. This is, however, only suggested to have occurred in the dry structure 6407/10-1 south of Njord, due to it being laterally sealed off from the compartments in the main field. The rest of the structures in the study area are suggested to have received sufficient migration into the reservoirs.

6.4 Oil versus gas distribution

A large number of the structures in the eastern part of Haltenbanken show traces of both oil and gas (Heidrun, Midgard, Nona, Smørbukk, Smørbukk South, Tyrihans North and Tyrihans North and Tyrihans South). Most of the oil bearing structures in the area are located along a SSW-NNE trend, while most of the purely gas filled structures are located in the western part of Haltenbanken. As evident from the suggested fill-spill routes and from the general E-W maturity of the hydrocarbons in the area, lateral migration distances from structure to structure is relatively short (Karlsen et al., 2004). In addition, a large portion of the structures appear to be filled, indicating that migration into the structures has been sufficient.

Most of the deeper structures, such as Trestakk, Smørbukk and Smørbukk South have received oil from the deep basin areas in the western part of the study area, and hydrocarbons from the Smørbukk area most likely spills towards the shallow Heidrun area. Heidrun is still located above the depth where oil and gas generation occurs in the Spekk Formation, which is estimated at approximately 3900 m and 4700 m respectively (Heum et al., 1986). As further basin subsidence leads to cracking of oil into gas, the Heidrun structure received sufficient supply of gas as well as oil. Gas, having lower density than oil, will migrate towards the top of the reservoir. Sufficient supply of gas into the reservoir will thus "flush" the oil, as it pushes the oil column downwards below the spill point. This leads to oil being spilled towards shallower traps, and the oil column is eventually replaced by a gas column. As Heidrun has received sufficient supply of gas from the large Smørbukk area, it would be likely to believe that there would be less quantities of oil left in the reservoir than what is observed today. This indicates that some mechanism has allowed for the large oil column to be preserved in the structure. As described in the previous chapter, it is possible that vertical leakage of gas through the cap rock occurs while the structure receives a continuous supply of oil and gas. Another possibility is that the faults are partly sealing, restricting oil flow, while gas is spilling towards Heidrun North. However, it would then be expected to find more oil in Heidrun North.

Another unusual observation in the study area is the apparent lack of oil in Midgard North and Yttergryta, while both oil and gas is present in Nona and Midgard South. As mentioned in chapter 6.1.3, it is suggested that a similar oil leg could in fact be present in the end of this fill-spill route. As reported by Heum et al. (1986), a shaly lithology at the critical level resulted in the nature of the hydrocarbons near the water contact in Midgard North not being clearly defined. However, it should not be ruled out that the faults in Midgard could be sealing some oil but allowing gas to spill further towards Yttergryta.

Furthermore, oil is found in the spill route from Tyrihans South and Tyrihans North, but in the end of the spill route, in Natalia, only gas is encountered. It might be possible that the oil has spilled further north, however this has not been detectable as the data coverage ends in this area.

Most of the investigated structures in the study area show similar characteristics in oil and gas distribution. In several of the structures it appears that the reservoir formations in the Fangst and/or Båt groups are in communication with each other. Three scenarios can possibly explain the observed distributions:

1) Shales between the formations are either sealing or allowing for communication between the formations. Several of the shallower structures have common contacts across different formations, indicating that they are in communication (e.g. Midgard, Heidrun). In other deeper structures, the shales could be sealing, and hydrocarbons are then accumulated in separate formations.
2) Communication/migration occurs along the erosion surface. This could be a possible scenario in structures where the crest has been eroded – such as in Heidrun, Heidrun North, Midgard and Tyrihans North.
3) Communication along the fault plane where rotated fault blocks are juxtaposed with shales.

6.5 Fluid contact variations within structures

Analysis of the hydrocarbon distribution and fluid contact depths has shown that several of the investigated structures have contact variations within the reservoirs. This includes several of the larger oil and gas fields in the area such as Smørbukk, Smørbukk South, Heidrun, Midgard and Njord. An overview of this occurrence is given in Table 6.4.

Table 6.4: Summary of fluid contact variations within structures with several wells.

Well	Fluid contact depth (mTVD)					
	Smørbukk	**Smørbukk S**	**Heidrun**	**Midgard**	**Njord**	**Njord WF**
6506/12-1	OWC≈4342					
6506/12-6	OWC=4117-4150					
6506/12-7	Shows					
6506/12-11 S	No contact					
6506/11-2	No contact					
6506/12-3		OWC=4216				
6506/12-5		OWC=4011				
6506/3-3		Shows				
6507/7-2			OWC=2476-2482 GOC=2318			
6507/7-3			OWC=2491			
6507/7-4			OWC=2498			
6507/7-5			OWC≈2475			
6507/7-6			OWC=2440 GOC=2339			
6507/7-8			OWC=2495			
6507/8-1			OWC=2480 GOC=2312			
6507/11-1				GWC=2526		
6507/11-3				OWC=2526 GOC=2514		
6507/11-5 S				OWC=2527 GOC=2515		
6407/7-1 S					OWC=3016-3045	
6407/7-3					ODT 2867(Ile) ODT 3068(Åre)	
6407/7-6						3777
6407/7-7 S						ODT 3678 (Åre)

Contact variations within these structures could result from various circumstances. The Smørbukk structure contains several compartments on different stratigraphic levels, but only a few fluid contacts are encountered in the well data. As previously mentioned, mostly hydrocarbon-down-to contacts are encountered by the wells in these repetitive clastic lithologies. The shale-dominated lithologies like the Not and Ror formations separate the reservoir sands in the structure and could vertically seal off reservoir units from shallower or deeper units. Furthermore, faults intersecting the reservoir can seal off segments with progressive burial-induced quartz diagenesis of the fault zone (Karlsen et al., 2004).

Observations from the Smørbukk South structure show varying contact depths, indicating compartmentalization. As information from the well reports give a fluid contact coinciding with the mapped spill point in the uppermost Garn Formation, it is interpreted as filled to spill. It is, however, possible that deeper contacts appearing to be located far deeper than the spill point could be a result of oil accumulations in multiple separate reservoir levels (in the Garn, Ile and Tilje formations respectively). This would mean that each reservoir level has a spill point controlling the hydrocarbon column. Furthermore, if this is the case, it would demonstrate that the structure as a whole is not over-filled, but has multiple hydrocarbon accumulations in the anticline structure.

Of the studied structures, Heidrun contains the most information of fluid contact depths. These varying contacts indicate a highly compartmentalized structure. This could be the results of sealing faults; however, it could also result from the presence of local channels and lobes in the reservoirs. The interpretation and suggested compartments in this study indicates that faults are likely restricting lateral communication, and thus are causing the compartmentalization. This is evident from the common contact across the Ile and Tilje formations within one segment (from wells 6507/7-2 and 6507/7-8). It is possible, however, that local lobes are causing the contact variations in other segments, especially in the Garn Formation delta lobe deposits.

In this study the Midgard structure has been divided into two segments, based on the different fluid content. The southern segment contains oil and gas while the northern segment only contains gas. The two segments do, however, have a common contact across the saddle point as the oil-water contact in the southern segment coincides with the gas-water contact in the northern segment. Additionally, the Midgard structure is suggested to be in communication with the Yttergryta structure to the northeast, as this structure also shares a common gas-water contact depth with the northern segment in Midgard.

The Njord and Njord West Flank structure is also comprised of compartments with varying fluid contacts, as observed in several of the large oil and gas fields in Eastern Haltenbanken. In this study, only four wells have been made available from Njord. However, several additional wells are drilled in the structure with varying contact depths – further illustrating the complex hydrocarbon distribution and geology in the structure. RFT data from the available wells show that Njord consist of differentially pressured reservoir units; 70 bar above hydrostatic in the south-east to approximately 120 bar in the north-west. Previous work by Lilleng and Gundesø (1997) suggested four main hydraulic compartments. This is in accordance with the observations in this study, as the NE-SW trending faults observed intersecting the structure are suggested to seal off interpreted segments. These major sealing faults are likely causing the division of the hydraulic compartments in the structure, explaining the variation in contact depths.

6.6 Seismic characteristics

Seismic amplitude anomalies in the overburden can be related to hydrocarbon leakage (Ligtenberg et al., 2005; Arntsen et al., 2007; Løseth et al., 2009; Heggland et al., 2013). In this study, the overburden above the Jurassic reservoirs have been closely examined for amplitude anomalies such as bright spots and dim zones in order to search for indications of hydrocarbon leakage. Such brights/strong amplitudes and dim zones/weak amplitudes have been observed in the overburden above several of the investigated structures. This subchapter provides a summary of these observations and a discussion on interpretation and their possible connection to hydrocarbon leakage.

The most commonly observed anomaly in this study is brights spots in the overburden, observed in the Tang and Tare formations of the Rogaland Group (Paleocene) and Nise and Kvitnos formations of the Shetland Group (Late Cretaceous). Bright spots in the study area are often observed as stacked brights throughout the overburden above the reservoir. These could be caused by a decrease in acoustic impedance due to gas accumulations or an increase in acoustic impedance due to highly cemented zones. Nonetheless, hydrocarbon-related diagenetic zones (HRDZ) could form when hydrocarbons leak into the overburden rocks, and produce localized intense carbonate cementation giving areas of localized high amplitudes (Ligtenberg, 2005).

Despite the fact that amplitude anomalies are observed above many of the structures in the study area, most of the structures appear to be filled - and are thus not expected to leak. Much of the observed brights in the area could therefore be a result of other processes, and are not automatically related to vertical leakage from the reservoirs. Amplitude anomalies due to the presence of hydrocarbons in the overburden could be a result of lateral migration derived from other sources. Leakage from nearby structures could also cause hydrocarbons to migrate laterally and can appear as dim zones above a close by structure. This could be the case in the Smørbukk structure. Wells 6506/11-1 immediately west of Smørbukk and 6506/12-4 to the north both proved dry structures, where fatal leakage possibly emptied the reservoirs. This could be the reason for the concentrated dim zone above the fault intersection in the western boundary of the structure.

The Tang and Tare formations of the Rogaland Group both consist primarily of claystones with minor sandstone and limestone stringers. The Nise and Kvitnos formations of the Shetland Group are also dominated by claystones with interbedded carbonate and sandstone stringers (Dalland et al., 1988). The high content of clay in these formations makes them unfit for preserving large hydrocarbon volumes. It is also important to note that due to the large lithological variations within the above mentioned groups, it is especially challenging to distinguish between changes in lithology and definite leakage within the successions. This is evident from amplitude maps from structures such as Smørbukk South and Nona, where there is no apparent localization of amplitude anomalies.

In general, amplitude anomalies observed sporadically within the Rogaland and Shetland groups appear to lack consistency, as they are observed above several filled structures, and are not necessarily directly related to leakage. Figure 6.7 shows examples of observed amplitude anomalies above various structures in the study area.

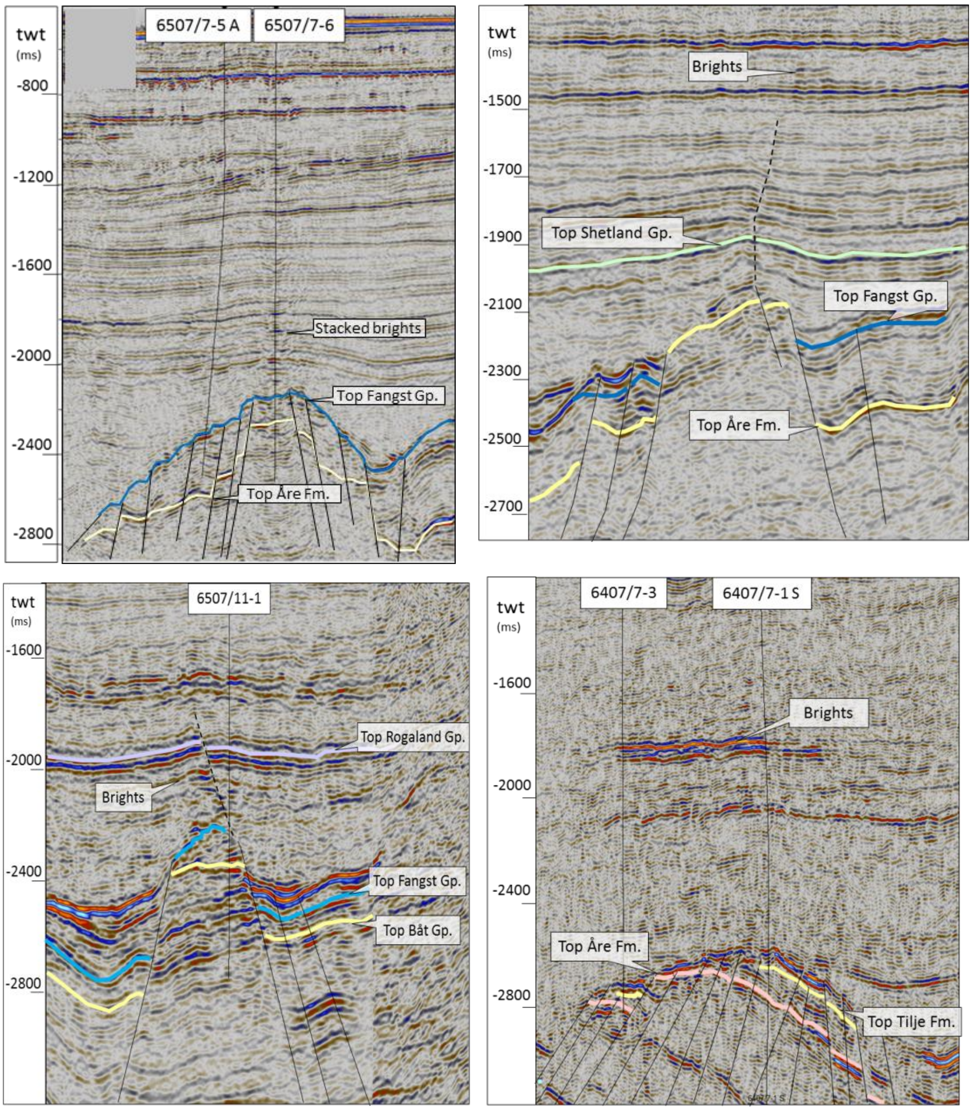


Figure 6.7: Seismic amplitude anomalies in the overburden, as observed in the Heidrun, Heidrun North, Midgard and Njord structures respectively.

7 Conclusion

The main focus of this study was to investigate the controls on hydrocarbon column-heights in the eastern province of Haltenbanken. Analysis of the 3-D seismic data and exploration well data has revealed that the position of the structural spill points is likely the main controlling factor on the hydrocarbon column-heights in majority of the investigated structures. Vertical leakage is also suggested to be the controlling factor on the hydrocarbon column-height in some structures. The main conclusions in this study are as follows:

- Among the 15 investigated structures in the study area, nine were suggested to be filled to their structural capacities. One of the structures was suggested to be filled in the deeper reservoir levels while the uppermost reservoir level is suggested to be underfilled. One of the structures is suggested to be underfilled. Four of the structures remain inconclusive, due to lack of information on fluid contacts or spill point position.
- Three main migration routes have been suggested in the study area, in order to better understand and explain the location of the present day fluid contacts. These routes were suggested based on the regional surface maps of top reservoirs combined with fluid contact information in the various structures.
- Observations from the analysis in this study can give the following categorization: fluid contacts coinciding with spill point, fluid contacts that do not coincide with spill point and columns where it is not possible to determine the controlling factors. Among the structures where fluid contact does not coincide with spill point fault seal and/or leakage was suggested to control the hydrocarbon column-height.
- Majority of the large oil accumulations in the area are located along a SSW-NNE trend, while most of the purely gas filled structures are located in the western part of Haltenbanken. An unusually large oil column in the northernmost Heidrun area is suggested to be present due to vertical leakage through the seal while the structure receives a continuous supply of hydrocarbons from the Smørbukk area, or due to partly sealing faults spilling the gas towards Heidrun North.

- Analysis of the hydrocarbon distribution and fluid contact depths has shown that several of the investigated structures have contact variations within the reservoirs. This is suggested to be caused mainly by compartmentalization within the structures, due to lateral fault sealing.
- Brights are observed in the Shetland and Rogaland groups above several of the structures; however these lack consistency and are not necessarily good indicators of leakage, as they appear above several filled structures.

Investigation of the migration routes and hydrocarbon distribution in the study area shows that all three major fill-spill routes are directed towards the north. The Grinda Graben in the central part of Haltenbanken appears to separate migration route A from migration routes B and C. Similarities in hydrocarbon content and source are observed throughout all fill-spill routes, however, the structures to the west of the graben contain far more oil than in the east. Furthermore, the migration routes to the east of the graben are more faulted and complex than in the west, where migration appears to be less restricted.

8 Proposal for further work

There are several uncertainties associated with interpretations and analysis of the column-heights and migration routes in this study. Regional interpretation of seismic data across a wide-spread area should not be expected to result in a complete understanding of the complex geology in the investigated areas. Some proposals for future work are suggested:

- Application of 3-D seismic data with improved quality would make seismic interpretation in the study area more accurate and would allow for more detailed interpretation of the structures. Merged datasets also contain seismic data of varying quality. Utilization of datasets covering more of the northern and eastern margins of Haltenbanken would further allow for mapping of spill points in structures such as Yttergryta and Heidrun North.
- Fault orientations, intersections and dip angles should be studied in detail in order to identify faults that are likely to re-activate or slip under the various stress conditions throughout the geological history, and thus their role in potential hydrocarbon leakage.
- Further investigation of how sealing properties of faults change through time.
- More detailed fault mapping beyond the current data resolution combined with Petrel tools is necessary for a more realistic image of the fault zone. The software Petrel only allows for a simplistic image of the fault plane in 3-D subsurface modelling.
- Additional geochemical investigations should be conducted for further understanding of the oil and gas migration and fill-spill routes in the study area, especially with regard to the latest discoveries made in recent years.
- In depth analysis of the oil/gas distribution should be carried out in the highly compartmentalized structures such as Heidrun, Smørbukk and Njord. A complete overview of all fluid contacts in different compartments and levels should be studied in greater detail.
- Investigation of controls on hydrocarbon column-heights could be conducted in structures where data are not yet released, such as the Pil and Bue and Boomerang structures in the southern part of Haltenbanken – allowing for improved knowledge of column restriction in Haltenbanken.

- Investigation of the significance of the observed fractured overburden above reservoirs in the study area.
- Further investigations of the true pressure distribution in the study area should be done in order to get a complete image of the different pressure regimes in the whole of Haltenbanken.

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