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Petroleum System Analysis of the Chalk Fields in the Danish and Dutch Sector of the Central Graben, North Sea

Niels Geert de Vries

Petroleum Geoscience and Engineering
Submission date: June 2014
Supervisor: Egil Tjåland, IPT
Co-supervisor: Dominique Roy, TOTAL E&P Norge AS

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Preface

This MSc thesis is written by Niels Geert de Vries during the spring of 2014, as part of the fulfilment for my Master´s degree in Petroleum Geophysics, TPG4930. It was written for the Department of Petroleum Engineering and Applied Geophysics, at the Norwegian University of Science and Technology, in cooperation with TOTAL E&P Norway AS.

Acknowledgements

First, I would like to thank my supervisor at the Norwegian University of Science and Technology, Professor Egil Tjåland, for constructive feedback and comments to the thesis.

I would also like to thank my co-supervisor at TOTAL E&P Norway AS, Dominique Roy, for suggesting the research topic and helping me during this thesis. I give my sincere gratitude to senior geophysicists, Philip Straw and Cécile Damstra and geologist, Tamsin Brown at TOTAL E&P Norway AS for teaching me the software and contributing with their experiences. Heartfelt thanks to all the people at TOTAL E&P Norway AS, who have always been patient with my every request and ready to offer help.

Cédric Depienne, thank you for the encouragement during this thesis and the many interesting discussions we´ve had during lunchtime, throughout my time at TOTAL E&P Norway AS.

Thank you!

Trondheim, 10th of June 2014

Niels Geert de Vries

Abstract

The purpose of this MSc thesis is to use seismic and well data to investigate and understand the petroleum system of the many hydrocarbon discoveries found within the chalk layers of the Danish and Dutch Central Graben. The conclusions from this petroleum system analysis are then used as a recipe to look for the remaining prospectivity within the area.

Seismic interpretation together with seismic to well correlation and well calibration has been performed in order to create different kinds of maps before conducting a petroleum system analysis on the Cretaceous chalk play of the Danish and Dutch Central Graben. Key aspects of the remaining chalk prospectivity in these areas are then brought into consideration as a result of the things learned from the previous petroleum system analysis.

Results showed that the discovered chalk fields in the Danish and Dutch Central Graben can be divided into five categories, based on their structural trapping characterization. The first three categories are found on top of salt structures in anticlinal four-way dip closures that are a result of halokinesis. The difference between them is based on how much the salt structure has pierced through the overlaying layers, ranging them as traps over salt domes with some degree of inversion overprint in category 1 to traps formed over heavily pierced salt diapirs in category 3. The category 2 is included in this selection based on the addition of a major fault that cuts the field in two. The fourth and fifth categories define fields that are either found within a structural closure created by an inversion-generated anticline or within a non-structural stratigraphic trap as a result of late structural tilting.

The source rock for all these fields is identified as being the Upper Jurassic Bo Member that belongs to the Farsund Formation in the Danish Central Graben and as the Lower Jurassic Posidonia Shale Formation in the Dutch Central Graben. Hydrocarbon migrations from these rocks have occurred mostly vertical, by using the major faults and fractures that are created as a result of the syn- and post chalk structural events. Cases of lateral migration have also occurred through the low permeability nature of chalk, especially in the case of the stratigraphic trap.

The four-way dip closures in category 1 to 4 act as one part of the trapping mechanism that controls the capture of the migrated hydrocarbons. A pinch out of the chalk layer against a ridge does this for the fifth category. The other part of the trap is constituted by the overlaying seal, which is represented by the Palaeocene Shale Formation. These shales have caused the chalk to become over-pressured, due to effectively closing off the Chalk Group hydrodynamically when rapid post-chalk deposition of the overburden rocks occurred. This has led to the maintaining of high porosities in the chalk and is one of the major effects of the success of the chalk play.

Throughout the work, an increasing understanding of how important the syn- and post chalk depositional structural events are for the success of the chalk play has been obtained. By knowing when and in what kind of scale these events have occurred, are crucial in order to better determine if the essential elements and processes of the petroleum system are placed correctly in time and space for a prospect to be of economical value or not.

Sammendrag

Hensikten med denne Master oppgaven er å bruke seismikk og brønndata til å undersøke og forstå petroleumssystemet til de mange hydrokarbon funnene i kalk-lagene i den danske og nederlandske sentrale graben. Konklusjonene fra denne petroleumssystem analysen er så brukt som en oppskrift til å lete etter den gjenværende prospektiviteten i området.

Seismisk tolkning sammen med brønnkollerasjonen og brønnkalibreringen av seismikken har blitt utført for å skape forskjellige typer av kart, før en petroleumssystem analyse har blitt gjennomført på kalk prospektiviteten i Kritt i den danske og nederlandske sentrale graben. Sentrale aspekter av den gjenværende prospektiviteten i disse områder er så tatt i betraktning som et resultat av de tingene man har lært fra den tidligere petroleumssystem analysen.

Resultatene viser at de oppdagede kalk feltene i den danske og nederlandske sentrale graben kan bli delt opp i fem kategorier, basert på deres strukturelle felle-karakteristikk. De første tre kategorier er funnet på toppen av salt strukturer i antiklinale fire-veis lukkelser som er et resultat av halokinesis. Forskjellen mellom dem er basert på hvor mye salt-strukturen har trenget seg gjennom de overliggende lagene, noe som rangerer dem fra å være feller over salt domer met et hint av tektonisk oppløfting i kategori 1 til sterkt gjennomtrengende salt diapirer i kategori 3. Kategori 2 er inkludert i dette utvalget basert på tilsetning av en stor forkastning som kutter feltet i to. Den fjerde og femte kategorien definerer felt som enten er funnet i strukturelle lukkelser skapt ved tektonisk oppløftete antiklinaler eller i ikke-strukturelle stratigrafiske feller som er formet som et resultat av sen strukturell tilting.

Kildebergarten for alle disse felt er identifisert som den Øvre Jurassiske Bo Member som tilhører Farsund formasjonen i den danske sentral graben og som den Nedre Jurassiske Posidonia Shale formasjonen i den nederlandske sentrale graben. Hydrokarbon migrasjonen fra disse bergarter har stort sett skjedd vertikalt, gjennom traséer laget av forkastninger og sprekker som er skapt som følge av strukturelle hendelser som har skjedd imens og i etterkant av kalk-lag avsetningene. Perioder av lateral migrasjon har også skjedd gjennom den lave permeabilitets-egenskapen av kalk, spesielt i tilfelle av den stratigrafiske fellen.

Fireveis lukkelsene i kategori 1 til 4 oppfører seg som en del av felle-mekanismen som kontrollerer fangsten av de migrerte hydrokarboner. Fortynnelsen av kalk-laget mot en forhøyning gjør dette for den femte kategorien. Den andre delen av fellen er konstituert av den overliggende seglen, som er representert av Paleocene Shale formasjonen. Denne skifer

formasjonen har skapt et overtrykk i kalklaget, gjennom å effektivt forsegle kalk gruppen hydrodynamisk når raskt avsetning av de overliggende lagene fant sted. Dette har ført til at høye porositeter i kalken har blitt opprettholdt, noe som symboliserer en av de store suksess faktorer i kalk petroleumssystemet.

En økende forståelse av hvor viktig sammenhengen mellom de strukturelle avsetnings-hendelser som har funnet sted imens og i etterkant av kalk-lags avsetningene og det å oppnå suksess i petroleumssystemet for kalk, har blitt oppnådd gjennom dette arbeidet. Gjennom å vite når og i hva slags skala disse hendelser har skjedd, er avgjørende for å kunne bedre bestemme om de essentielle elementer og prosesser av petroleumssystemet er plassert riktig i tid og rom for at prospektet er av økonomisk verdi eller ikke.

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1. Introduction

1.1 Problem description

The exploration of hydrocarbons (HCs) in chalk in the North Sea sector of Denmark and the Netherlands has been going on as long as the exploration history of the North Sea. The North Sea Chalk Group has hereby long been the subject for research, where main themes like stratigraphy, palaeontology and geochemistry are well covered (Anderskouv & Surlyk, 2011). However, even though the chalk reservoirs have been part of the exploration history's first days, it is a paradox to say that these reservoirs are well understood[1]. Important aspects of this Cretaceous prospectivity still need to be developed due to the stratigraphic and structural complexity of the Cretaceous sedimentary system. This involves complexities created by sources, such as intra-chalk plays, Lower Cretaceous chalks, migration traps, re-deposited chalk reservoirs and silisiclastic plays. A consistent regional framework with the integration of seismic stratigraphic and petrophysical data are therefore not yet present (ens.dk (1)). In addition, the knowledge we have today of the potential stratigraphic traps, regional seals and migration paths in the Chalk Group is also scant (Ten Veen, 2012). Without a better understanding of this, it is difficult to reconstruct the older and deeper structural configuration of the Central Graben in order to improve our knowledge of non-structural chalk traps (ens.dk(1)).

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[1] Discussions with my supervisor at TOTAL E&P Norway AS, Dominique Roy.

1.2 What´s known about the problem?

Most chalk fields produce from the uppermost part of the chalk, within the Maastrichtian Tor Formation and Danian Ekofisk Formation in the Central North Sea. These formations are generally characterized by high porosity and low permeability, where the reservoirs within the Ekofisk Formation usually have a larger permeability and porosity then the reservoirs in the Tor Formation (Ten Veen, 2012; Lindgreen et al, 2012).

The main factors controlling the success of the Chalk Group as a HC reservoir are the presence of an underlying mature source rock, the preservation and further development of favourable reservoir properties, and the existence of an effective top seal. Other important factors are overpressure, early entrapment of HCs and a suitable structure (Surlyk et al, 2003).

The Lower Cretaceous chalks and shales are considered to act as a regional seal restricting the flow of fluid and gas and thus maintaining high overpressures in the underlying units (Ten Veen, 2012). Results from a study on evaluating the porosity and permeability characteristic of this non-reservoir part of the chalk, reveals that faulting and fracturing near salt structures may locally influence the pressure and the fluid migration conditions, possibly providing vertical pathways for oil and gas to enter and move through the chalk (Ten Veen, 2012). In cases where Palaeocene sands are present above the chalk reservoir, no HC saturation can be present, since there will not be a closed pressure system (Hardman, 1982).

According to Hardman (1982), salt induced structural growth caused fractures that allowed the HCs to migrate upwards and build up in fracture systems within structural closures in the chalk (Hardman, 1982). The presence of these natural fractures ensured higher recoveries than predicted, and the use of specific technologies such as horizontal drilling, well stimulation, and water or gas injection has further enhanced recovery factors (Surlyk et al, 2003). Hardman also concluded that there were four dominating factors controlling the reservoir quality of the chalk reservoir. The purity in terms of calcium carbonate of the sediment; the deposition rate of the chalk; the tectonic setting of the field area during deposition; and the size distribution of the coccoliths being deposited (Hardman, 1982).

As of today, almost all of the HC production in Denmark is from the Upper Cretaceous and Danian chalk fields in the Central Graben. The fields consist of a variety in structural styles, chalk sedimentology and varying times of HC migration into the structures (Megson, 1992). Since 1990 the chalk exploration has entered into a new phase, which shows evidence of non-structural trapping mechanisms for the HCs within existing chalk fields and discoveries. These diagenetic trapping mechanisms can be divided into oil trapped within chalk by an intra-chalk top-seal and hydrodynamic trapping of oil (Megson, 1992). In addition, if there are indications of gas at the top chalk level on high-resolution seismic data, it can be used as a direct hydrocarbon indicator (DHI) for finding and developing new plays and prospects (Megson, 1992).

The Dutch chalk prospectivity is on the other hand poor, with one producing oil field, the Hanze field, and one producing gas field, the Harlingen field (tno.nl). As a characterization scheme, The Netherlands Organization for Applied Scientific Research (TNO) conducted a study based on the sedimentary development, the seismic stratigraphy and the burial compaction of the Chalk Group in the Dutch North Sea (tno.nl). Preliminary results of this study indicated that the under-compacted chalk of reduced thickness (0-300 m) in the inverted Central Graben behaves as an aquifer, while the normal thicker chalk (600-1200 m) on the adjacent Schill Grund High acts as an aquitard with permeability's comparable to those of shales (tno.nl).

The Hanze field study from TNO revealed three conditions that seem to be crucial for a successful chalk play next to the traditional play and reservoir conditions:

- Late Tertiary to Quaternary HC generation from the Lower Jurassic Posidonia source rocks.
- Paleoenvironmental, i.e. shallow paleowaterdepth conditions during deposition of chalk.
- Absence of the lower chalks and Lower Cretaceous Shales as seal, thus favouring the migration of the oil in the reservoir.

(Guasti et al, 2010).

1.3 Objectives of the study

The objectives of this MSc thesis are to perform a petroleum system analysis on the chalk reservoirs in the Central Graben of the Danish and Dutch North Sea area. This consists of establishing a consistent seismic-stratigraphic framework for the Cretaceous and Danian ages, which will give us a better understanding of all the geological components and processes necessary to generate and store the HCs. This includes the definition of chalk as a reservoir rock with its seal and trap and analysing how the HCs have migrated from the Jurassic source rocks into the Cretaceous formations. A better understanding of the basin evolution within the Danish and Dutch Central Graben could hereby be provided and a synthesis of the Cretaceous prospectivity and HC plays can be presented.

1.4 Impact of the study

With the results of this MSc thesis, it could be possible to understand the cause of the previous successes and failures within the exploration of Danish and Dutch North Sea chalk reservoirs. In addition a re-assessment of the exploration potential of these petroleum plays can be given and a new evaluation of the associated risk of drilling other potential chalk reservoirs can be presented. The results of my MSc thesis can in this way aid to future reservoir exploration and production.

2. Geological background

2.1 Area of study

The study area of this MSc thesis is located within the Danish and Dutch sector of the Central Graben, which is an intracratonic rift basin that represents the southern branch of the North Sea triple rift system. The Central Graben is found over a large area in the North Sea where it reaches into the Dutch, German, Danish, British (UK) and Norwegian waters (Gautier, 2005).

In the Dutch sector it is known as the Dutch Central Graben, which is flanked by the shallower Step Graben and Terschelling and Vlieland basins (De Jager, 2007). In the north the Central Graben extends from the northern termination of the Dutch Central Graben to the western end of the Ringkøbing-Fyn High in the Danish sector of the North Sea. From here it continues in a NW direction into the UK sector of the North Sea where it intersects with the southern part of the Viking Graben (Gennaro, 2011). The Central Graben itself is characterized by Late Jurassic complexes of grabens, with extensional tectonics and failed rifting, where complex sedimentary sequences have been deposited (Feazel et al, 1990).

The main focus in this area has been on the following blocks (See Figure 2.1.1):

- Blocks 5603, 5604, 5503, 5504 and 5505 in Denmark
- Blocks F and B in the Netherlands.

Information has been gathered from the following chalk fields:

- Harald East, Gorm, Regnar, Roar and Halfdan in Denmark
- Hanze in the Netherlands

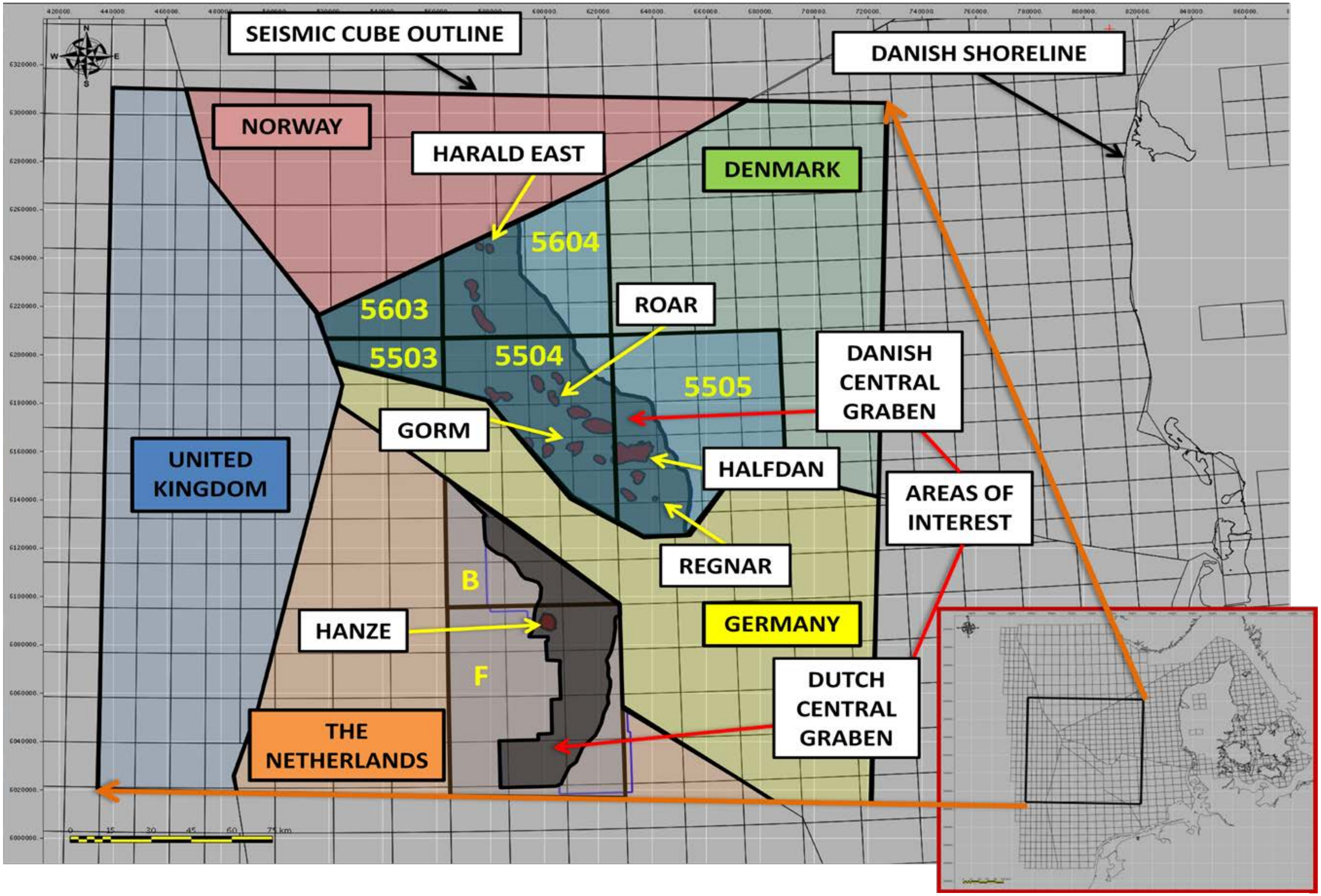


Figure 2.1.1: Shows an overview of the blocks and chalk fields on the Danish and Dutch North Sea sector, on which the main focus has been based on during this thesis (Map created from (SISMAGE).

2.2 Tectonic evolution

The following sub-chapter gives an overview of the tectonic evolution of the Central Graben from the first related event of its formation until the present day (See Figure 2.2.1).

2.2.1 From Carboniferous to Permian to Triassic

The first tectonic evolution phases of the Central Graben can be dated back to Late Carboniferous, when the Arctic-North Atlantic rift system was initiated between Greenland and Scandinavia. The rift system symbolizes the breakup of the supercontinent Pangaea and was a time of intense volcanic and intrusive activity. Evidence of this is found within boreholes in the Central Graben showing cores of alkaline lavas (Pharaoh et al, 2010). During the Permian the rift system propagated southwards, resulting in a northerly trending chain of Permian basins. Thermal subsidence and the gradual incorporation into the westward-expanding Rotliegend Basin dominated this age, where thick successions of halites filled the basinal areas during sea-level low-stands (Pharaoh et al, 2010).

Later on during the Early Triassic, the rifting between Greenland and Scandinavia intensified, resulting in the development of the Viking and Central grabens that transacted the Northern and Southern Permian basins (Pharaoh et al, 2010). During the rifting, continues thermal subsidence and deposition of thick successions of salt and continental clastic sediments continued to occur. The deposits were particularly thick in the Northern and Southern Salt Dome provinces (Jorgensen, 1992) (See Figure 2.2.2). Faults originated from the Triassic within the northern Dutch offshore area show that they are decoupled from those below the thick salt layers. This indicates that the down faulting and the formation of salt swells in the Central Graben were well underway by Mid-Triassic times (Pharaoh et al, 2010). At the end of the Triassic the piercing of salt diapirs began to break out of the earlier salt swells to initiate the development of spectacular rim-synclines (Pharaoh et al, 2010). These structures have become important HC plays in the Central Graben; especially on the Danish North Sea area (See sub-chapters 2.3 and 2.5; and chapters 4, 5 and 6).

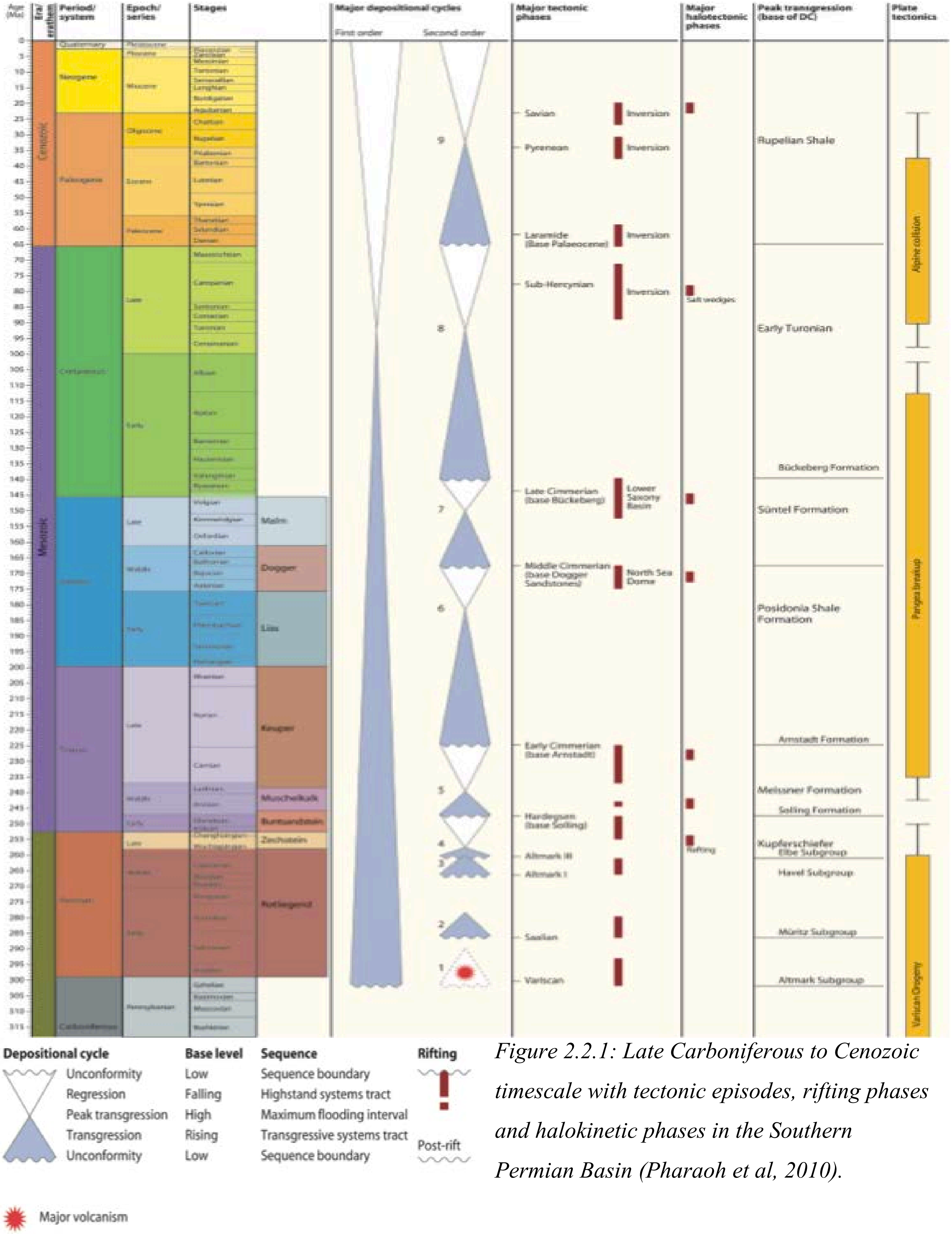


Figure 2.2.1: Late Carboniferous to Cenozoic timescale with tectonic episodes, rifting phases and halokinetic phases in the Southern Permian Basin (Pharaoh et al, 2010).

2.2.2 From Jurassic to Cretaceous

During the Late Triassic and Early Jurassic the Central Graben started to deepen, as a result of the early Cimmerian tectonic pulse. This pulse made the depositional regime change from being continental to being predominantly marine, which led to the deposition of thick sequences of shale (Jorgensen, 1992). Later on, during the Middle Jurassic, an uplift of the central North Sea area occurred, presumably in response to the impingement of a transient plume on the lithosphere (Pharaoh et al, 2010). The development of this thermal dome caused deep truncation of the Lower Jurassic and Triassic sediments and the development of the Mid-Cimmerian Unconformity (Pharaoh et al, 2010; Gennaro, 2011). Major volcanic activity accompanied this event, causing deltaic complexes to prograde into the Central Graben (Pharaoh et al, 2010). By the end of the Mid-Jurassic times, the Central North Sea Dome had subsided sufficiently enough as a result of the continuous extension, for open-marine conditions to be restored in the North Sea (Pharaoh et al, 2010).

During the Late Jurassic and Early Cretaceous, the Cimmerian rift pulses occurred. These pulses caused differential movement, uplift and tilting of fault blocks and made Permian salt, which had already been actively moving during the Triassic, to remobilize and form a number of salt pillows and salt diapirs in the Northern and Southern Salt Dome provinces of the Central Graben (Jorgensen, 1992). This led to a variable subsidence across the Central Graben and gave rise to great differences in the thickness of the Jurassic sequences (Jorgensen, 1992) (See Figure 2.2.3 and 2.2.5).

The crustal extension across the North Sea Graben system gradually decreased during the Early Cretaceous and erosion of the structural heights caused the regional Base Cretaceous Unconformity to be formed over the entire area of the Central Graben (Gowers et al, 1993). This age also marked the opening of the Atlantic Ocean, which changed the regional stress regime drastically, making the horizontal stress more compressive with an E-W direction. This resulted in a stop of the rifting and the local shortening and inversion of the Triassic-Jurassic faults, with transpressive movements along the NNW-SSE oriented faults (Gennaro, 2011). The landscape became more transgressive during this age, a pattern that became much more significant during the Late Cretaceous. This was characterized by a reduced influx of clastic material and an overall deposition of chalk in the entire North Sea area (Jorgensen, 1992). The chalk continued its deposition from Late Cretaceous to Tertiary and it ranges in variable thicknesses across the Salt Dome provinces. This variability is mainly a result of the then existing fault blocks and Salt Dome topography (Jorgensen, 1992).

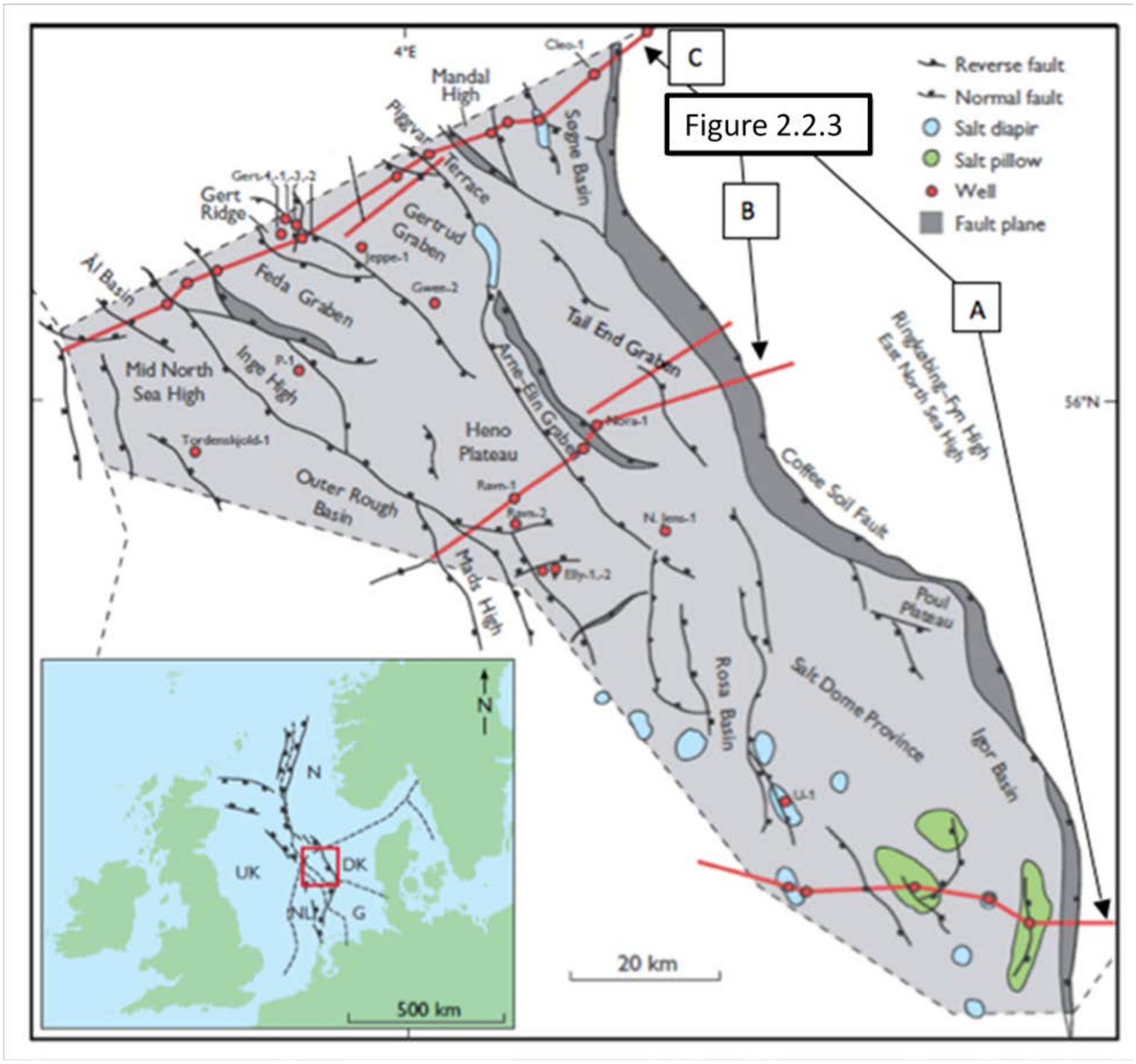


Figure 2.2.2: Structural elements map of the Danish Central Graben showing basins, highs and platforms (Møller & Rasmussen, 2003). The lines A, B and C in the figure correspond to the geological cross-sections in Figure 2.2.3.

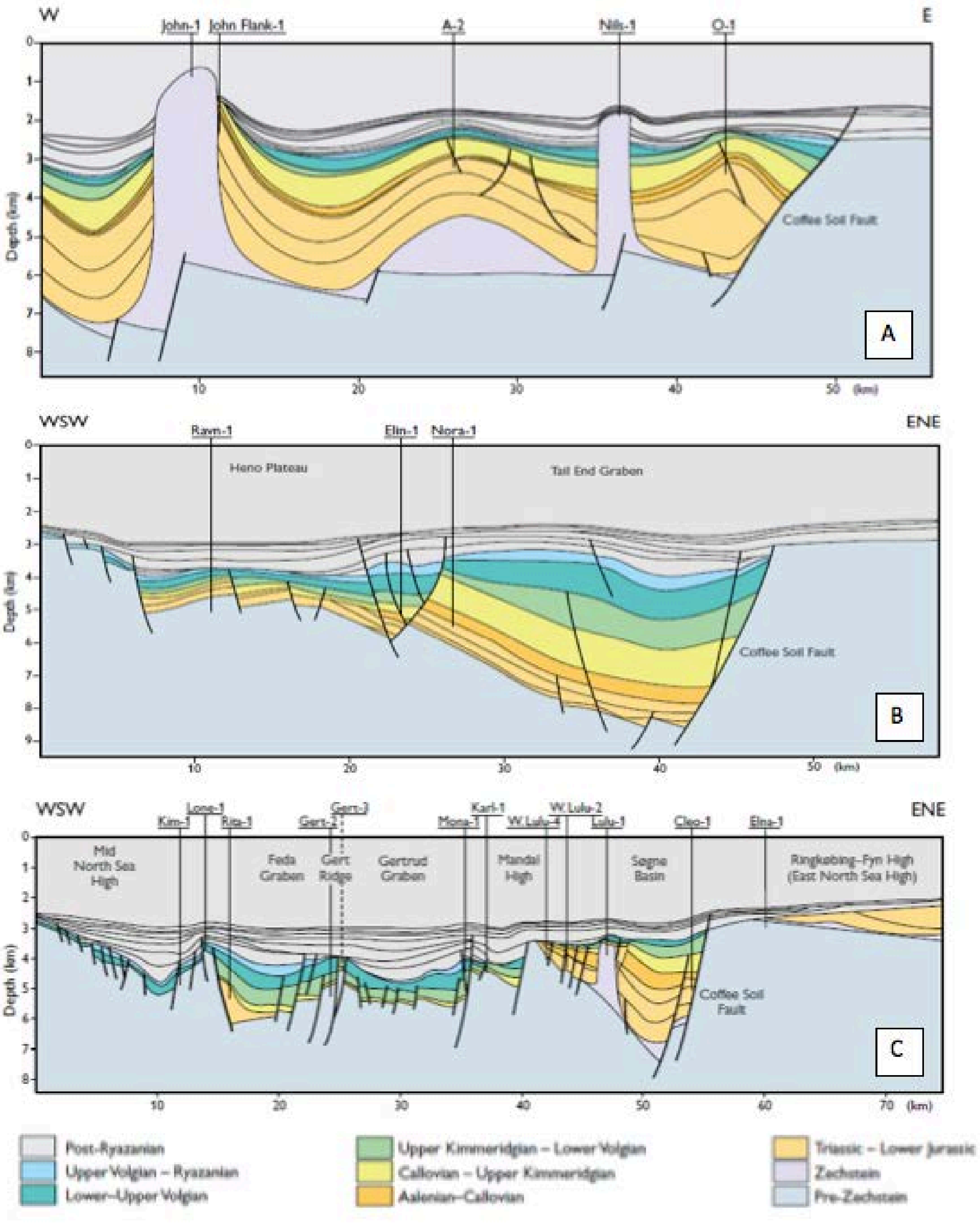


Figure 2.2.3: Three cross-sections across the northern, mid and southern part of the Danish Central Graben from a SW to NE direction in B and C and a NW to SE direction in A (Møller & Rasmussen, 2003). See Figure 2.2.2 for location of the cross-sections.

2.2.3 From Tertiary to Quaternary

At the end of the Late Cretaceous and throughout the Palaeogene, periods of NNE-SSW compressional tectonic pulses happened frequently in the Central Graben area. These pulses are known as the Sub-Hercynian and Laramide phases of intraplate compression and basin inversion (Pharaoh et al, 2010; Gennaro, 2011). The Sub-Hercynian Phase was the first pulse and was apparently not as intense as the Laramide Phase. This can be seen in the change of depositional regime, which changed from being carbonate-dominated to clastic-dominated during the Laramide pulse, while no change in depositional regime occurred during the Sub-Hercynian pulse (Pharaoh et al, 2010). The Laramide phase marks in other words the end of the Chalk Group deposition and the start of the silisiclastic North Sea Group deposition (De Jager, 2007). Both phases happened during gradual subsidence as part of the North Sea thermal sag basin and are the cause of reverse reactivation of pre-existing faults (Pharaoh et al, 2010; Jorgensen, 1992). Widespread diapirsm of Zechstein salts was triggered by this reactivation, which caused renewed halokinetic activity in the Southern Salt Dome Province (Gennaro, 2011; Jorgensen, 1992).

After the Laramide tectonic pulse, regional post-rift thermal subsidence and sedimentation continued throughout the Tertiary and Quaternary. During this time, increased fine-grained clastic influx was deposited through major delta systems, that prograded westwards into the deeper-water North Sea Basin (Pharaoh et al, 2010). These clastics became the predominant depositions throughout the North Sea Basin during the Tertiary (Jorgensen, 1992). Erosion of uplifted blocks and accompanying rapid sedimentation in the sub-basins and half-grabens are the cause of the variable thicknesses (Gautier, 2005). It is also believed that these processes are the cause of initiating salt tectonics in the Central Graben, which has continued into the Holocene (Gautier, 2005).

Figures 2.2.2 through 2.2.5 give an overview over the various highs and grabens on the Danish and Dutch North Sea area, and show examples of cross-sections through the Danish and Dutch Central Graben.

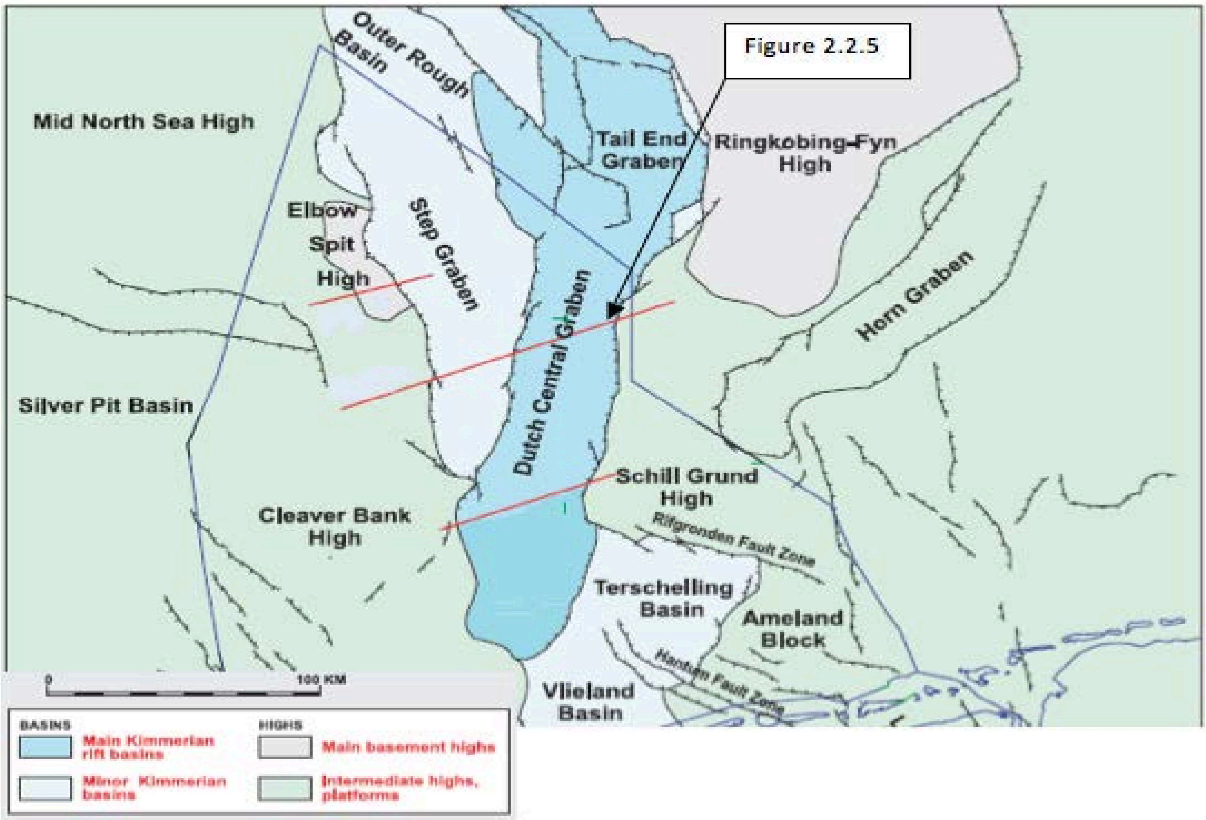


Figure 2.2.4: Structural elements map of the northern Dutch offshore area showing Jurassic and Early Cretaceous basins, highs and platforms (De Jager, 2007). The red line in the middle is shown as a cross-section of the area in Figure 2.2.5.

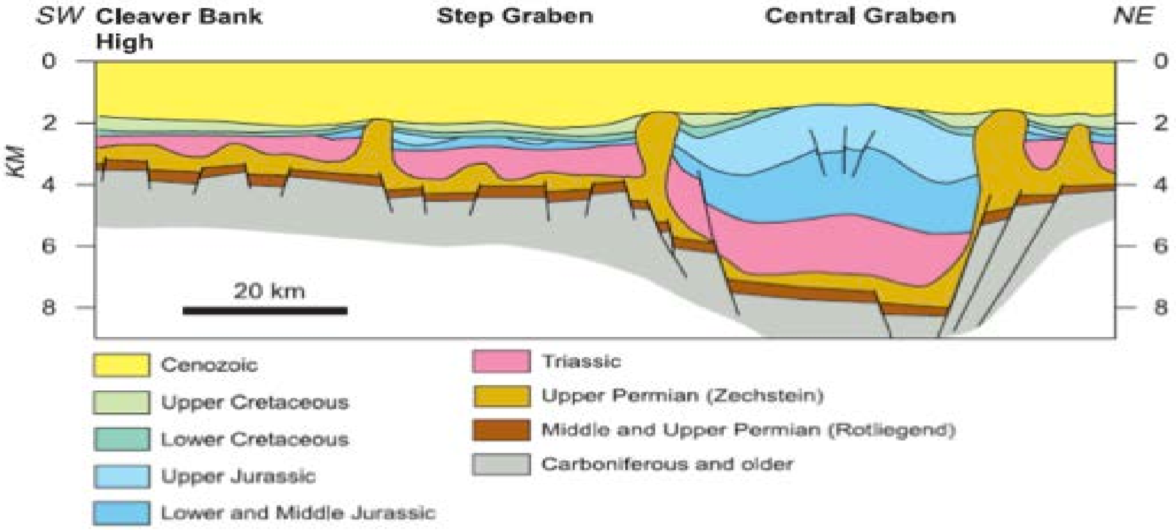


Figure 2.2.5: Cross-section across the Dutch Central Graben from a SW-NE direction (De Jager, 2007). See Figure 2.2.4 for location of the section.

2.3 Salt movements

The movements of the Zechstein salt have greatly influenced the post-Permian structuration of the Danish and Dutch North Sea area. Because of its great thickness, its low density and visco-plastic behaviour during deformation, it has led to the formation of a large number of halokinetic structures (See Figure 2.3.1). Structures, which have provided anticlinal structures within the chalk, that act as traps for the HCs. Something that is shown through the many chalk discoveries within the Central Graben (Goldsmith et al, 2003; Geluk$_{\text{(Permian)}}$, 2007).

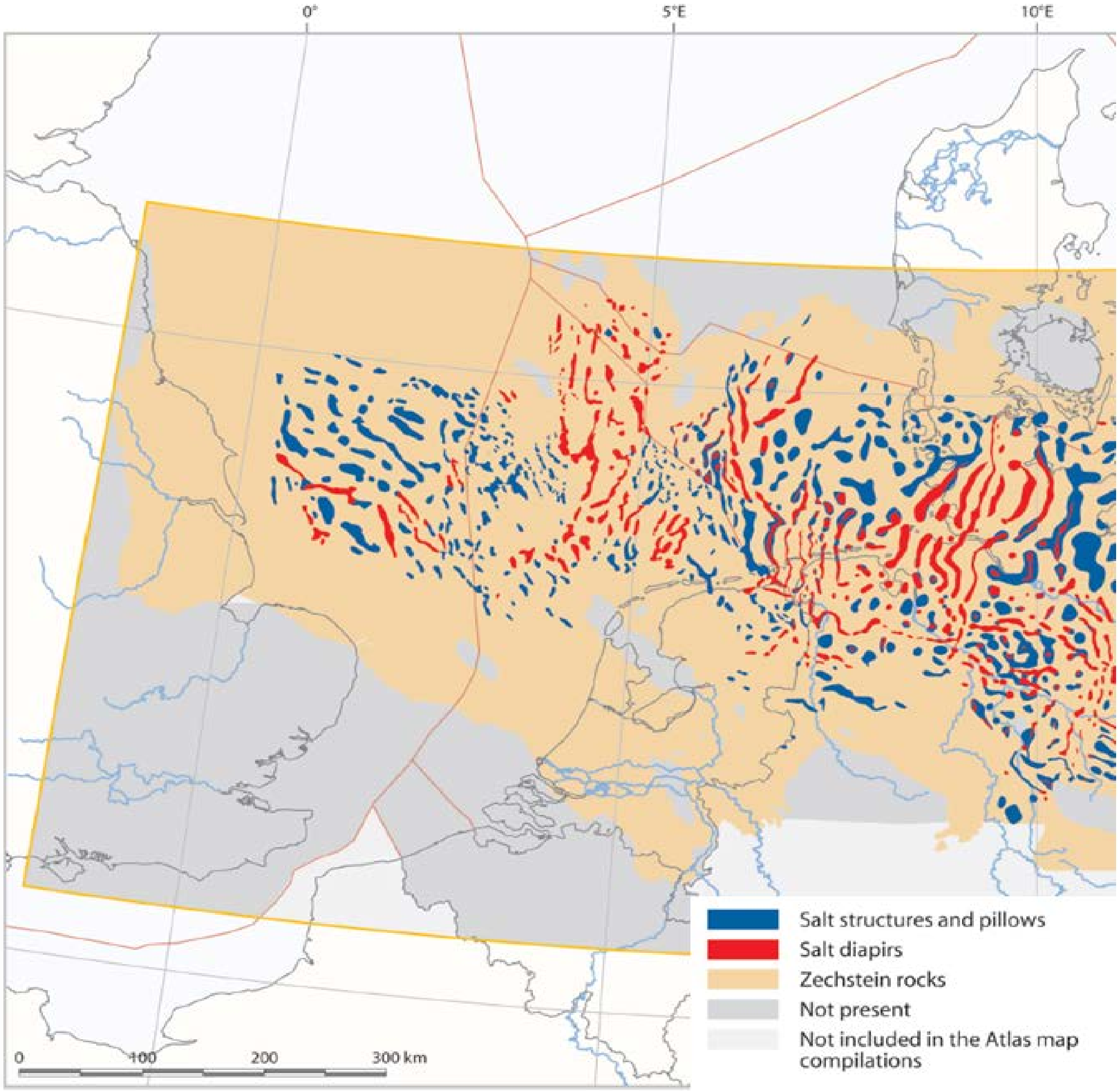


Figure 2.3.1: Map of the distribution of salt tectonics in the Dutch and part of the Danish Central Graben (Pharaoh et al 2010).

There are several periods of structuration during which halokinesis have been triggered, such as a long period of extension from the Mid Triassic to the Early Cretaceous, and a phase of compression during the Late Cretaceous to Early Tertiary (Geluk et al, 2007). The general salt movement started on a small scale during the Early Triassic and culminated during the Jurassic in response to extensional tectonics (Geluk$_{\text{(Permian)}}$, 2007). During this tectonics, the halokinetic movement has strongly influenced the Triassic sedimentation by creating basins in which thick successions of Triassic sediments have accumulated (Goldsmith et al, 2003). Later on, many of the salt structures were laterally squeezed and strongly deformed as a result of the rapid subsidence and compressive movements originated from the Cimmerian tectonic pulses during the Late Jurassic to Early Cretaceous. This made it complicated to understand what kind of affect the first halokinetic structures had on the Triassic sedimentation (Geluk$_{\text{(Permian)}}$, 2007; Goldsmith et al, 2003). Distinct pulses of renewed salt movements are also seen in the Tertiary, which are likely to have been triggered by the Sub-Hercynian and Laramide tectonic phases and their Late Cretaceous and Palaeogene inversion (Pharaoh et al, 2010).

Salt itself is recognized as having a buoyancy effect, which is observed through the upward moving of salt during extensional tectonics. This is because there are fewer forces available to mobilize the salt, when extension occurs. It can therefore be said, that tectonic stresses in general result in an increase of the rate of salt movement (Geluk$_{\text{(Permian)}}$, 2007). Moving salt acts as major detachment zone, separating the sub-salt fault system from the faults in the overburden (Geluk$_{\text{(Permian)}}$, 2007). Many of the Zechstein salt structures are therefore controlled by large faults in the elongated salt walls or they are found as isolated, circular domes developed over intersecting faults (Geluk et al, 2007)(See Figure 2.3.2). The total volume of sediments these structures have replaced within the Triassic domain has reached a total of 30% (Goldsmith et al, 2003).

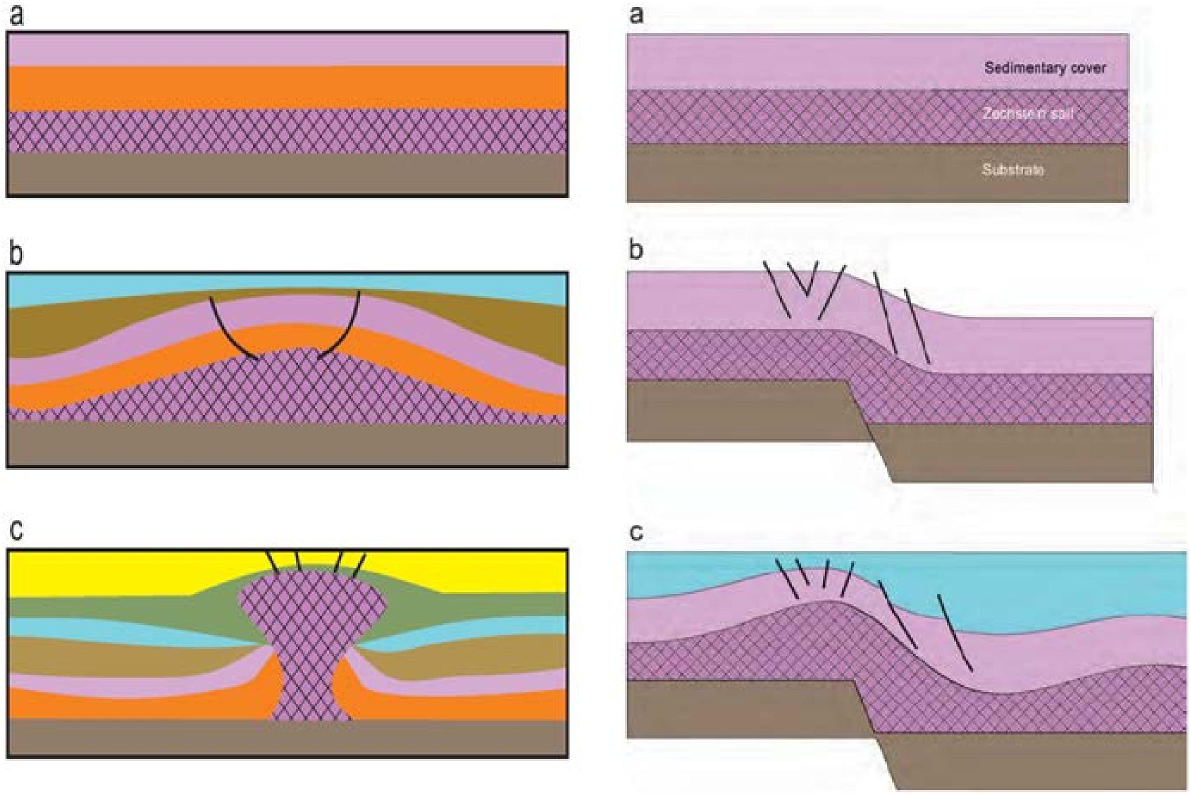


Figure 2.3.2: The process of how salt behaves during extensional tectonics. Left side represents the formation of a salt diaper and the right side describes a model for basement-fault related salt movement (Geluk et al, 2003).

The different architectures of salt structures combined with the Triassic sediment supply found within the Central Graben, are characterized as rafts and pods with intervening salt swells, walls and diapirs. Generally the rafts, which are more continuous, tend to be more present in the northern Central Graben, whereas the isolated pods are found more in the southern Central Graben (Goldsmith et al, 2003). The main difference between the two structures is characterized by the initiation of the two. The rafts are believed to be younger, since they were initiated in the Late Triassic whereas the pod development was active throughout the Triassic (Goldsmith et al, 2003).

The majority of the salt pods grounded on the underlying Rotliegend to form welds, and created the accommodation space for supra-salt mini-basins by deflation and dissolution of the salt walls and swells. Many of these pods continued grounding through the Jurassic (Goldsmith et al, 2003). Mapping of the southern Central Graben indicates that the salt has almost been completely dissoluted during the Triassic and post-Triassic times. This could indicate that the initial salt layer in the southern Central Graben is thinner than to the north (Goldsmith et al, 2003). The northern rafts occur as rotated pairs, with layer parallel Triassic sequences developed in between salt swells and mini rifts (Goldsmith et al, 2003).

A distinct fact concerning the halokinetic structures is observed when moving towards the margins of the Central Graben. The structures become progressively younger, which may relate to the footwall collapse of the graben with time (Pharaoh et al, 2010).

To understand the structural development of the Danish and Dutch North Sea area, it is important to distinguish between areas with thick salt and those without salt. The structural elements of these areas are completely different from each other, as were the responses to the inversion tectonics (Geluk$_{\text{(Permian)}}$, 2007). The salt movements also play a major role on a local scale. For example the process of salt flow piercing through the chalk layers has created reworked chalk areas, which has provided various types of structural traps for HCs. On the other hand in places where salt has undergone withdrawal, extra accommodation space for sediments has been provided (Geluk$_{\text{(Permian)}}$, 2007).

2.4 Stratigraphy and depositional environments

The following sub-chapter gives a quick overview of the stratigraphy and depositional environments found within the Central Graben (See Figure 2.4.1). Even though the Central Graben commenced its formation during the Early Triassic, the overview includes a stratigraphic description of the sequences deposited during Permian times. This is mostly done, because of the close relation the Upper Permian salt structures have with the petroleum plays in the Central Graben.

2.4.1 Permian

The Permian age depositions within the Dutch and Danish North Sea area are divided into the Lower Rotliegend, Upper Rotliegend and Zechstein groups (Geluk$_{\text{(Permian)}}$, 2007)(See Figure 2.4.1). The Lower Rotliegend Group was deposited during Middle Permian times and is of volcanic origin. The group is only locally present and consists mostly of red-brown to green spilitic, basaltic volcanics, with rhyolites and infill of clastic rocks. It has a thickness of almost 150 m in the Dutch Central Graben and the succession is lithologically similar to the Karl Formation found during the same age on the Danish North Sea area (Geluk$_{\text{(Permian)}}$, 2007). The group is overlain by the Upper Rotliegend Group, which is comprised of fine-grained clastics and evaporates originated from fluvial, eolian and playa-lake deposits. It was deposited under warm and arid climatic conditions and has a maximum thickness of 700 m in the northern offshore area, but thins rapidly to both the north and south (Gast et al, 2010; Geluk$_{\text{(Permian)}}$, 2007).

The Zechstein Group consists of five evaporate cycles with and upper claystone formation on top. The cycles are comprised of marine evaporates and carbonates, while the claystones contain subordinate clastics. The cycles represent events where we have a gradual retreat of the sea during deposition (Geluk$_{\text{(Permian)}}$, 2007). The group overlays the Upper Rotliegend as a conformable contact, but as an unconformable contact where it overlays the Lower Rotliegend (Geluk$_{\text{(Permian)}}$, 2007).

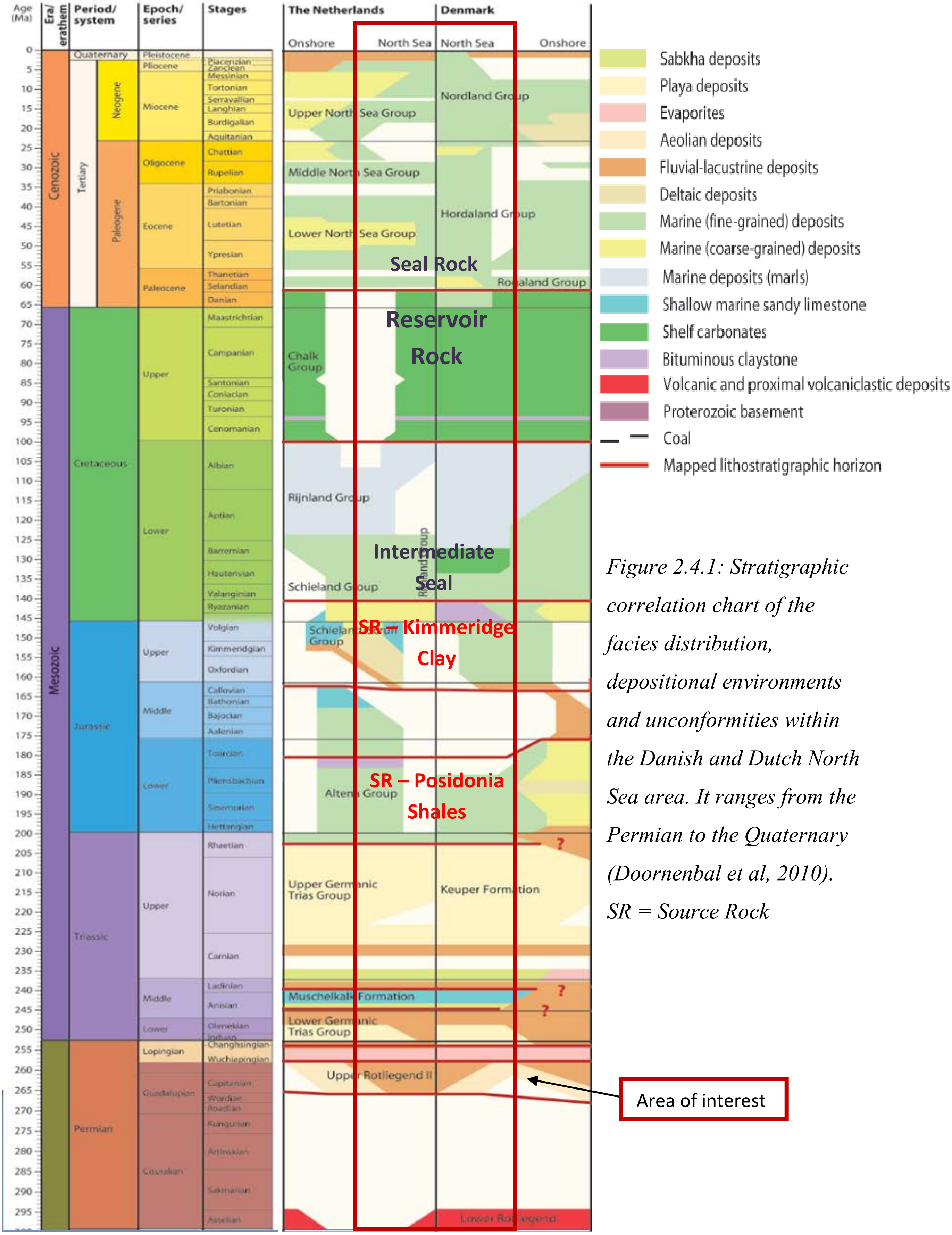


Figure 2.4.1: Stratigraphic correlation chart of the facies distribution, depositional environments and unconformities within the Danish and Dutch North Sea area. It ranges from the Permian to the Quaternary (Doornenbal et al, 2010). SR = Source Rock

2.4.2 Triassic

The Triassic rocks on the Dutch and Danish North Sea area have an almost similar subdivision of stratigraphic groups, which is comprised of the Lower and Upper Germanic Trias Group (See Figure 2.4.1). The main difference is shown when moving further to the north into the Danish-Norwegian basin, where other formations interfinger with the formations found within the Central Graben (Bachmann et al, 2010).

The Lower Germanic Trias Group is further divided into the Lower Buntsandstein, Volpriehausen, Defurth and Hardegsen formations, where the last three formations together make up the Main Bundsandstein Subgroup (Geluk$_{\text{(Triassic)}}$, 2007). It is mainly made up of fine-grained silisiclastic deposits with sandstone and oolite intercalations. The finer sediments represent a lacustrine depositional environment, whereas the sandstones are characterized as fluvial and eolian. The thickness and distribution are mainly controlled by the rift tectonics, but it measures up to 800 m thick in the areas most affected by subsidence (Geluk$_{\text{(Triassic)}}$, 2007).

The Upper Germanic Trias Group is further made up of the Solling, Röt, Muschelkalk and Keuper formations. It consists of lacustrine, brackish-water and marine, fine-grained silisiclastics, carbonates and evaporates. Its thickness and distribution is significantly influenced by the Early Cimmerian rift tectonics, but still reaches a thickness of 1700 m within the Central Graben (Geluk$_{\text{(Triassic)}}$, 2007).

2.4.3 Jurassic

The Jurassic layers within the Danish Central Graben consists of the seven formations, Fjerritslev, Bryne, Lulu, Middle Graben, Lola, Heno and Farsund (Vollset & Doré, 1984). Within the Dutch Central Graben the Altena, Schieland, Scruff and Niedersachsen groups represent these layers (Wong, 2007)(Figure 2.4.2). When correlating these two successions with each other some similar lines can be drawn.

The Fjerritslev Formation can be correlated to the Altena Group, where they both represent the Lower Jurassic. The Altena Group can be further divided into the Sleen, Aalburg, Posidonia Shale and Werkendam formations (Wong, 2007). Both sequences consist of slightly calcareous, argillaceous sediments with silty claystones interbedded with thin marlstone stringers. It has a grey to dark grey marine colour and is classified as shallow marine sediments deposited during a widespread marine transgression (Vollset & Doré, 1984; Wong, 2007). The sequences on the Dutch side vary in thickness, mainly because of erosion on the surrounding highs, which lead to thicker layers in the basins (Wong, 2007).

The Bryne, Lulu, and Middle Graben formations on the Danish North Sea area represent the Middle Jurassic (Vollset & Doré, 1984). These formations can be correlated to the Schieland Group, which is subdivided into the Lower Graben, Middle Graben, Puzzle Hole and Upper Graben formations in the Dutch Central Graben (Lott et al, 2010). The Lower Graben and Bryne formations both contain alternations of sandstones, claystones and coal beds, which represent a coastal-plain to a shallow-marine environment on the Dutch North Sea area and a fluvial to deltaic environment on the Danish North Sea area (Wong, 2007; Vollset & Doré, 1984). The Lulu Formation represents a shallow marine depositional environment of sandstones with a light grey and fine-grained characteristic (Michelsen et al, 2003). The formation cannot be correlated particularly to the remaining formations present in the Schieland Group. On the other hand, the Middle Graben Formation on the Danish North Sea area can be correlated to the remaining formations on the Dutch North Sea area, which both consist of dark grey claystones interbedded with siltstones and rare sandstone beds. The depositional environment is likely to have occurred within a swampy environment (Michelsen et al, 2003).

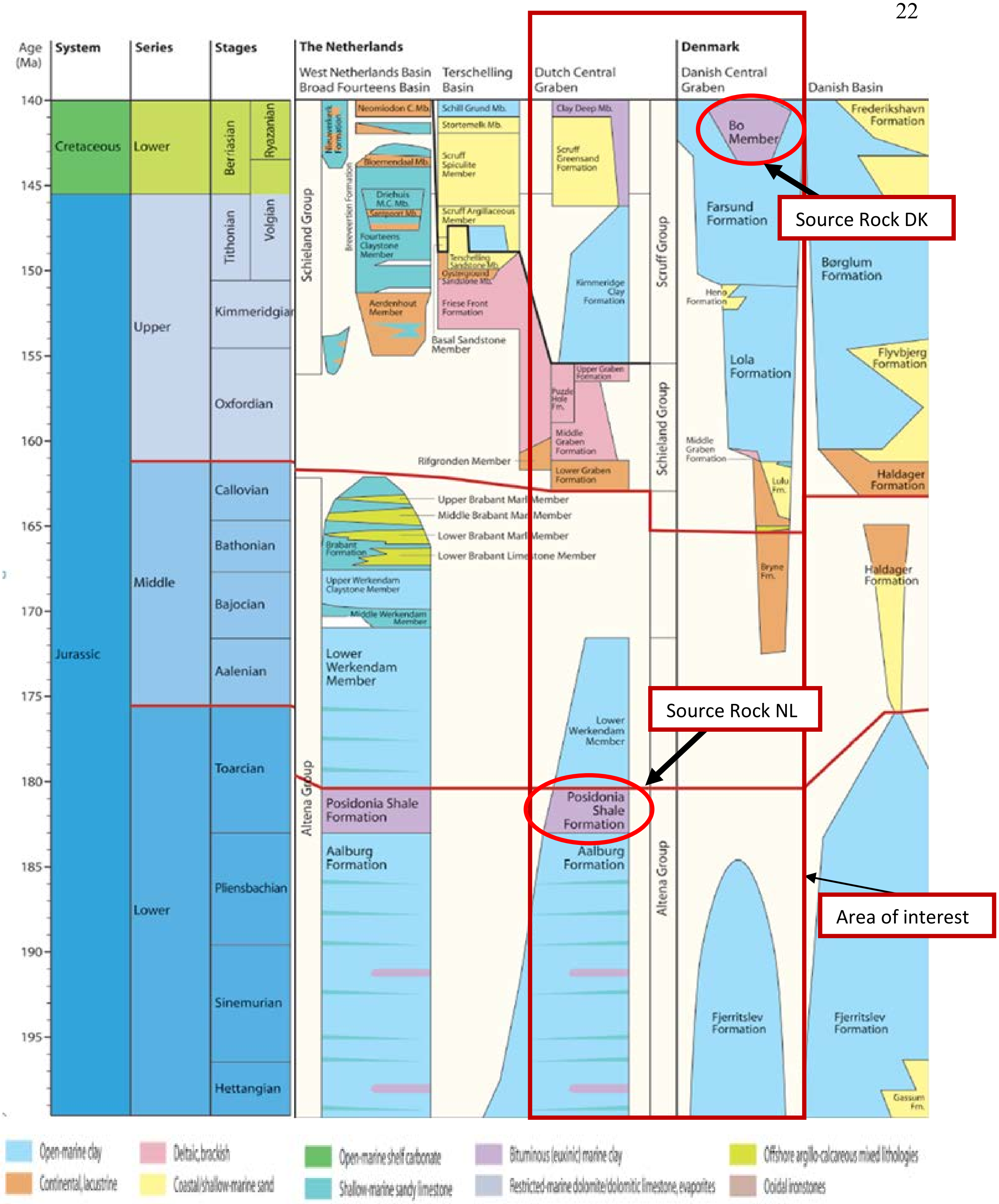


Figure 2.4.2: Stratigraphic correlation chart of the Jurassic showing the depositional environments and formations within the Danish and Dutch North Sea area (Lott et al, 2010).

In the Upper Jurassic we find the Lola, Heno and Farsund formations on the Danish North Sea area, while we find similar depositions within the Scruff Group on the Dutch North Sea area (Michelsen et al, 2003; Wong, 2007). The Scruff Group can further be divided into the Kimmeridge Clay and Scruff Greensand Formation (Wong, 2007). Here the Lola and Farsund formations can be correlated to the Kimmerigde clay, which all three took place in a low energy, deep offshore marine environment and consists of marine, locally bituminous dark grey claystones which are carbonaceous and variably calcareous (Michelsen et al, 2003; Wong, 2007). The Heno Formation is on the other hand similar to the Scruff Greensand Formation, which both consists of very fine to fine-grained sandstones that are deposited within a back-barrier and marine shoreface environment (Michelsen et al, 2003; Wong, 2007).

2.4.4 Cretaceous

The Cretaceous age consists of the Cromer Knoll Group and the Chalk Group in the Danish Central Graben. The Rijnland Group and the Danian and Chalk Group represent this age on the Dutch North Sea area (Isaksen & Tonstad, 1988; Herngreen & Wong, 2007)(See Figure 2.4.3).

The Cromer Knoll Group is made up of the Åsgard, Tuxen, Sola and Rødby formations within the Danish Central Graben. They show similarities to the Rijnland Group, which is divided into the Vlieland Sandstone, Vlieland Claystone and Holland formations (Isaksen & Tonstad, 1988; Herngreen & Wong, 2007). The lowermost Åsgard Formation and Vlieland Claystone consists of brownish to grey claystones with common mica and lignitic matter. The sediments are likely to have deposited into an open marine environment with low energy (Isaksen & Tonstad, 1988; Herngreen & Wong, 2007). The Vlieland sandstone occurs as intersections within the Vlieland claystones as clean glauconitic sandstones, which represent a shallow marine depositional environment (Herngreen & Wong, 2007).

The next formation on the Danish North Sea area is the Tuxen, which is dominated by white calcareous claystones and marlstones, which sometimes grade into purer limestones along structural highs. The deposition happened through pelagic marl and chalk oozes, which covered large areas of the North Sea (Isaksen & Tonstad, 1988). These depositions are absent at the Dutch North Sea area, so no correlations between Denmark and the Netherlands are possible here. The Sola and Rødby Formations can on the other hand be correlated to the Holland formations, where they both are deposited in a marine environment with alternating anoxic and oxygenic bottom conditions. They consist of shales interbedded with marls, marly claystones and limestones, which have a black to dark grey colour (Isaksen & Tonstad, 1988; Herngreen & Wong, 2007).

The Chalk Group is comprised of the Hidra, Plenus Marl, Hod and Tor formations in Danish Central Graben, while the group is divided into the Texel, Ommelanden and Ekofisk formations in the Dutch Central Graben. All the formations have an open marine depositional environment in common, with a turbiditic origin for the sediments (Isaksen & Tonstad, 1988; Herngreen & Wong, 2007).

The Hidra and Texel formations are comprised of white limestones and marly hard chalks, with thin interbeds of grey shale in the lower part of the formation (Isaksen & Tonstad, 1988; Herngreen & Wong, 2007). Both the Danish and Dutch North Sea area have the presence of the Plenus Marl Formation, which is comprised of thin relatively fossiliferous, green-coloured marls and marly limestones (Isaksen & Tonstad, 1988; Herngreen & Wong, 2007). The following Hod and Tor formations in the Danish Central Graben can be correlated to the Ommelanden Formation in the Dutch Central Graben. They both consist of generally homogeneous hard, white to grey limestones, which may become argillaceous or chalky in places (Isaksen & Tonstad, 1988; Herngreen & Wong, 2007). The last formation belonging to the Chalk Group is the Ekofisk Formation, which is present in both the Dutch and Danish Central Graben. It contains similar sediments as the rest of the Chalk Group, with white crystalline limestones, but it is also comprised of some thin beds of grey, calcareous and often pyritic shales. In age it actually belongs to the Tertiary, but is included here as part of the Chalk Group (Isaksen & Tonstad, 1988; Herngreen & Wong, 2007).

It is important to notice that the overall distribution of the Chalk Group is present over most of the Dutch and Danish offshore areas. However, there are some exceptions where the chalk is not present due to erosion. The Dutch Central Graben is such a place, where the Chalk Group is missing or is only present as a patchy thin cover (Herngreen & Wong, 2007).

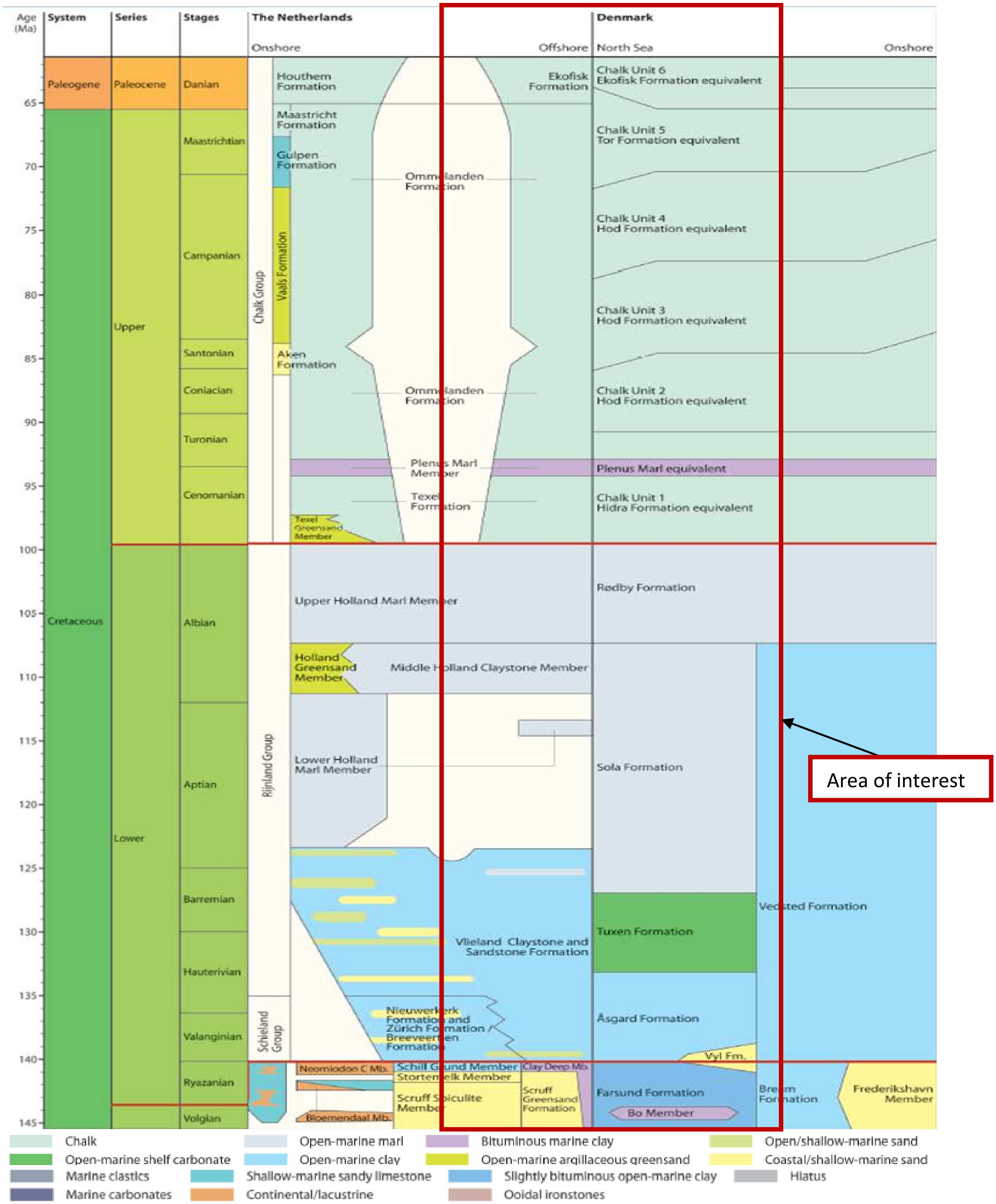


Figure 2.4.3: Stratigraphic correlation chart of the Cretaceous showing the depositional environments and formations within the Danish and Dutch North Sea area (Vejbæk et al, 2010).

2.4.5 Tertiary

The stratigraphic groups deposited during Cenozoic times within the Danish and Dutch North Sea area are divided into the Rogaland, Hordaland and Nordland groups on the Danish area, and into the Lower-, Middle- and Upper North Sea Group on the Dutch area (Knox et al, 2010)(See Figure 2.4.1).

The Rogaland Group can be correlated to the lower part of the Lower North Sea Group, which both consist of mainly sandstones interbedded with shales and marls that are characterized as argillaceous marine sediments. They are deposited in a relatively deep marine environment, by submarine fans, which built out from the west and possibly SE. The Rogaland Group consists of the Våle, Lista, Sele and Balder formations, while the Lower North Sea Group is divided into the Landen and Dongen formations (Isaksen & Tonstad, 1988; Knox et al, 2010).

The Hordaland Group can be correlated to the upper part of the Lower North Sea Group, the whole Middle North Sea Group and the lower part of the Upper North Sea Group. It consists of marine shales, with thin limestone and dolomites streaks at the bottom, which are likely to have been deposited within an open marine environment, due to its fossiliferous content (Knox et al, 2010). Further up in the formation it is dominated by dark, non-fissile mudstones with thin layers of white carbonate and sandstones that are interbedded throughout the formation. The depositional environment is still open marine, but signs of considerable influx from land are present (Knox et al, 2010). Comparing the Hordaland Group with the Middle and Upper North Sea groups, the deposits are comprised of sands, silts and clays in the Middle group and of clays, fine to coarse-grained sands and locally gravel and brown coal seams in the Upper group. The depositional environment is also here characterized as being open marine (Wong et al, 2007).

The Nordland Group is also dominated by marine claystones and can be correlated to the upper part of the Upper North Sea Group. They are grey, soft and locally silty and micaceous, where deposition has occurred within an open marine environment. However, in the upper part of this group, signs of glacial deposits are found (Isaksen & Tonstad, 1988).

2.5 Petroleum system

“The petroleum system is a unifying concept that encompasses all of the disparate elements and processes of petroleum geology” (Magoon & Beaumont, 1999). This means that elements like the source-, reservoir-, seal- and overburden rock are essential to the petroleum system, in addition to the processes concerning the trap formation and generation, maturation, migration and accumulation of HCs. If these elements and processes are all correctly placed in time and space, there is a good possibility that organic matter has generated within a source rock and converted into a petroleum accumulation. In whichever place these essential elements and processes are known to occur or are thought to have a reasonable probability to occur, is characterized as a petroleum system (Magoon & Beaumont, 1999).

2.5.1 Source rocks

Kimmeridge Clay

The HCs produced from the chalk reservoirs of the Danish Central Graben have mostly been originated from a succession of radioactive “hot shales” referred to as the Bo Member. This succession is found within the Upper Jurassic Farsund Formation, which is an equivalent to the Kimmerigde Clay Formation (Ineson et al, 2003). The Bo Member covers large parts of the Danish Central Graben and is a quite persistent feature. It is truncated on some structural highs and has lateral variation in both thickness and organic richness as a result of intrabasinal structural topography and to the location of sediment input centres (Figure 2.5.1). The thickness varies typically between 15-30 m and it has Hydrogen Index values exceeding 500 mg/g, which is somewhat dependent on the level of thermal maturity (Ineson et al, 2003). The rock in the member is classified as being marine type II shales with a highly organic-carbon-rich content. A content, which varies from 2 to more than 15 weight percent of total organic carbon (TOC), and that reflects an anoxic depositional environment to have occurred within areas of closed bathymetric basins during sea level rises (Gautier, 2005). This content is easily recognizable from their high values on the Gamma Ray (GR) log, which has in return given them the name of “Hot Shales” (Gautier, 2005). Moving upwards in the Farsund Formation, the TOC content generally increases, along with a shift from generally gas-prone to generally oil-prone characteristics (Pletsch et al, 2010). The source-rock potential of the Farsund Formation is on the other hand variable in various places. This is because; the uppermost Farsund Formation has not reached the level of maturity necessary to generate enough HCs to explain in-place reserves (Pletsch et al, 2010).

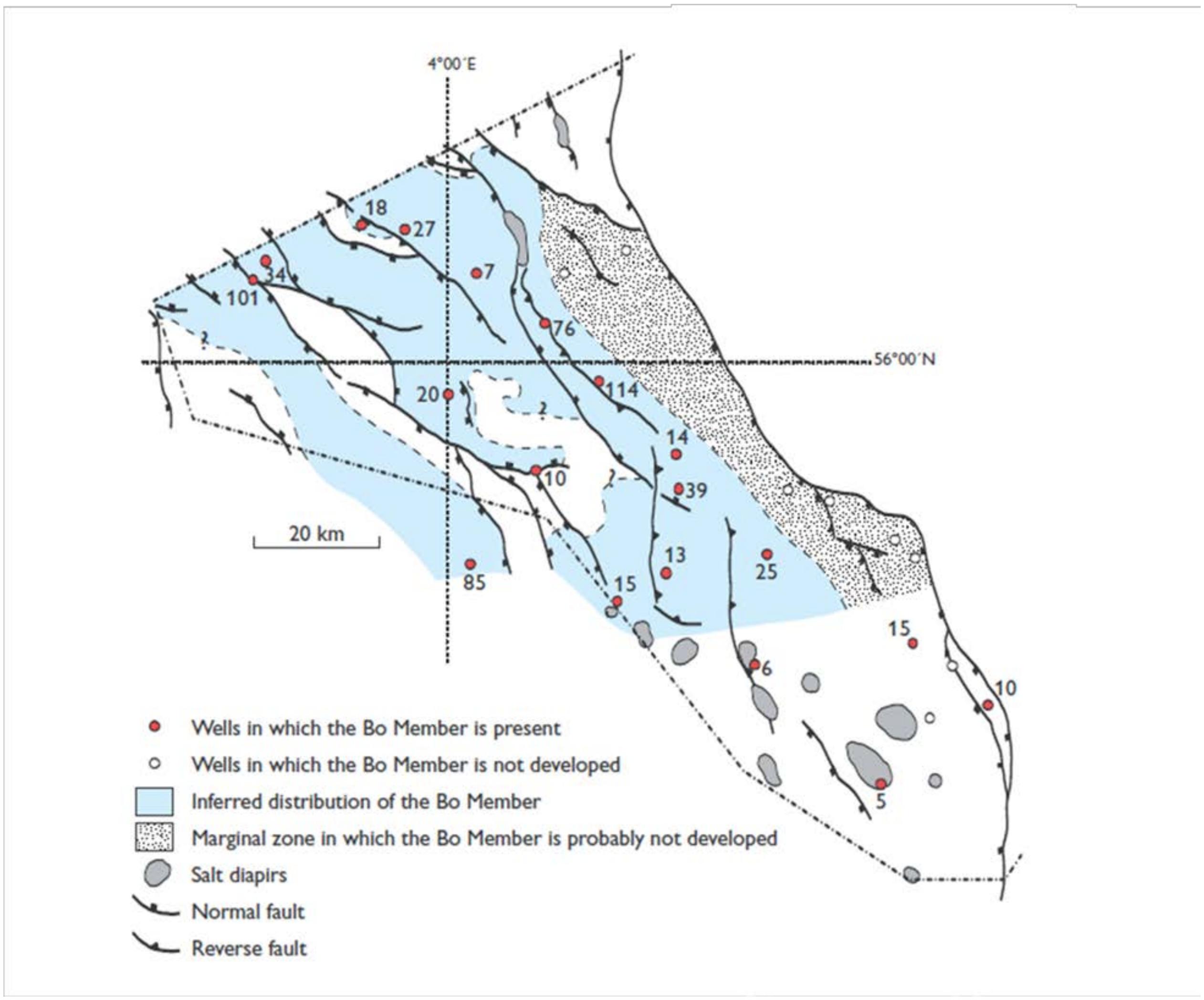


Figure 2.5.1: Map showing the thickness in meters of the Bo Member in well sections and its lateral distribution deduced from well and seismic data. The distribution of the member is not inferred for the southern area corresponding to the Salt Dome Province, due to sparse data points and thin, irregular development of the member in this region (Ineson et al, 2003).

Posidonia Shale

In the Dutch sector of the North Sea, the main source rock for oil accumulated in the chalk is found in the Lower Jurassic, Toarcian, Posidonia Shale Formation (De Jager & Geluk, 2007). The thickness of the formation varies considerably across the Dutch Central Graben as a result of the syn-sedimentary salt movements during deposition. On the other hand, where the rock is located it has a uniform thickness indicating a relative tectonic quiescence during deposition

(Pletsch et al, 2010). Because of this uniform thickness, it is believed that the formation was probably deposited over a greater area. However, its present day distribution reflects the erosion that occurred on the basin margins and bounding highs, since it's only preserved within the Late Jurassic rift basins (Pletsch et al 2010, De Jager & Geluk, 2007)(See Figure 2.5.2).

The rock itself is classified as a rich, marine, type-II source rock, with a gross thickness ranging from 15 to 35 m, an average TOC of ca. 10%, and a Hydrogen Index of up to 850 mg/g (De Jager & Geluk, 2007; Pletsch et al 2010). It is believed to have been deposited in a shallow epi-continental basin, where the restricted sea-floor circulation and the preservation of organic matter are considered to be a consequence of an oceanic anoxic event (Schulz et al, 2013). As a result of a rise in sea level during the deposition of the Posidonia Shales, the TOC content and the quality of the organic matter varies both vertically and laterally (Schulz et al, 2013).

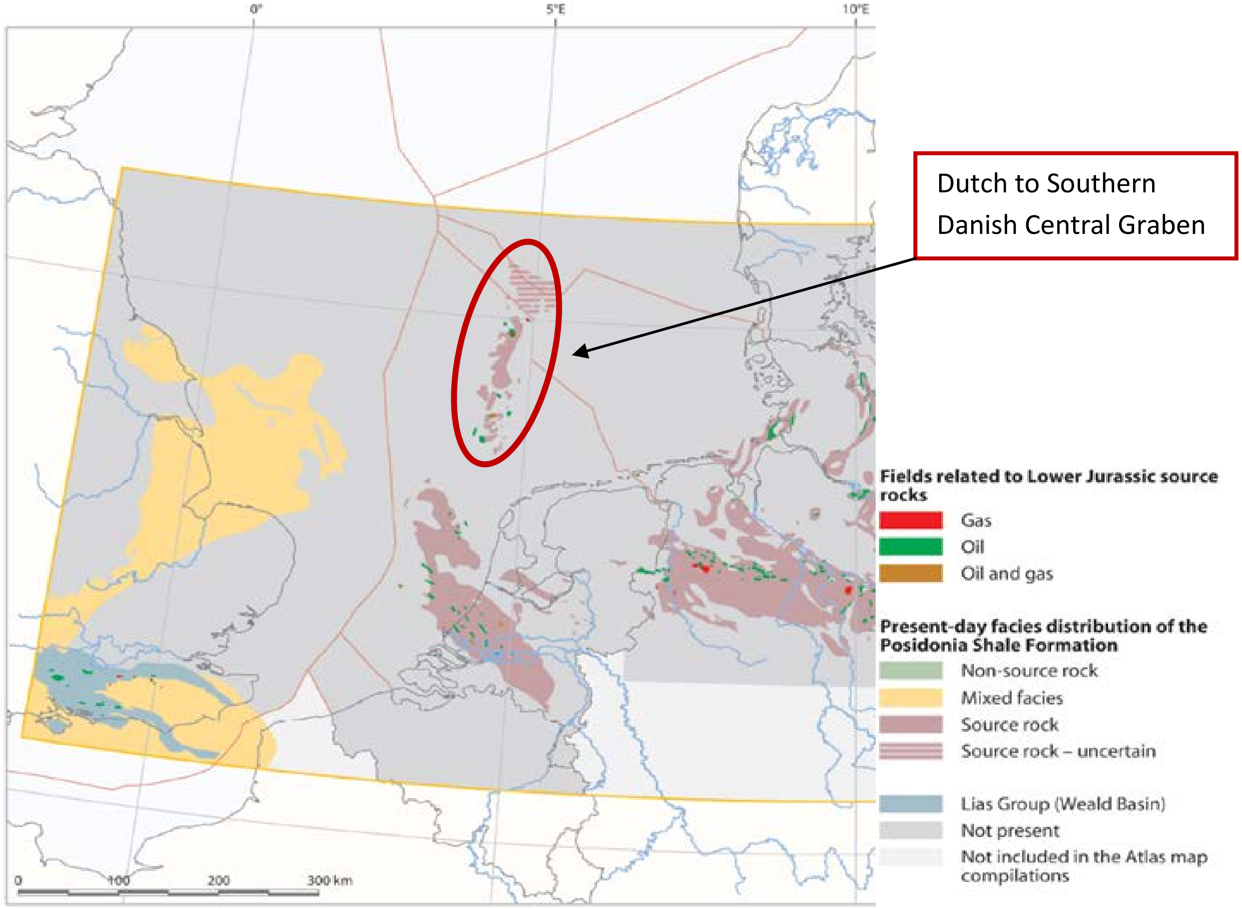


Figure 2.5.2: The present-day facies distribution of the Posidonia Shale Formation within the Dutch North Sea area and on the onshore area of the South Permian Basin area (Lott et al, 2010).

2.5.2 Generation and Maturity

Previous studies have shown that the oil generation in the deepest part of the Central Graben started during the Maastrichtian and reached its peak in Early Miocene to Pliocene times. However, major amounts of oil have also been generated during Palaeocene times and are still generating at the present day (Surlyk et al, 2003). Nearly continuous sediment accumulation across the North Sea has occurred since the Latest Cretaceous times, which in return has resulted in great burial depths of the Kimmeridgian clays. It is hereby believed that this rapid accumulation of sediments is responsible for Kimmeridge Clay to have reached its thermal maturity stage during this time (Gautier, 2005; Lott et al, 2010).

The burial history of the Posidonia Shale Formation in the Central Graben shows large variations, resulting in very different temperature and associated maturity histories, depending on the structural position (Guasti et al, 2010). The ratio of generated petroleum to potential petroleum in a source rock indicates that the Posidonia Shale Formation started generating HCs already during the Late Jurassic to Early Cretaceous times in the southern part of the Dutch Central Graben. This generation reached a maximum just before the Late Cretaceous uplift and resumed in the Palaeogene times, where it stops at the end of this age (Verweij et al, 2009; Lott et al, 2010). Because of the major inversions that happened within the southern Dutch Central Graben, no oil generation is currently happening here, since the present-day temperatures in the Posidonia shales are lower than those reached before inversion. However, when moving more to the north, the Posidonia Shale Formation reached its deepest burial and is thereby still generating oil as of today (Pletsch et al, 2010).

2.5.3 Migration

Within the Danish Central Graben, a thick Lower Cretaceous argillaceous sequence separates the source rocks in the Upper Jurassic from the HC accumulations in the chalk (Gautier, 2005; Surlyk et al, 2003). Fractures in this sequence have been created as a result of extensive evaporates deposits in the Zechstein Group below the Central graben, which have moved closer to the subsurface through halokinetic structures. It is believed that these fractures have strongly influenced the migration pathways from the source rocks and facilitated vertical migration (Gautier, 2005; Kubala et al, 2003). In addition, it seems likely that vertical migration in the

Central Graben has occurred along the line of maximum flexuring over the graben-bounding faults (Kubala et al, 2003)(See Figure 2.5.4). Another form for HC migration could have been through regional lateral movements of the fluids between the fields within the chalk. Even though the chalk has a low permeability, which makes the migration slow, it might have been possible (Surlyk et al, 2003).

As mentioned from the introduction, we know that the chalk across the Dutch North Sea sector behaves as an aquifer, because the pressure change with depth follows a hydrostatic trend across the entire thickness of chalk in the wells (tno.nl). This means that the pressures in the chalk are able to equilibrate vertically. The flow of HCs from the underlying source rock will hereby be more restricted, which makes the Lower chalk act as a seal (tno.nl). If there on the other hand is no Lower chalk present, this will then be crucial in forming migration pathways for the HCs into the reservoir, when the right structural environment is in place (Guasti et al, 2010). On the other hand, the Chalk Group on the Dutch North Sea sector is comparable to the Chalk Group on the Danish and Norwegian North Sea sectors, meaning that it is likely that the migration pathways also here have been triggered through salt tectonics and major faults (De Jager & Geluk, 2007)(See Figure 2.5.4).

2.5.4 Reservoir rock

The North Sea chalk reservoirs are known for their high porosity and low permeability relationship. They are most commonly found within the Maastrichtian Tor Formation and Danian Ekofisk Formation, where the Tor Formation is of higher quality considering it has better porosity and permeability conditions (Vejbæk et al, 2010). The porosity of chalk is known to decline significantly with depth, and diagenetic changes would normally cause porosity reduction from about 70 or 80 % at the surface to around 10 % at burial depths of 2000 m. However, various factors like the burial depth, overpressure, halokinesis, post-depositional tectonics and the presence of HCs have prevented diagenesis from exercising its full potential in some parts of the chalk in the North Sea. This is believed to be the reason for chalk reservoirs to have retained their high porosities (Surlyk et al, 2003; Gautier, 2005).

Chalk itself is composed of particles, which are mainly single crystal laths of calcite produced by the disaggregation of coccoliths. The size and distribution of these crystals together with the pore throat size characterizes the chalk as a micropore reservoir rock and determines the reservoir quality of chalks (Hardman, 1982). The Danian chalk consists of coccoliths with smaller pore throats, which explains the lower permeability and the lower quality of the Danian chalk reservoirs. However, this effect diminishes with increasing porosity, since the permeability becomes less significant (Surlyk et al, 2003). The amount of clay content in the chalk is strongly related to the reservoir quality. The more clay that is present, the lower the quality becomes, since the clay increases the residual water saturation, lowers the permeability, and causes an increase in capillary entry pressures (Vejbæk et al, 2010). The North Sea chalk is also known to contain hairline, stylolite and tectonic fractures, where the last one is responsible for the main permeability enhancement in the North Sea chalk reservoirs. Most of these tectonic fractures are related to the halokinetic activity and deep-seated tectonic activity, and give rise to very variable permeabilities (Surlyk et al, 2003).

The primary sedimentation mechanism of chalk has been through the settlement of coccoliths from suspension, where the deposition has likely occurred in a wide range of water depths. This primary formation of chalk is also known as “autochthonous” chalk and is described as the bioturbated periodite facies (Van der Molen, 2004). Various mass-movement mechanisms can on the other hand result in the re-deposition of chalk. Such chalk is known as being reworked chalk and is either re-deposited through turbidity currents, debris flows or in the form of chalk slumps (Van der Molen, 2004)(Figure 2.5.3). In some cases, the re-deposited chalk remains internally intact when moving downslope. In these cases the re-depositions define interesting areas that could be potential reservoirs.

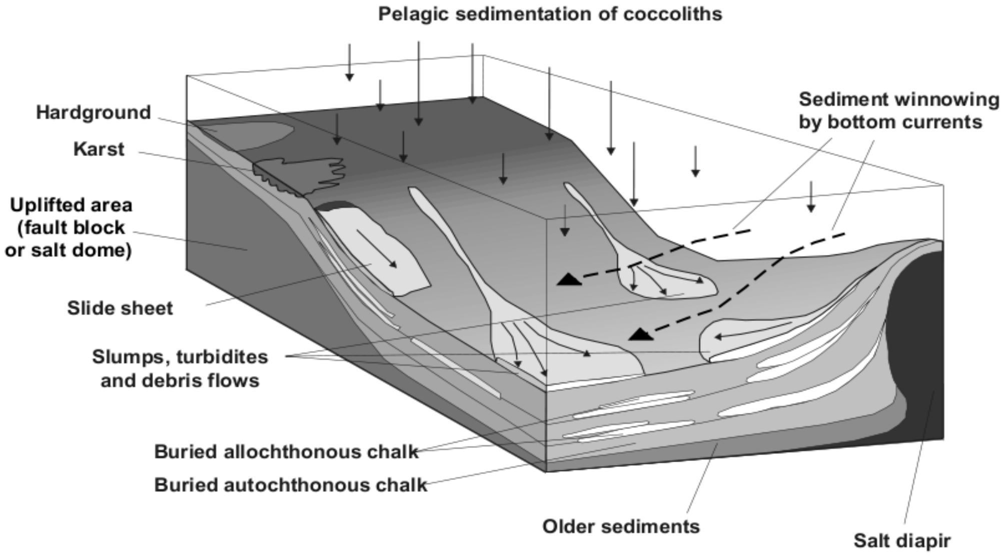


Figure 2.5.3: Overview of various depositional processes often seen in the chalk (Van der Molen, 2004).

2.5.5 Traps

All the chalk fields that have been discovered are mostly formed by structural closures, as a result of inversion-generated anticlines and traps over salt domes and salt diapirs (See Figure 2.5.4). However, each field is still characterized as having some sort of stratigraphic element incorporating within the trap (Vejbæk et al, 2010; Surlyk et al, 2003). The salt induced traps are commonly located within the deeper part of the basins were thick, laterally continuous intervals of potentially good reservoir quality chalk is present. The trapping structures differ through various stages of halokinesis, from swells that only gently deflect the overburden, to diapirs rupturing the sub-chalk intervals, which strongly deform the chalk (Surlyk et al, 2003).

The inversion structures occur mostly along the western hanging wall of the Coffee Soil Fault, that were initially created by inversion of the Late Jurassic half-graben during the Late Cretaceous and Cenozoic transpressive events. These structures are often characterized by chalk successions that are stratigraphically incomplete, because of occurrence of syn-depositional erosion due to their structurally high position (Surlyk et al, 2003).

A stratigraphic trap has also been discovered within the Danish chalk field, Halfdan (Figure 2.5.5). This is an encouraging fact and will be the topic of future exploration within chalk, since all of the structural closures within the main chalk-field provinces have been drilled (Surlyk et al, 2003).

The traps forming the structural closures are characterized as four-way dip closures (turtle back structures) and as tilted fault blocks. The trapping of HCs within the chalk itself is related to the dynamic-fluid phases, since the fluids require time to reach equilibrium due to the low permeability of the chalk (Vejbæk et al, 2010).

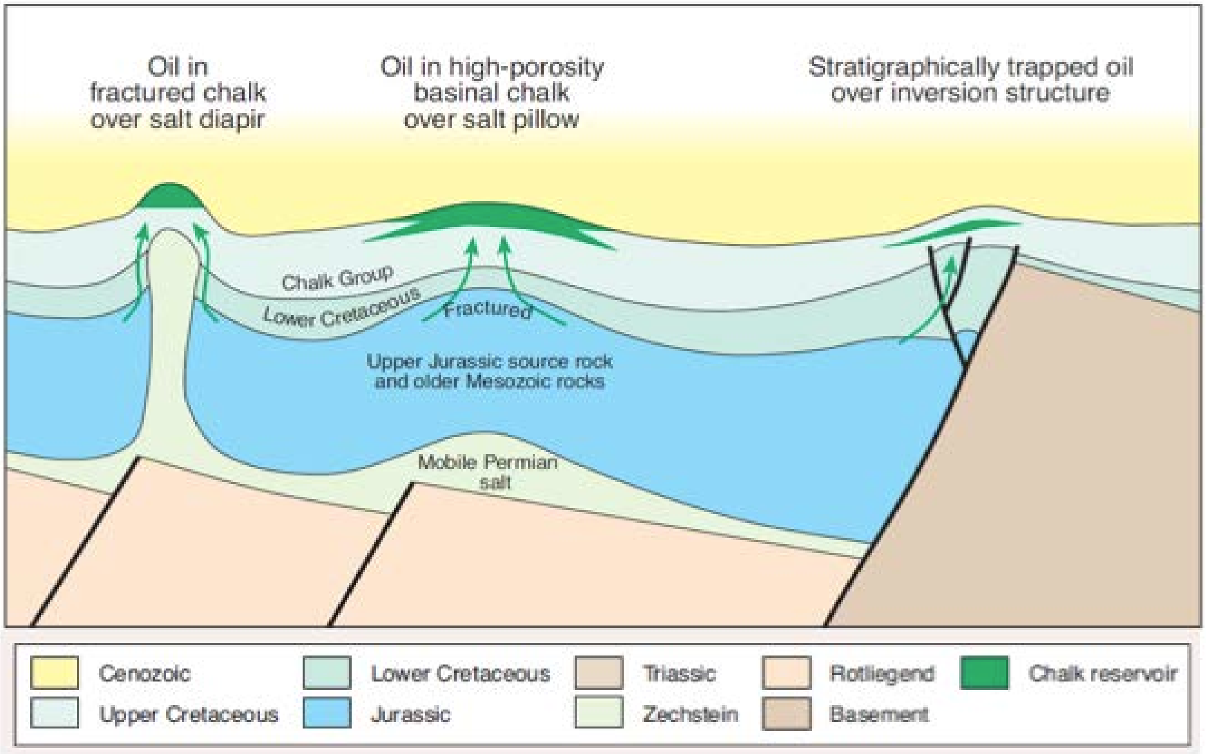


Figure 2.5.4: Oil trapped in chalk above salt diapirs, salt pillows and inversion structures (Surlyk et al, 2003).

2.5.6 Seals

The oil entrapment has likely occurred soon after the deposition of the Late Cretaceous chalks. During this time a Palaeocene mudstone was deposited, which is comprised of fine-grained facies. This mudstone acts as a seal and efficiently captures the HCs within the chalk reservoirs (Gautier, 2005). It is important to note that the chalk play is confined to the areal extent of this

Palaeocene mudstone, because in places where we have Palaeocene sandstones above the chalk will compromise the top-seal effectiveness. This is because the HCs will continue along their migration path into the Palaeocene sandstones and the overpressures are unable to develop, which leads to a porosity loss in the chalk reservoirs. No chalk fields are in other words found where early Tertiary sandstones overlie chalk (Surlyk et al, 2003).

Another fact that makes the Palaeocene mudstone an effective top-seal is the over-pressured chalk fields, which helps to preserve the high porosities within the chalk. By isolating the overpressures with an effective seal, will help to store the pressures, which is one of the major effects of the success of the chalk play (Surlyk, 2003).

2.5.7 Danish and Dutch chalk reservoirs

Within the Danish Central Graben we have the Svend, South Arne, Rolf, Dagmar, Gorm, Skjold, Dan, Kraka, East Harald and Regnar fields, which are salt-induced structures. Further on we have the Roar, Tyra, Valdemar, and Boje field induced through inversion structures and the Halfdan field confined within a stratigraphical trap (See Figure 2.5.5). On the other hand on the Dutch sector we have one chalk field, the Hanze field, induced through salt tectonics. A more detailed petroleum system analysis on some of the fields will be given in chapter 6.

From an initial perspective, the chalk play on the Danish North Sea area seems to be rather different from the Dutch North Sea area, when comparing the number of chalk reservoirs that are discovered. However, a comparison between the Dutch and Danish reservoirs shows that there are lot of similarities that can be drawn, even though the reservoir characteristics of the Chalk Group in the Netherlands is characterized as a poor play, while the opposite is true for Denmark (De Jager & Geluk, 2007). This poor success rate in the Netherlands is partly related to the shallow burial depth and limited charge of the chalk, which results in a reduced sealing capacity of the Lower Tertiary above the somewhat over-pressured chalk reservoirs, causing leaky traps (De Jager & Geluk, 2007).

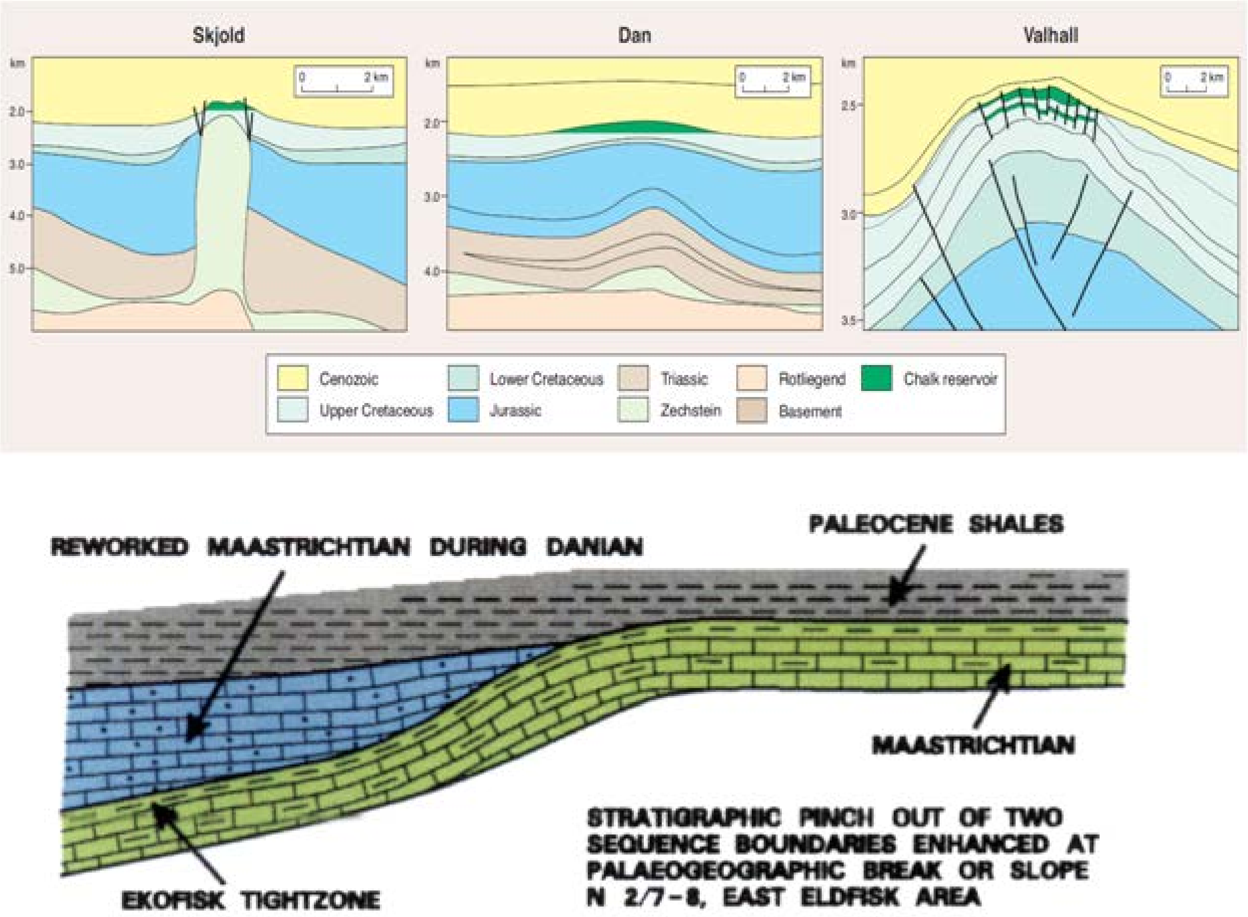


Figure 2.5.5: Examples of the Danish chalk fields, located above salt diapirs, salt pillows, and inversion structures and in stratigraphical traps (Vejbæk et al, 2010; Bramwell et al, 1999).

3. Database and methodology

3.1 Interpretation software

The interpretation software that has been used during this thesis is TOTAL´s seismic interpretation platform, SISMAGE (Figure 3.1.1). The Software offers a 3D visualization environment, which allows its users to display all the available data needed for the interpretation. This includes horizons, faults, bodies, wells, satellite images, attributes and seismic with all its picking operations in a manually or automatic way (Guillon & Keskes, 2004). In this thesis the Software has been mainly used for horizon and fault picking, seismic to well tie correlations and the generation of different kinds of maps.

Figure 3.1.1: TOTAL's seismic interpretation platform, SISMAGE.

3.2 Seismic database

The seismic interpretation in this thesis has been concentrated on the 3D seismic survey, MC3D-N_SEA_MegaSurvey_DK_D_NL, which is shown in Figure 3.2.1. The survey is a merge of several 3D datasets, something that can often be seen in the seismic (Figure 4.3). The data is obtained from Petroleum Geo-Service (PGS) and covers a large area in the North Sea that includes sections from Norway, Denmark, Germany, the Netherlands and the United Kingdom.

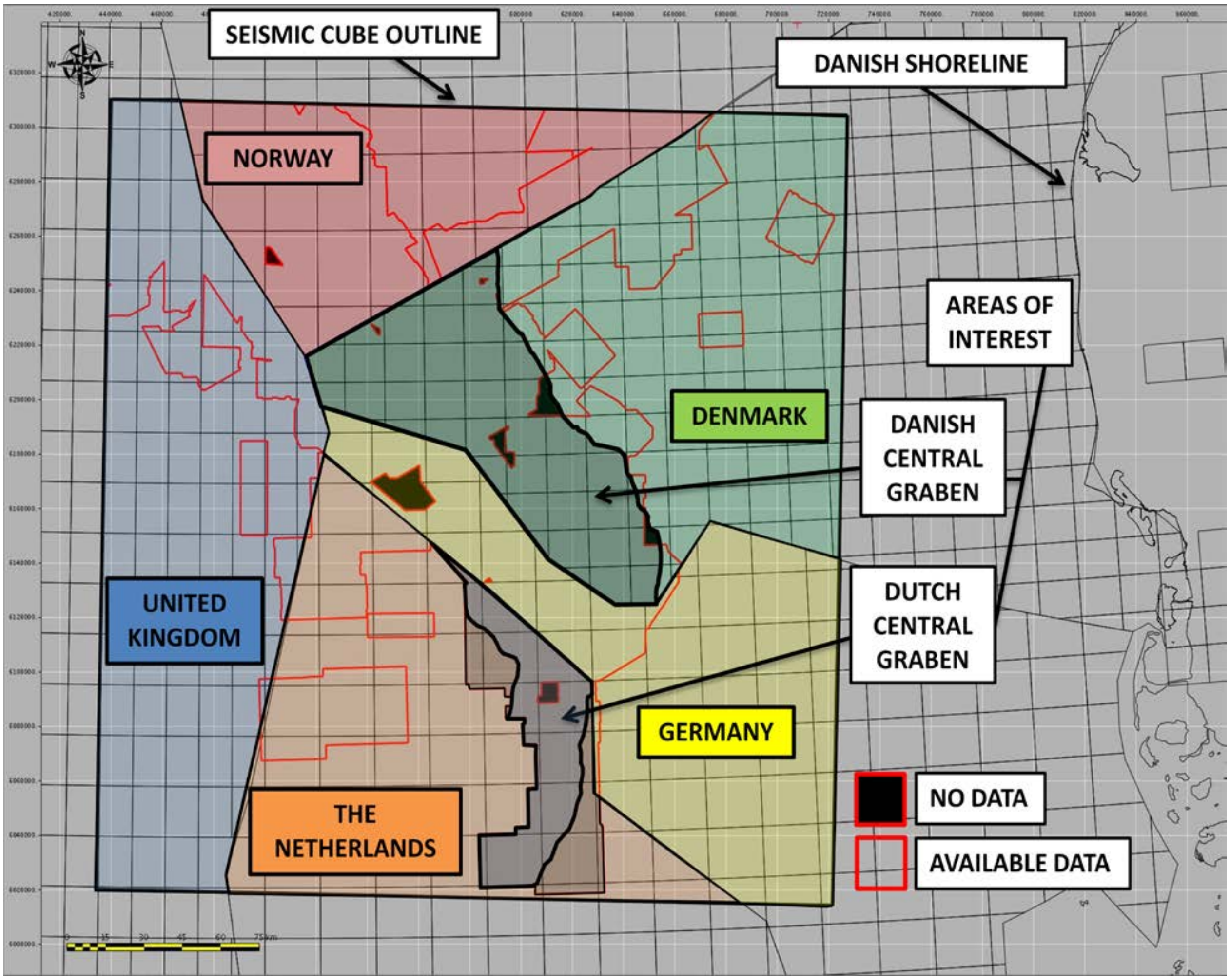


Figure 3.2.1: Overview of the 3D seismic survey, MC3D-N_SEA_Megasurvey_DK_D_NL, from PGS. The available data is covered within the red polygons, with the areas of interest marked within the darker polygons on the Danish and Dutch North Sea sector (SISMAGE).

3.3 Well database

The wells used in this thesis are listed within Table 3.1, with their location shown in Figure 3.3.1. The wells that have been considered for the petroleum system analysis are marked by the red colour. They have helped with the understanding of correlating the wells to the seismic and a few of them are considered for well calibration to check the performed interpretation. The remaining wells are studied based on their completion reports, where the composite well logs were concentrated on. These reports and logs were found at the GEUS webpage (geus.dk) and were chosen based on their location and depth.

Danish Wells:	Well Block Number:	Field:	Structure:	Total depth (m):	TD Group Formations or Geological Age	Completion Year
Liva-1	5503/04-01.		Liva	4627	Rotliegende Group	1984
Heno-1/W-1X	5504/01-01.		Heno	4381	Rotliegende Group	1976
Elin-1	5504/02-01.		Elin	4719	Jurassic Units	1983
BO-1X	**5504/07-02.**	**Valdemar**	**Bo**	**2743**	**Jurassic Units**	**1977**
Roar-2 & 2a	**5504/07-03.**	**Roar**	**Bent**	**2719**	**Cromer Knoll Group**	**1981**
Gorm-2/N-2X	**5504/16-01.**	**Gorm (B)**	**Vern**	**2289**	**Chalk Group**	**1975**
Gorm-Deep/N-22	**5504/16-05.**	**Gorm (B)**	**Vern**	**3968**	**Triassic Units**	**1987**
John-Flanke-1	5504/20-02.		John	2455	Triassic Units	1985
Halfdan-1X/HDN-1X	**5505/13-07.**	**Halfdan (NW)**	**Nana**	**2341**	**Chalk Group**	**2000**
S.E. Igor-1	**5505/14-01**		**S.E. Igor**	**3298**	**Jurassic Units**	**1983**
Nils-1	**5505/17-05.**	**Regnar**	**Nils**	**2033**	**Zechstein Group**	**1978**
Ryan-1/O-1X	**5505/21-01**		**ryan**	**3578**	**Zechstein Group**	**1973**
Vagn-2	**5505/21-02.**		**Vagn**	**1931**	**Zechstein Group**	**1978**
Tove-1	**5505/21-03.**		**Tove**	**1879**	**Zechstein Group**	**1978**
Rita-1	5603/27-05.		Rita	4801	Triassic Units	1993
Gert-2	5603/28-01.		Gert	5073	Devonian	1985
Hejre-1	5603/28-04.			5302	Permian	2001
Kim-1	5603/30-01.		Kim	4683	Rotliegende Group	1985
Inge-1/P-1X	5603/32-01.		Inge	3495	Carboniferous	1973
Lulu-1	**5604/22-01.**	**Harald (East)**	**Lulu**	**3720**	**Zechstein Group**	**1980**
Otto-1	5604/25-02.	Svend	North Arne	2784	Zechstein Group	1982
Gwen-1/Q-1X	5604/29-02.		Gwen	4494	Rotliegende Group	1973
Iris-1	**5604/30-01.**		**Iris**	**4645**	**Jurassic Units**	**1985**

Dutch Wells:		Field:		Total depth (m):	TD Group Formations or Geological Age	Completion Year
F2-5		**Hanze**		**1695**	**Zechstein Group**	**1996**
F3-3				3917	Jurassic Units	1974
F3-6				**3700**	**Jurassic Units**	**1978**
F9-1				1585	Zechstein Group	1971

Table 3.1: Shows the wells used during this thesis. The highlighted red wells are considered for the petroleum system analysis.

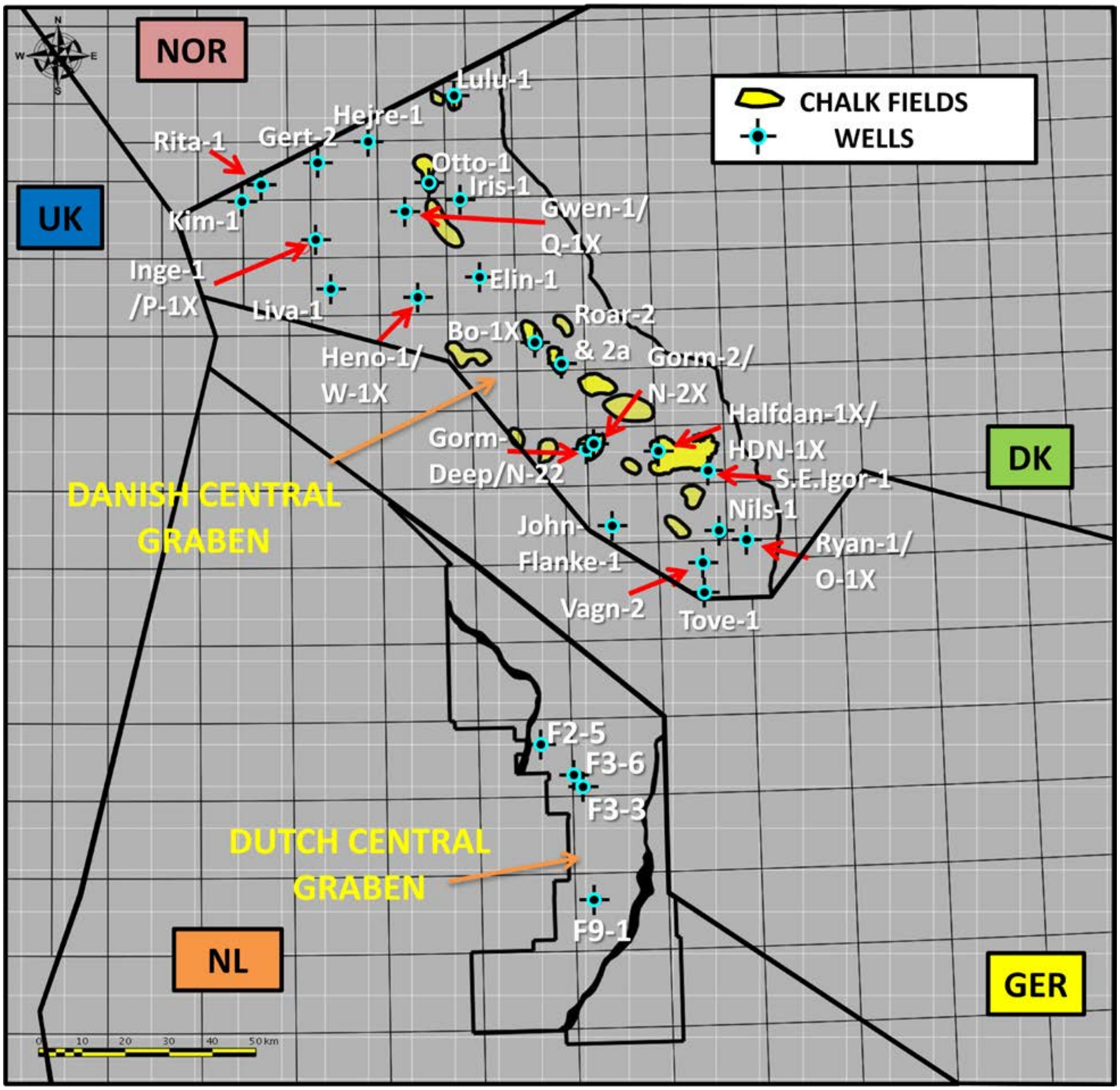


Figure 3.3.1: Map showing the location of the wells from Table 3.1 (SISMAGE).

3.4 Methodology

The general workflow used in this thesis is shown in Figure 3.4.1.

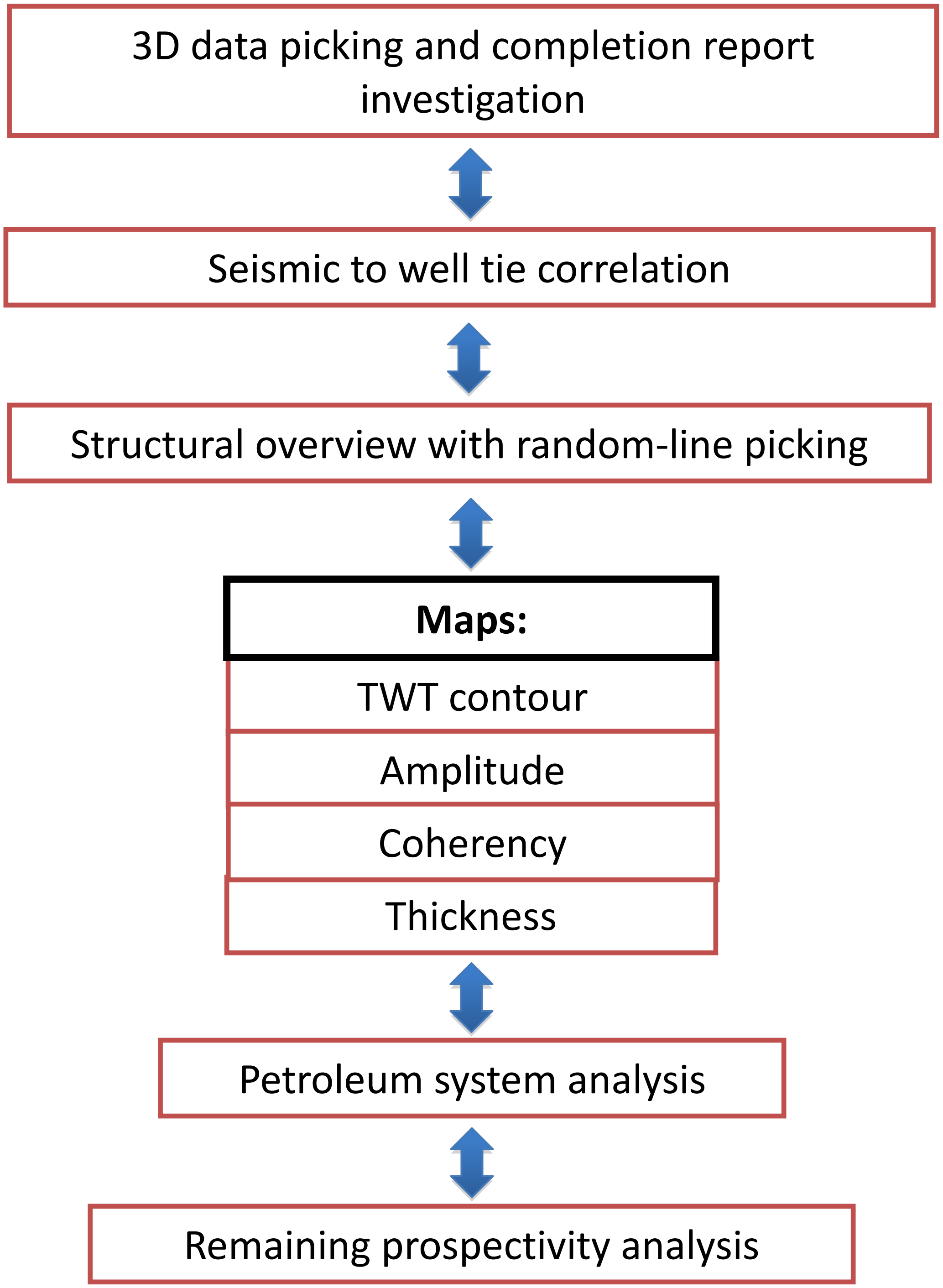


Figure 3.4.1: An overview of the general workflow used in this thesis.

3.4.1 3D data picking and completion report investigation

3D-data picking of the three horizons, Top & Base Chalk and the BCU has been performed on a detailed scale within the **Danish** Central Graben. (See locations of the Danish and Dutch Central Grabens in Figure 3.2.1). This has not been done in the **Dutch** Central Graben, since previous interpretations of the senior geophysicists, Philip Straw, were already present here. The same is true for the northern-part of the Danish Central Graben, close to the Norwegian border within the Siri Trend (See Figure 5.2.1). During the picking, completion reports with their composite logs were used to help with the interpretation of the horizons. Some of these logs were directly correlated from depth to two-way-travel-time (TWT) and could be used to find the right markers on the seismic, while the ones without this correlation were used to see the general thickness of the chalk and Lower Cretaceous layers.

The picking was performed in order to get an understanding of how the chalk layer and the Lower Cretaceous layer varied throughout the Central Graben. With this, one could get a feel for the area and notice how the different structural elements have affected these horizons. While interpreting, a focus on different DHI´s, such as bright spots, dims spots, flat spots and phase reversals was always kept at the back of my mind. This has helped me to recognize the DHI’s of the already producing HC fields and to look for remaining new prospects. The horizon picking has been used later on within the random-line picking and to generate different kinds of maps.

A couple of Tertiary markers where also picked on a larger scale within the Danish Central Graben. This was done in order to create a map of the gas anomalies on top of the various producing fields throughout the two grabens and to see if some remaining gas anomalies were still undrilled. In SISMAGE it is possible to pull out the strong amplitudes between two layers and since the gas anomalies are seen as strong amplitudes a map of this can be generated.

3.4.2 Seismic to well tie correlation

When working with 3D seismic in SISMAGE, it is possible to connect the wells of interest directly, which is a great advantage. However, the number of wells available for doing this is scarce. At the beginning of this thesis some wells were available in the NW part of the Danish Central Graben, but not in the main part of the graben. There has therefore been an on-going process during this semester for buying the necessary logs within SISMAGE from the GEUS webpage. Before these wells were bought, I made a list of some wells on which I wanted to look more closely. These wells where chosen, based on their location and depth and can be seen in Table 3.1. In the end I received three wells from my list, which are considered for well calibration (See chapter 6).

The study of wells was performed with the purpose of controlling the seismic interpretations of the horizons, by doing a seismic to well tie correlation. The chosen wells are all positioned at various types of producing chalk reservoirs, where differences like the thickness of chalk and the structural location are considered. Some of these reservoirs are therefore located on the top or flanks of salt diapirs, which made the tracing of the three main reflectors difficult, since the seismic data is of varying quality here. The other wells are located at more salt-free areas and vary in depth. At the deeper ones that go all the way into the Jurassic layers, I have tried to look for the source rocks that have been responsible for the HC generation within the different fields. However, to correlate this to the seismic is difficult, since the Kimmerigde Clay reflector is not easily recognized in the seismic. The Posidonia Shale reflector has on the other hand a more distinct character and proved to be easier to recognize in the Dutch Central Graben (See chapter 4).

The seismic to well calibration that was performed, provides us with a consistent picture of the subsurface. It is based on calibrating the seismic response observed in the seismic data with the response we expect based on the observations in wells. The main procedure when calibrating is done by computing a synthetic trace by using a simple convolution between a wavelet and the reflectivity series. The reflectivity series are computed by using Zoepprits equations on the acoustic well logs (Landrø, 2011). I.e. one ties the seismic data that provides a good overall picture of a large subsurface area to well data, which delivers a detailed and quantitative picture of the subsurface at a single location, in order to obtain a detailed quantitative picture of an areal subsurface (pdgm.com).

3.4.3 Structural overview with random-line picking

After the seismic interpretation of the horizons and their correlation with the wells, several random-lines were picked going across the Danish and Dutch Central Graben. The lines were picked going in either a SW-NE or a SE-NW direction across the two grabens (Figure 4.1). This was done in order to get a seismic perspective of the general structures that are present in the two grabens and to get a small taste of what kind of structures that usually provide the petroleum plays.

3.4.4 Maps

A set of TWT contour-, coherency- and amplitude maps were generated from the 3D picking for each of the three main horizons, Top & Base Chalk and the BCU. Afterwards two thickness maps were generated for the main chalk layer and the Lower Cretaceous sediments. This was done mainly for the Danish Central Graben, while already generated maps were used for the Dutch Central Graben.

By interpolating the spacing area in between the picks for each horizon, one can make TWT contour maps. These maps show how the horizons change in depth across the two grabens and where various structures, such as highs, grabens, basins and salt diapirs are located.

The coherency map makes use of the seismic post-stack attribute that calculates the localized waveform similarity in both in-line and cross-line directions throughout the 3D seismic data. Since the seismic data are generally binned into a regular grid, the continuity between seismic traces in a specified window along a picked horizon is measured and the 3D seismic coherency is obtained (Bahorich & Farmer, 1995). Faults, stratigraphic boundaries, channels or other discontinuous features that result in a sharp discontinuity in the local trace-to-trace coherence, will hereby afford the viewer the opportunity to see these structural and stratigraphic changes more clearly (Bahorich & Farmer, 1995).

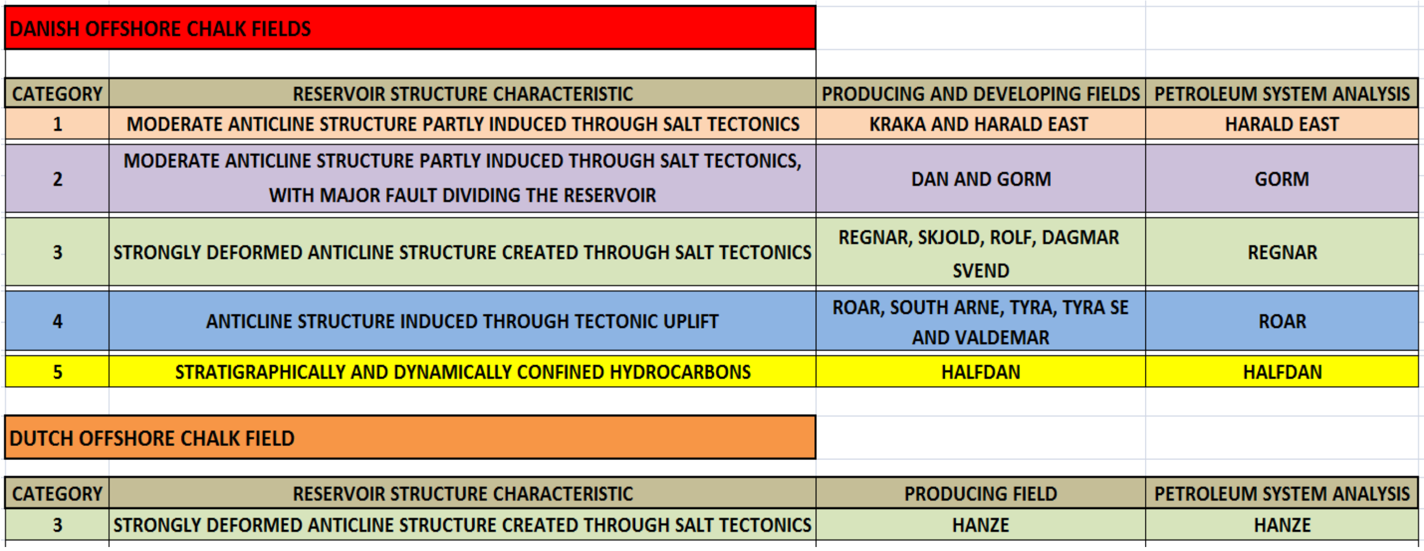
The amplitude map makes use of the post-stack attribute that computes the arithmetic mean of the amplitudes of a trace within a specified window. In other words it shows the change in acoustic impedance between two layers in the form of amplitudes on the seismic (petrowiki.org). Since the change in porosity and/or fluid saturation has a strong effect on the acoustic impedance, an amplitude map is often found to correlate strongly with these changes. Such maps are therefore seen as useful tools to identify HC bright spots at the various horizons. However, other non-HC changes in the lithology can result in large amplitude reflections misleading the interpretation (petrowiki.org)

The thickness map calculates how the TWT between two layers varies throughout a specified area. In other words it subtracts the TWT of each point within the upper TWT contour map from the lower TWT contour map. In this way an understanding of how the thickness varies throughout the two grabens is obtained and areas where the layer is not present are noted.

3.4.5 Petroleum system analysis

A petroleum system analysis of the chalk discoveries found in the Danish and Dutch Central Graben was done after the maps were generated. I have divided the chalk discoveries in five categories based on the structural characteristic of the reservoir (See Table 3.2). One reservoir in each category is therefore considered for a detailed petroleum system analysis and they can be seen in the table below. In addition I have included the only producing offshore chalk discovery in the Dutch Central Graben and I have provided the post mortem of some dry wells corresponding to similar petroleum plays as the ones described in the five categories, but they do not represent any discovery of economical value.

The analysis is build up with a general introduction and a geological setting that describes how the petroleum system is formed. Then a petroleum system cross-section will be given, that shows the migration pathways and the spatial relation of the active source rock to reservoir rocks (Magoon & Beaumont, 1999). Some thoughts of mine are included here, based on how the different elements and processes of the petroleum system make the fields work and if other possibilities reveal themselves (Magoon & Beaumont, 1999).



DANISH OFFSHORE CHALK FIELDS

CATEGORY	RESERVOIR STRUCTURE CHARACTERISTIC	PRODUCING AND DEVELOPING FIELDS	PETROLEUM SYSTEM ANALYSIS
1	MODERATE ANTICLINE STRUCTURE PARTLY INDUCED THROUGH SALT TECTONICS	KRAKA AND HARALD EAST	HARALD EAST
2	MODERATE ANTICLINE STRUCTURE PARTLY INDUCED THROUGH SALT TECTONICS, WITH MAJOR FAULT DIVIDING THE RESERVOIR	DAN AND GORM	GORM
3	STRONGLY DEFORMED ANTICLINE STRUCTURE CREATED THROUGH SALT TECTONICS	REGNAR, SKJOLD, ROLF, DAGMAR SVEND	REGNAR
4	ANTICLINE STRUCTURE INDUCED THROUGH TECTONIC UPLIFT	ROAR, SOUTH ARNE, TYRA, TYRA SE AND VALDEMAR	ROAR
5	STRATIGRAPHICALLY AND DYNAMICALLY CONFINED HYDROCARBONS	HALFDAN	HALFDAN

DUTCH OFFSHORE CHALK FIELD

CATEGORY	RESERVOIR STRUCTURE CHARACTERISTIC	PRODUCING FIELD	PETROLEUM SYSTEM ANALYSIS
3	STRONGLY DEFORMED ANTICLINE STRUCTURE CREATED THROUGH SALT TECTONICS	HANZE	HANZE

Table 3.2: Gives a selection of the various chalk fields within the Danish and Dutch Central Graben that are either under production or development. They are divided into five categories based on their structural or stratigraphic trapping characteristic.

3.4.6 Remaining prospectivity analysis

After the petroleum system analysis, a remaining prospectivity analysis is mainly done on the Danish Central Graben. Results from the previous analysis are here used to look for similar areas that have not been drilled and to look for other regions where the same characteristics can be applied. This opens the possibility to think outside the box.

4. Structural overview

An overview of the main structural elements present in the Danish and Dutch Central Graben can be seen in Figure 4.1. A quick look at the figure tells us that the Danish Central Graben consists of a main salt dome province with salt diapirs and pillows in the SE part, while it contains a lot of highs, basins, grabens, ridges and plateaus in the NW part. The NW area of the graben is therefore covered by a lot more faults that define the boundaries between the various highs and lows.

The Dutch Central Graben can on the other hand be viewed in a similar way as the Tail End Graben on the Danish Sector, since it represent a common subsidence between two faults in the crust. The graben is at some places affected by salt diapirs that vary drastically in size and act as the highs within the structure.

Both grabens have defined boundaries that are represented by a major fault at the W to NW side of the grabens. This fault is known as the Coffee Soil Fault and marks the transition from the Danish Central Graben to the Ringkøbing-Fyn-High at the Danish sector, while the graben goes over into the Schill Grund High at the Dutch sector. On the other side of the grabens, the Mid North Sea High marks the boundary at the Danish sector, whereas the Step Graben marks the boundary at the Dutch Sector before it also goes over into the Mid North Sea High.

From Figure 4.1 one can see various red lines throughout the grabens, which correspond to the picked random-lines seen as seismic cross-section in figures 4.2 to 4.10. Some wells are marked onto these sections and most of them have a corresponding composite well log that can be seen in the figures in appendix A. A rough interpretation of the well logs is given here, which has helped me with interpreting the three main horizons.

One last thing from Figure 4.1 is that the available 3D seismic data does not cover the whole of the Dutch Central Graben. The project work is therefore mostly based on the Danish Central Graben, with minor inputs from the Dutch sector.

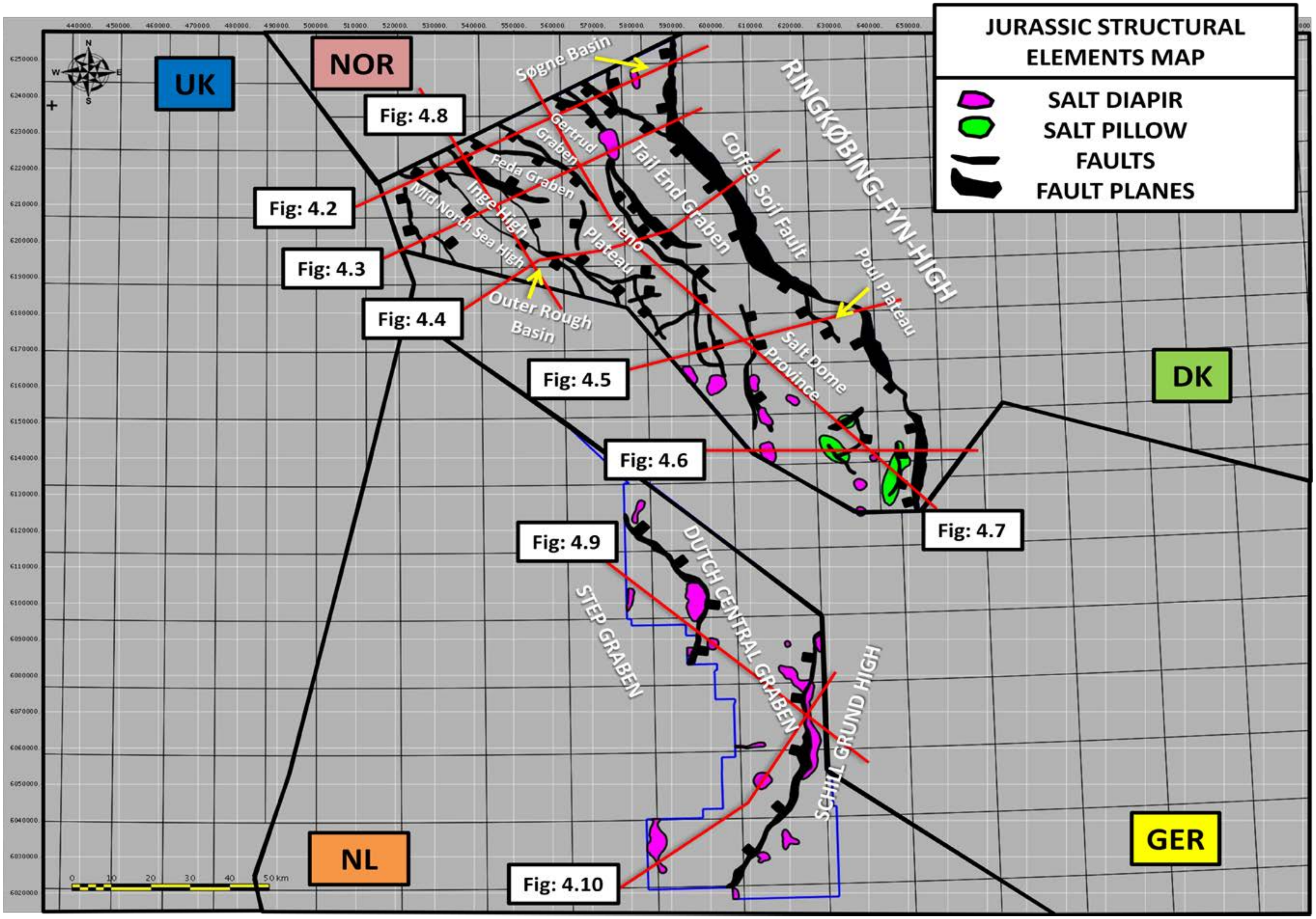


Figure 4.1: Shows an overview of the Jurassic structural elements present within the Danish and Dutch Central Graben. The different red lines correspond to random-lines that are seen as seismic cross-sections within the figures 4.2-4.10 (SISMAGE).

SW-NE random-line nr. 1 & 2 across the Danish Central Graben

The first two random-lines viewed in figures 4.2 and 4.3 crosses through the upper NW part of the Danish Central Graben (Figure 4.1). From the figures, one can see that the seismic moves through several highs and lows and give the overall extend of the graben, since both the Mid North Sea High and Coffee Soil Fault are present on these sections. Because of the many highs and lows, many faults are present in the seismic; however, most of them only affect the BCU and Base Chalk horizons.

The color-code for the interpreted horizons can be seen on the right hand side in the figures and represent the BCU in yellow through Base Chalk in light blue, Top Chalk in red, Top Hordaland in purple and the two Miocene markers in bluish-green and yellow. The interpretation of these horizons started with the Top Chalk marker, which might seem strange since one usually first pick the sea floor horizon to confirm which color in the seismic represents the positive reflector. However, when starting to pick I was warned to neglect trusting the sea floor horizon, since the water depth is so shallow in this area that the horizon becomes distorted (See Figure 4.2)[2]. My Top Chalk was therefore picked as the first horizon. This was done with the help from an already picked Top Chalk from Philip Straw, which had picked the more northern part of the Danish Central Graben that crosses into the Norwegian North Sea sector. Help from completion reports and the wells that were available in SISMAGE confirmed this picking further south into the graben.

The next two horizons that were picked were the BCU and Base Chalk. When picking the Base Chalk it was important that a strong reflector was picked, which had opposite amplitude polarity compared to the Top Chalk horizon. Chalk as a rock is considered to have generally high acoustic impedance, meaning that a positive response is expected when moving into the chalk. The Base Chalk horizon should therefore have an opposite response since it moves out of the chalk into the Lower Cretaceous sediments. This made also sense in the seismic since the Base Chalk reflector was most clearly and continuous in the opposite polarity.

The BCU was picked together with the Base Chalk and it is therefore important to notice that where the Base Chalk horizon onlaps onto the BCU in the seismic, the Base Chalk is not eroded

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[2] Discussion with Philip Straw, Senior Geophysicist at TOTAL E&P Norway AS.

away, but instead acts as the BCU. The BCU is therefore also picked with the opposite amplitude polarity than Top Chalk, since it in most cases acts as the Base Chalk horizon.

The remaining horizons are all picked as Tertiary markers and function only as to creating a map of the gas anomalies throughout the Central Graben. However, a general description of them should be in place. The purple horizon represents the Top Hordaland marker and marks the transition from the Hordaland Group to the Nordland Group. It is a strong continuous reflector throughout the whole area and has the same amplitude polarity as the Base Chalk and BCU. The following Miocene 1, 2 and 3 horizons represent markers within the Nordland Group. The Miocene 2 marker is found further to the SE in between Miocene 1 and 3, where it downlaps onto Miocene 3 before getting this far north (See Figure 4.7). As seen from Figure 4.2 the Miocene 1 marker also downlaps onto another horizon. Miocene 1 has the same polarity as the Top Chalk horizon, whereas Miocene 2 and 3 have the same polarity as the Base Chalk and BCU.

One salt diapir close to the coffee soil fault can be seen in both figures, however, they don´t represent the same one. The diapirs mark the point on the map where halokinesis has affected the area again and both represent similar structures that have provided a petroleum play. They have acted as the main structural event that has caused the overlaying chalk to deform and create an anticlinal four-way dip closure for the HCs. Both the Lulu-1 and Otto-1 wells are therefore HC discoveries belonging to the Harald East and Svend fields (See figure 4.2 and 4.3, and chapter 6 for more information on Harald East). One difference between the two salt diapirs can be noted in how much they have pierced through the overlaying layers. The one at the Otto-1 well has gone a lot further and led to more fracturing of the overlaying chalk, which again has led to more favourable production properties (ens.dk(2)). Similar structures as these two salt diapirs have provided the most discovered petroleum plays within the Danish Central Graben.

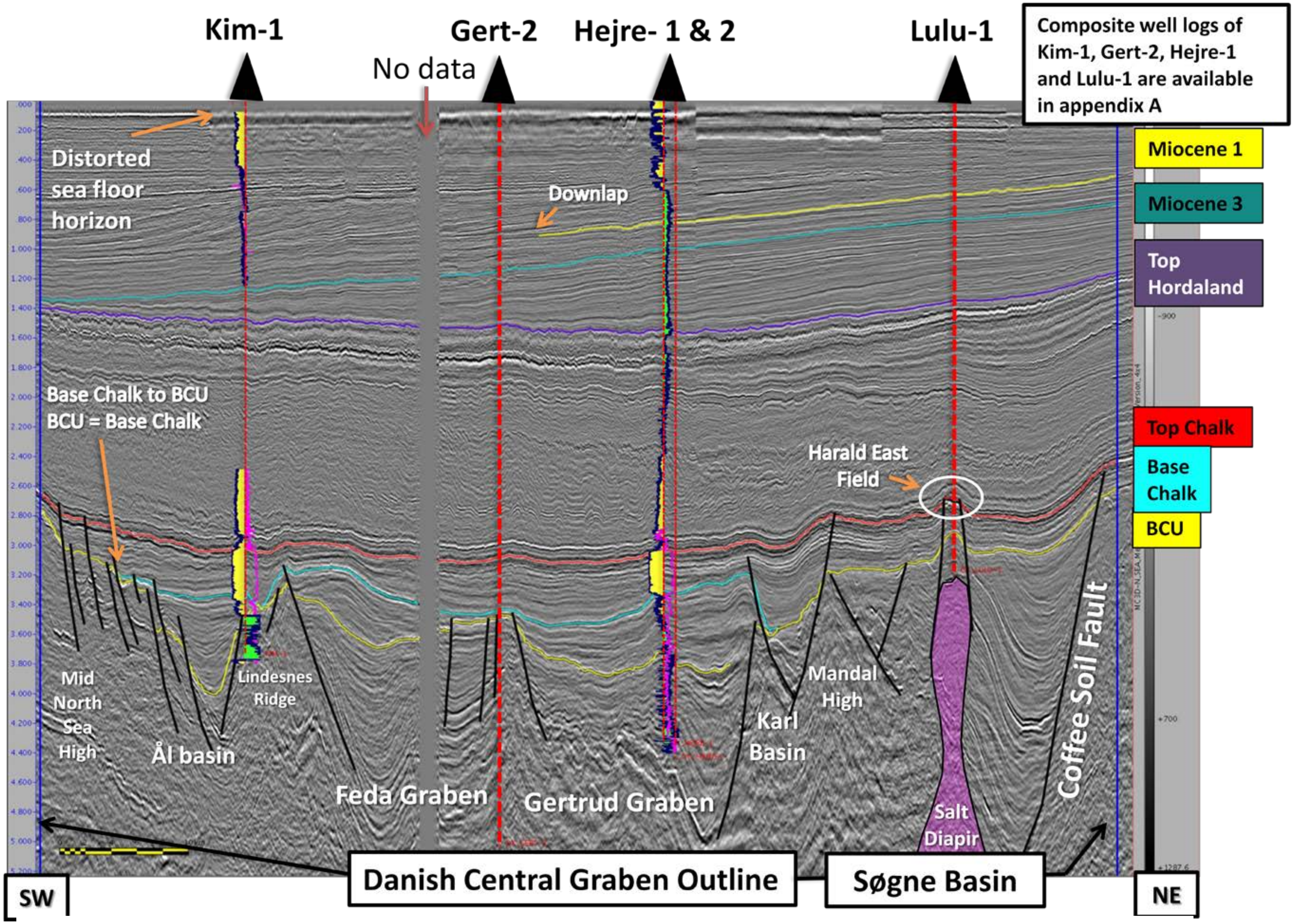

Figure 4.2: Seismic cross-section of random-line nr 1, shown in Figure 4.1 (SISMAGE).

The two sections also go through several more wells, where two of them in Figure 4.2 have the Gamma Ray (GR) log (yellow) and velocity log (violet) available in SISMAGE. By checking these readings there can be seen a clear trend in the GR and velocity when following it down from the Top Chalk marker for both wells. The first thing one notices is the increase in velocity when entering the chalk and the vice versa effect when leaving it. As mentioned before, this looks reasonable since the chalk is considered to have generally high acoustic impedance. The other thing that pops out is the decrease in GR when entering the chalk and the increase when leaving it. Since the clay content has a proportional effect on the GR log because of its radioactive content, this could mean that the chalk in this area has quite low clay content and can be considered as being pretty clean (slb.com). With this well information, two characteristics have shown themselves in helping the interpretation of the chalk layer other than that all three main reflectors are quite continuously throughout the seismic.

At the other wells the completion reports were used to help the interpretation of the three main reflectors. As an example the Lulu-1 composite well log seen as Figure B in appendix A, has helped by giving information about the Paleocene Shales on top of the chalk, the presence of the source rock within the Kimmeridge Clay Formation down in the Jurassic layers and that there is no Lower Cretaceous layers present in the well.

Another example is given from the composite well log from well Inge-1, which marks a very thin Lower Cretaceous Shale layer (Figure C in appendix A). In other words it is practically gone, which is the case as seen in the seismic in Figure 4.3.

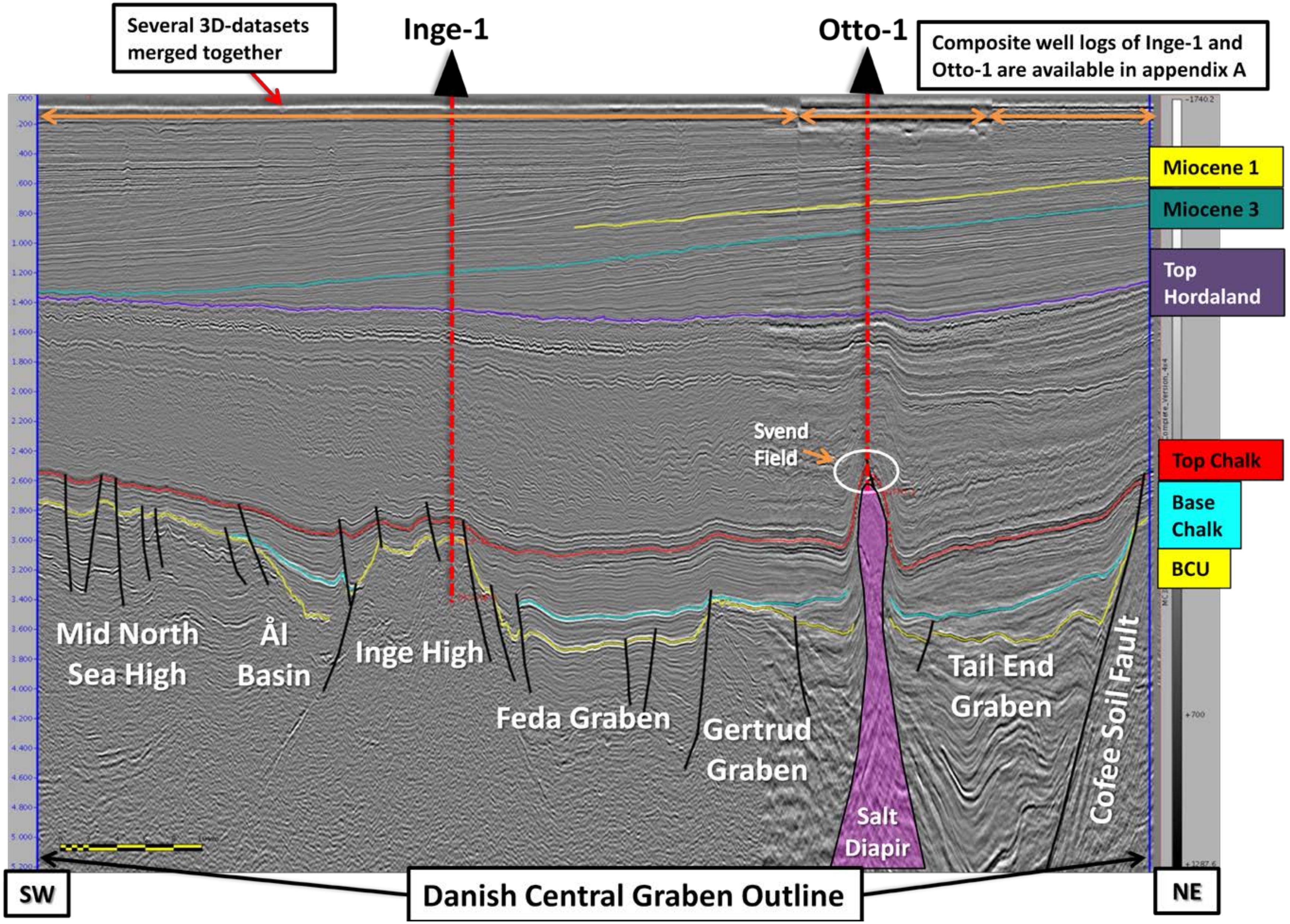

Figure 4.3: Seismic cross-section of random-line nr 2, shown in Figure 4.1 (SISMAGE)

SW-NE random-line nr. 3 & 4 across the Danish Central Graben

The third and fourth random-lines can be seen in figures 4.4 and 4.5 and show the seismic cross-sections of the Danish Central Graben further to the SE. The one in Figure 4.4 gives quite a similar impression as the two previous ones with a lot faults, highs and lows. The difference lies in the absence of the salt diapir and the various structural elements that are shown. For example in this section a good view of the Tail End Graben is provided, in addition to the Outer Rough Basin and the Heno Plateau. One often sees that the Lower Cretaceous layers are absent on top of the highs and are present within the grabens. This makes sense since the grabens are less exposed to erosion than the highs, and provide extra accommodation space for the sediments.

The section in Figure 4.5 also gives a good view of the Tail End Graben and one can see the slightly tectonic uplift caused within the chalk layer. The line actually goes through a part of the Tyra Field, which is a HC field with an accumulation of free gas overlying an oil zone (ens.dk(2)). This tectonic uplift has caused the trapping mechanism for the HCs and characterizes the second group of petroleum plays that are commonly found within the Danish Central Graben. With a closer look one might notice a slight bright spot representing the gas, but it is very vague. As seen from Figure 4.1, both random-lines cross through the “Middle part” of the Danish Central Graben and no salt structures can be seen in this part. This could mean that the area has been undergoing salt withdrawal that commenced during the Triassic and continued to the Cretaceous (Erratt, 1993).

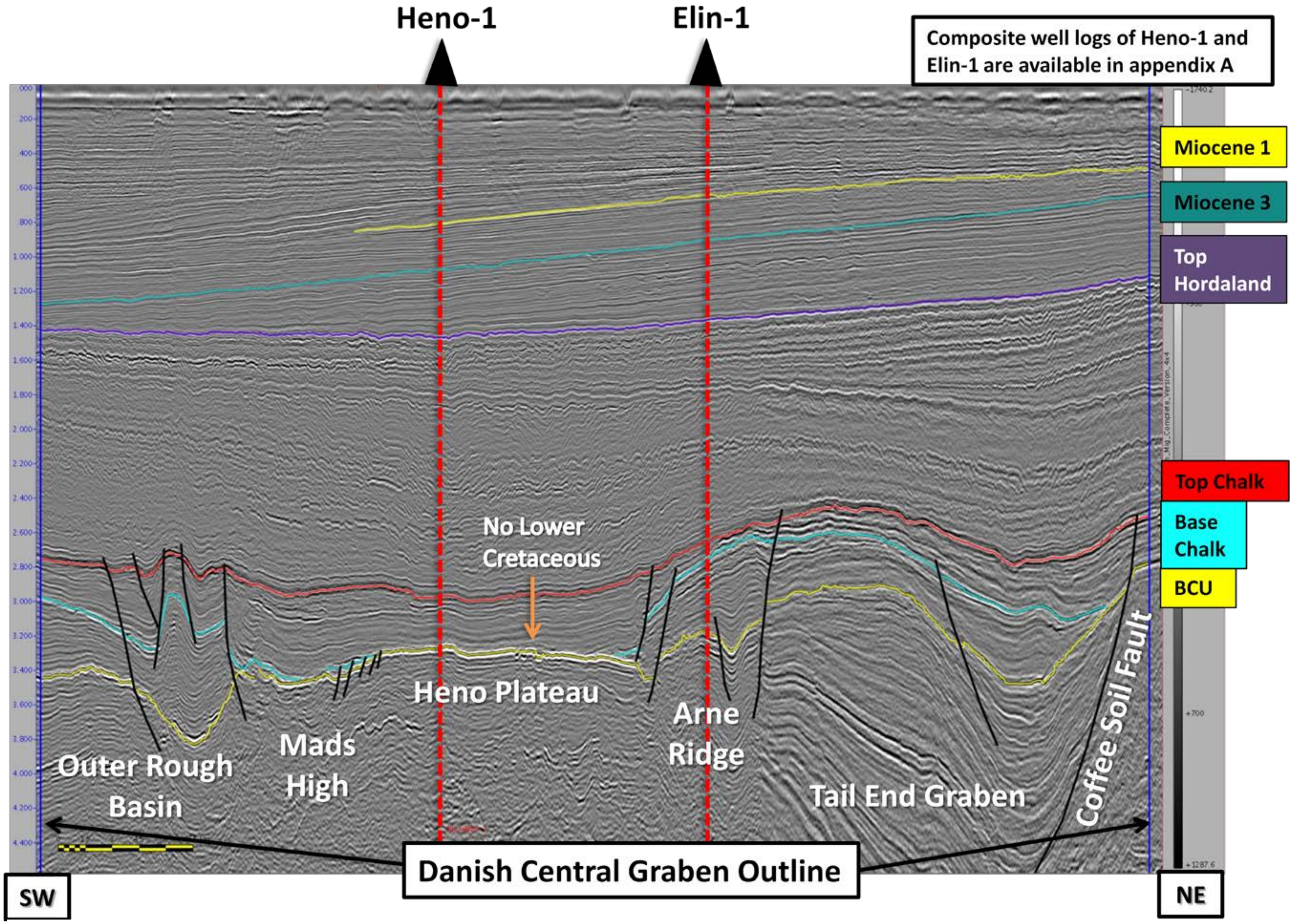

Figure 4.4: Seismic cross-section of random-line nr 3, shown in Figure 4.1 (SiSMAGE).

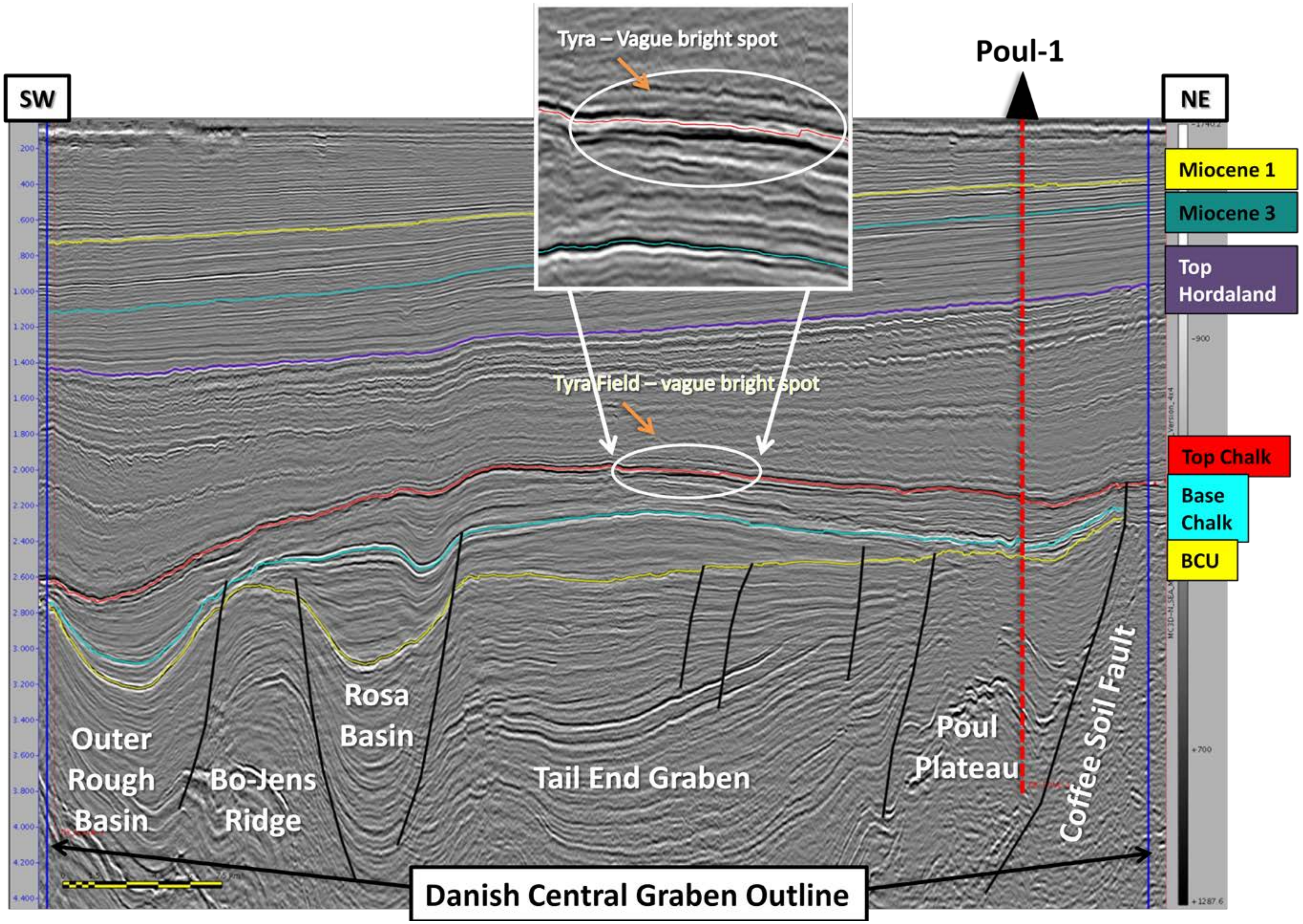

Figure 4.5: Seismic cross-section of random-line nr 4, shown in Figure 4.1 (SISMAGE).

SW-NE random-line nr. 5 across the Danish Central Graben

The fifth random-line in Figure 4.6 shows the seismic cross-section through the SE part of the Danish Central Graben. The line goes through the Salt Dome Province and gives a nice perspective of the different salt structures present here. The salt pillow in the middle has acted as the main structural event that has cause a structural trap further up within the chalk layers. This structural trap represents the Kraka Field, which is an oil field with a minor gas cap in the reservoir. With a closer look one might see that the horizon goes through a phase reversal on top of the field, which is caused by the gas that lowers the acoustic impedance within the chalk.

On top of the other two salt structures, no HC fields have been found other than a Tertiary oil discovery from John-Flanke-1 well at the flank of the salt diapir. However, because of the success rate of HC discoveries on top of salt structures one would of course take the other salt pillow into consideration. A theory could be that the HCs have migrated past the Coffee Soil Fault and have been captured somewhere on top of the Ringkøbing-Fyn high[3]. However, this is outside the scope of this thesis.

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[3] Discussions with my supervisor at TOTAL E&P Norway AS, Dominique Roy.

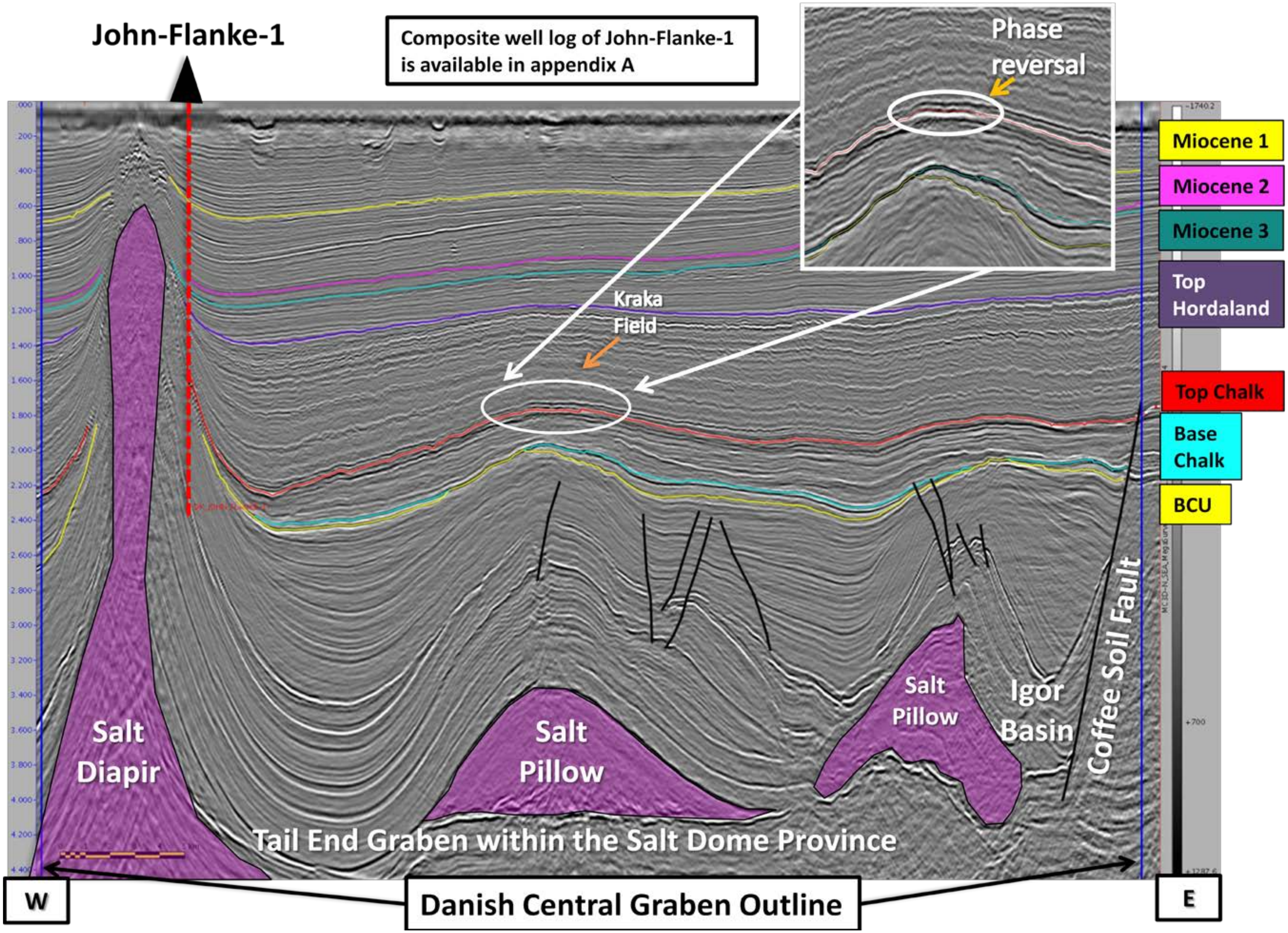


Figure 4.6: Seismic cross-section of random-line nr 5, shown in Figure 4.1 (SISMAGE).

SE-NW random-line nr. 6 & 7 across the Danish Central Graben

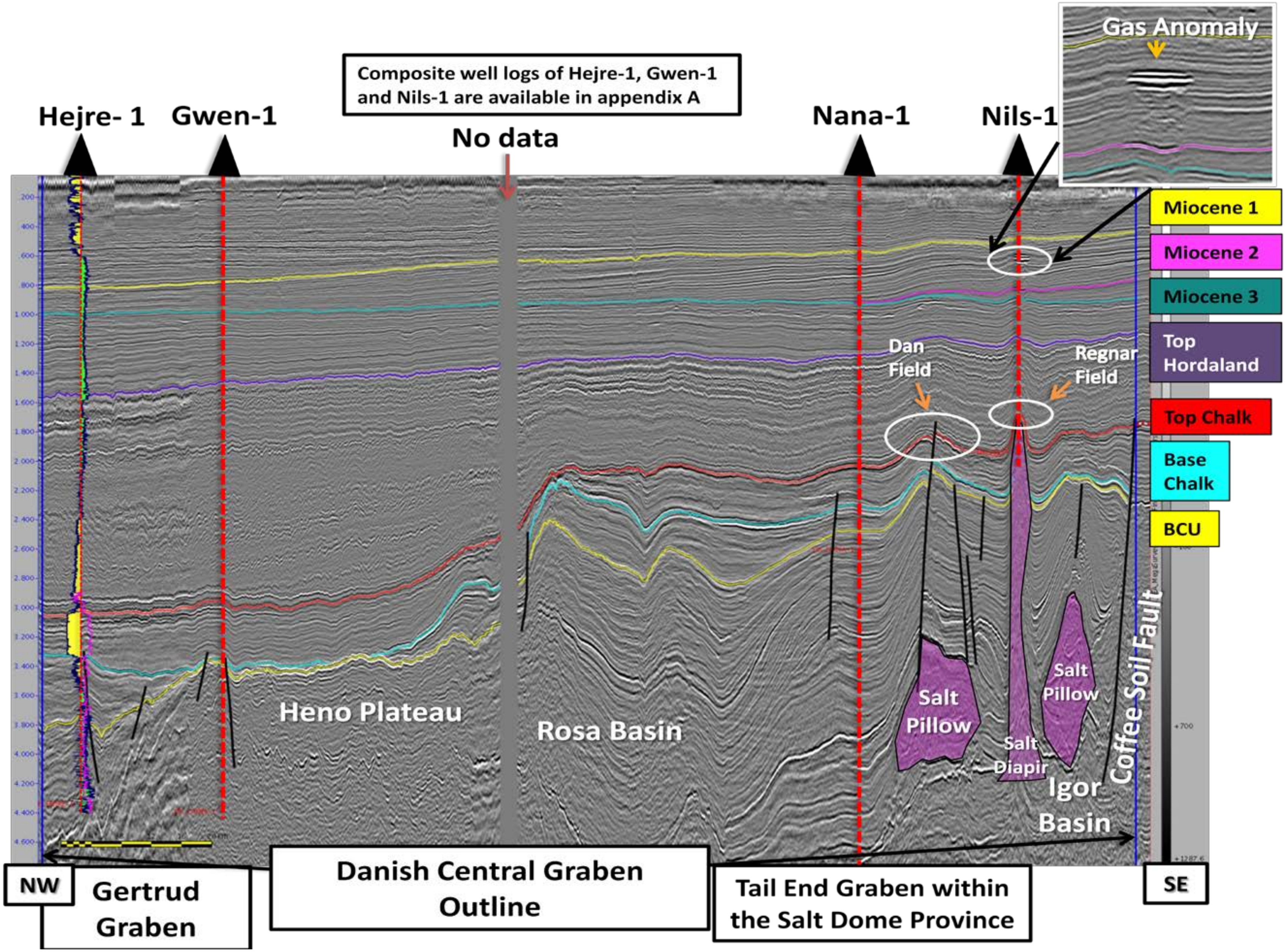
The sixth and seventh random-lines show the opposite direction (SE-NW) through the Danish Central Graben in comparison to the previous five lines (Figures 4.7 and 4.8). The difference between these two directions is that the previous five give a better view of the structural elements, since most of them are oriented in the opposite SE-NW direction. However, I wanted to also make some lines in the other direction to be able to include some other important structures that are better viewed in this way.

In Figure 4.7 one can see that the line moves through the salt dome province over into the Rosa Basin, Heno Plateau and the Gertrud Graben at the end. An interesting structure is where the three main reflectors are cut by a major fault, which represents the largest oil field, Dan on the Danish North Sea sector. The original anticline structure here is again a result of a salt pillow that has caused the uplift and provided a HC trap. The addition of the fault has provided both an easier migration way for the HCs and acts as an extra trapping mechanism for the HCs on both sides of the fault.

On top of the salt diapir the Regnar Field is located, which is a similar petroleum play to Harald East Field. The difference between them is marked by the larger degree of piercing of the salt diapir at the Regnar Field, so the anticline structure is more abrupt (See chapter 6 and Figure F in appendix A). Gas anomalies in the upper layers can be noticed by looking closely at the seismic.

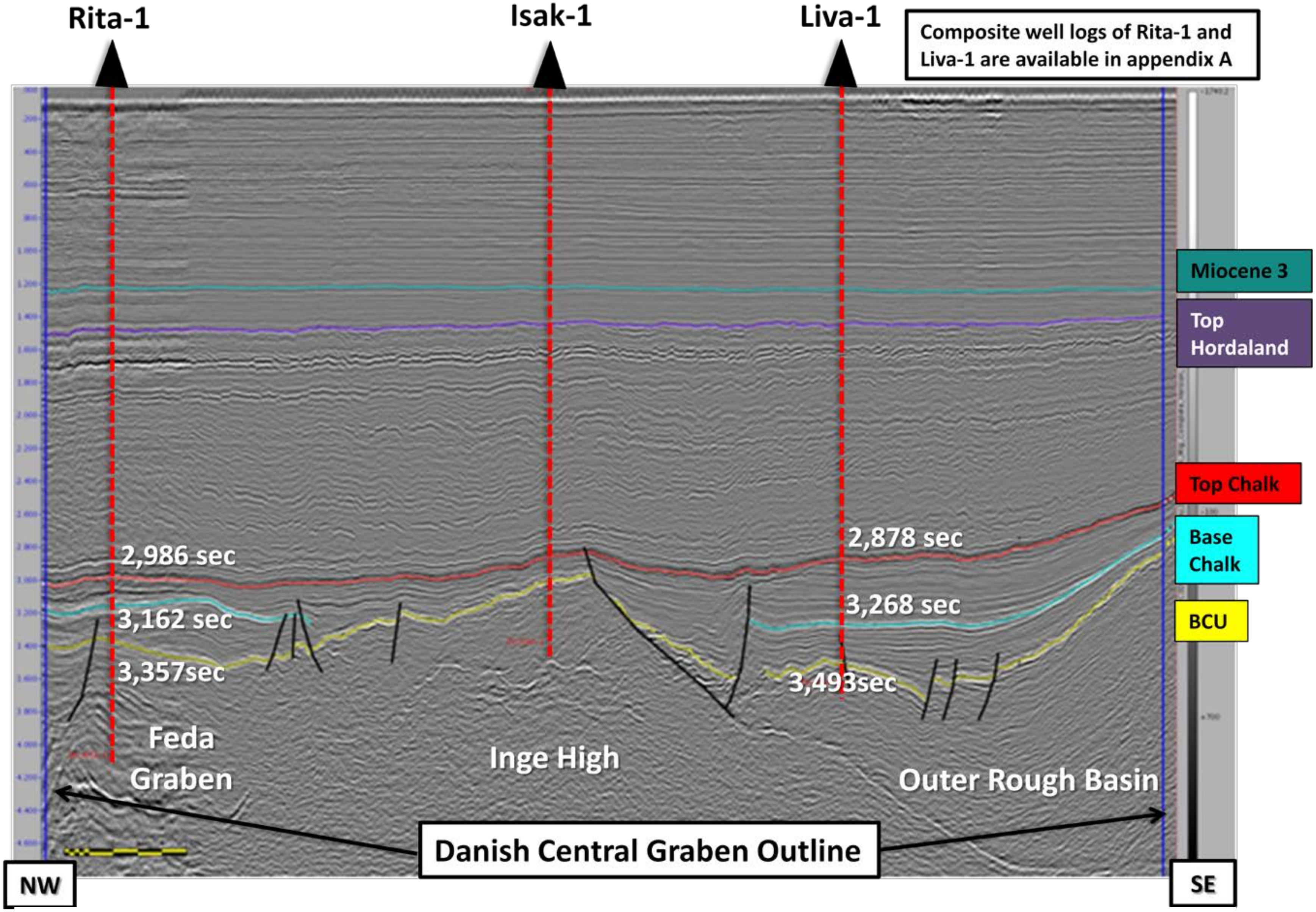
The random-line in Figure 4.8 shows the transition from the Outer Rough Basin to the Inge High and at the end going over into the Feda Graben. The line does not show any HC fields despite the few wells within the section. This is something that can be taking into consideration, since the Inge High provides a nice structural closure at the Top Chalk horizon, where HC migration can have occurred using the fault as a pathway.

Both Rita-1 and Liva-1 had composite well logs that were directly correlated from depth to TWT and were used to find the right markers on the seismic. The logs can be seen in figure F and G in appendix A, where the depth is directly correlated to the time on the seismic.



Composite well logs of Hejre-1, Gwen-1 and Nils-1 are available in appendix A

Figure 4.7: Seismic cross-section of random-line nr 6, shown in Figure 4.1 (SISMAGE).



Composite well logs of Rita-1 and Liva-1 are available in appendix A

Figure 4.8: Seismic cross-section of random-line nr 7, shown in Figure 4.1 (SISMAGE).

SE-NW and SW-NE random-line nr. 8 & 9 across the Dutch Central Graben

The figures 4.9 and 4.10 show two seismic cross-sections throughout the Dutch Central Graben. The first one in Figure 4.9 gives an overview of the northern part of the graben with a SE to NW direction. The interesting thing one can notice here is the location of the Hanze Field on top of the left salt diapir. Again the field is a result of salt tectonics that has created an anticlinal four-way dip closure on top of the structure and it resembles the Regnar Field on the Danish North Sea sector. An additional point that needs to be mentioned is the presence of the source rocks, marked by the green Posidonia Shales horizon. As mentioned earlier in chapter 3, this horizon has a distinct reflector shape and can be recognized fairly easily. However, in the section below it was not so straight forward and I managed to do it by looking at previously interpreted Posidonia Shales markers and completion reports from well F3-6 and F3-3 shown as H in appendix A. The section gives in general a great example of the standard petroleum play mostly found in the Danish Central Graben. It has the presence of a source rock, with available HC migration pathways that are provided by the faults, which in turn are a result of the piercing salt diapir. A trap is formed in the overlaying reservoir rock chalk and a seal is given by the shales on top of the chalk layer (See Figure G in appendix A). In addition we have a DHI in the form of a gas anomaly further up within the Tertiary layers.

Another interesting point is the very thin chalk layer seen in the middle part of the graben. As mentioned in sub-chapter 2.4.4, the chalk group must have been above sea-level during deposition and afterwards, which has led to a large scale erosion of the better part of the group. In Figure 4.10 the entire chalk layer is in fact totally absent within the middle part.

The cross-section in Figure 4.10 shows the southern part of the graben in a SW to NE direction. It gives a quite similar view as the one in Figure 4.9, with salt diapirs, thin chalk layers and a possible petroleum play on top of the salt diapir in the middle of the section. The play resembles the Hanze Field from almost every aspect, but the well F9-1 (Not shown on the section) that was drilled on top of this structural closure found that the chalk section was mostly argillaceous and water saturated. A minor gas indication and isolated spots of dead oil were observed at the top of the Chalk, but electrical logs proved the section to be water bearing (Figure I in appendix A)

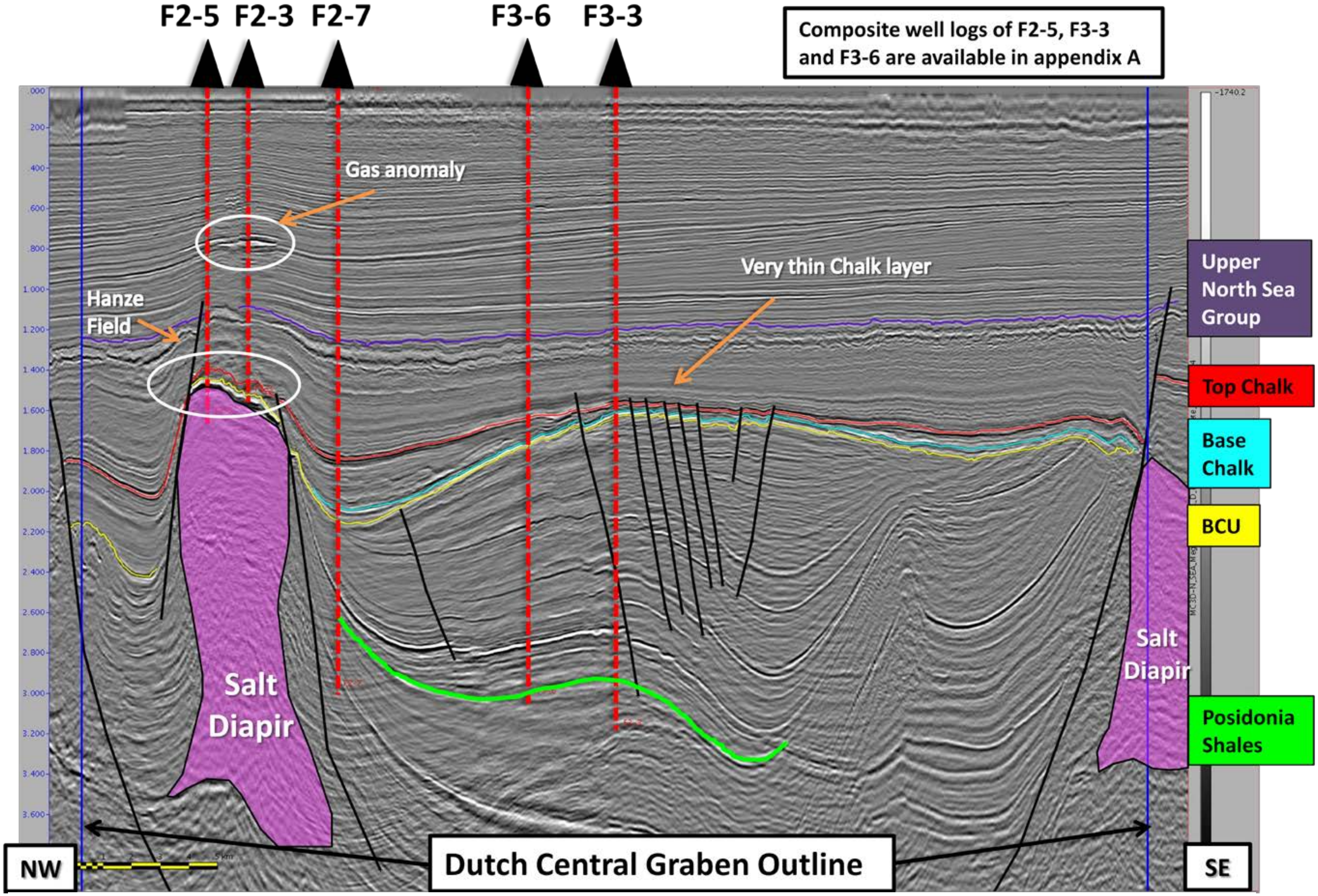


Figure 4.9: Seismic cross-section of random-line nr 8 shown in Figure 4.1 (SISMAGE).

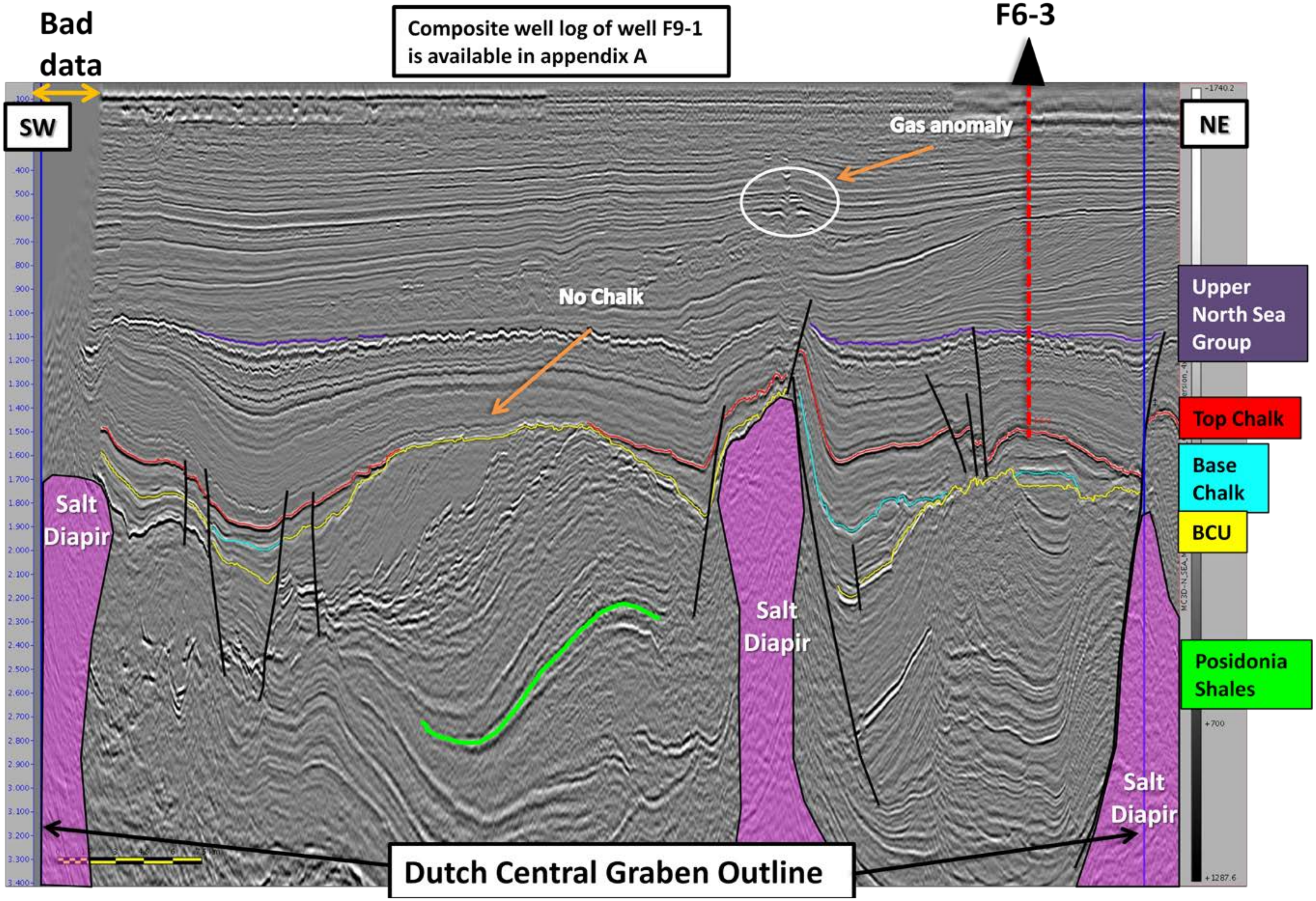


Figure 4.10: Seismic cross-section of random-line nr 9, shown in Figure 4.1 (SISMGAE)

5. Maps

5.1 TWT-contour maps in the Danish Central Graben

The TWT contour map for the interpreted Top Chalk, Base Chalk and BCU horizons can be seen in the figures 5.1.1 to 5.1.3. The Top Chalk horizon marks the top of the Danian chalk, which is represented by the top of the Ekofisk Formation over the better part of the Danish Central Graben. The time scale of the map that represents the main depth of the horizon is found between 1800-3000 milli-seconds (ms).

When following the contours on the Top Chalk map, it is possible to locate several structural closures formed by the Top Chalk layer. Most of them are found as red dots with a black outline on top of salt structures. All of these structures have been drilled and the better part of them has led to HC discoveries. The other closures are seen as white dots with a black outline and are a result of tectonic uplift. This play has also proven itself to be successful in many cases.

The Base Chalk does on other hand not represent a distinct formation top throughout the Danish Central Graben, but marks the end of the chalk layer. This means that the Base Chalk is instead seen as the top of the Lower Cretaceous shales at some places and as the top of Jurassic shales or Zechstein salt at other places. The same counts for the BCU, which marks the transition from chalks or Lower Cretaceous sediments into the Jurassic shales or Zechstein salt in most cases. When going over into the Jurassic shales, it is often represented by the Farsund-, Mandal- or Kimmeridgian Clay formations that directly underlie the Cretaceous layers. The main depth of the Base Chalk horizon is found between 2000-3500 ms, whereas the BCU is found at a depth between 2100-3800 ms.

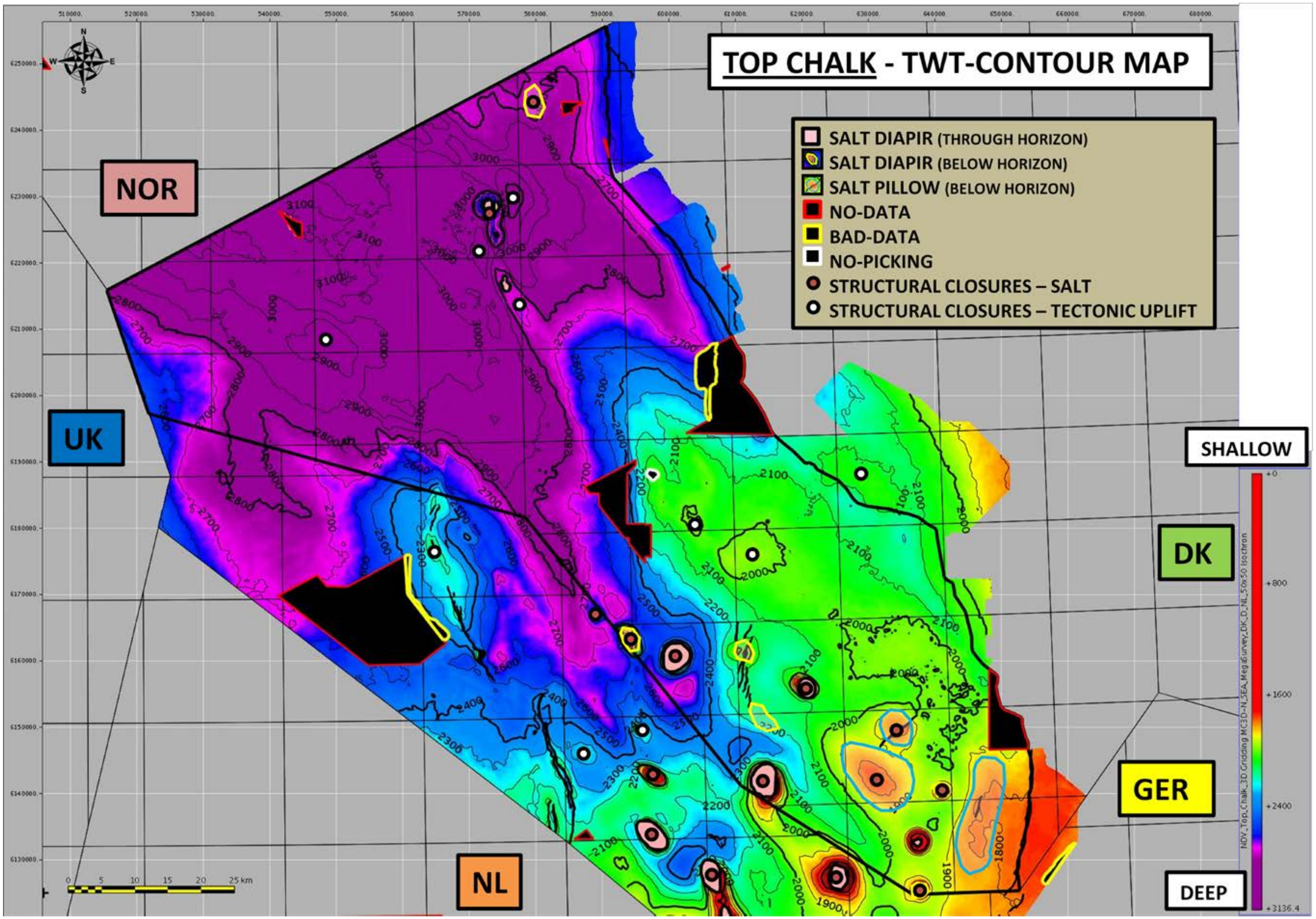


Figure 5.1.1: Top Chalk – TWT – contour map showing the elevation of the layer and the presence of the salt structures and structural closures within the Danish Central Graben (SISMAGE).

All three horizons show a general NW deepening within the graben, where the main structures that have drastically affected the elevation of the layer are the salt structures and the highs and grabens that define the Central Graben borders. By comparing the three maps it shows us that the main structural elements within the graben become more and more detailed when going to further depths. For example when looking at the NW part of the Top Chalk map in Figure 5.1.1, none of the many small highs and lows that are present here can be seen. This tells us that the upper Chalk layers are not really affected by them and that the chalk deposition has happened during a relatively quiet tectonic period, combined with intervals of transgression (See sub-chapter 2.2.2). However, when moving further down to the Base Chalk and BCU horizons, the structural elements become more visible and give a more detailed description of what the topography was like before the deposition of chalk and at the end of the Jurassic age.

The places where the horizons are not present are either marked as bad-data, no-data, no-picking or as areas where salt diapirs have pierced through the marker. However, at some places I have managed to follow the marker on top of the salt diapirs and pillows, which means that the marked salt diapirs seen as pink areas are not the only salt structures present in the graben. The other salt structures are also marked in the figure.

The red lines that form polygons throughout the Base Chalk map in Figure 5.1.2, define the areas where the Base Chalk horizon goes over into the BCU and acts as the marker between the Cretaceous and Jurassic age. I.e. there are no Lower Cretaceous sediments present here (See Figure 5.4.2).

As you can see, the German North Sea sector is shown only in the Top Chalk map in Figure 5.1.1. This is done, since the Top Chalk horizon was interpreted at the start of the semester, when I hadn’t really defined my area of interest yet. However, it would be a shame not to include it.

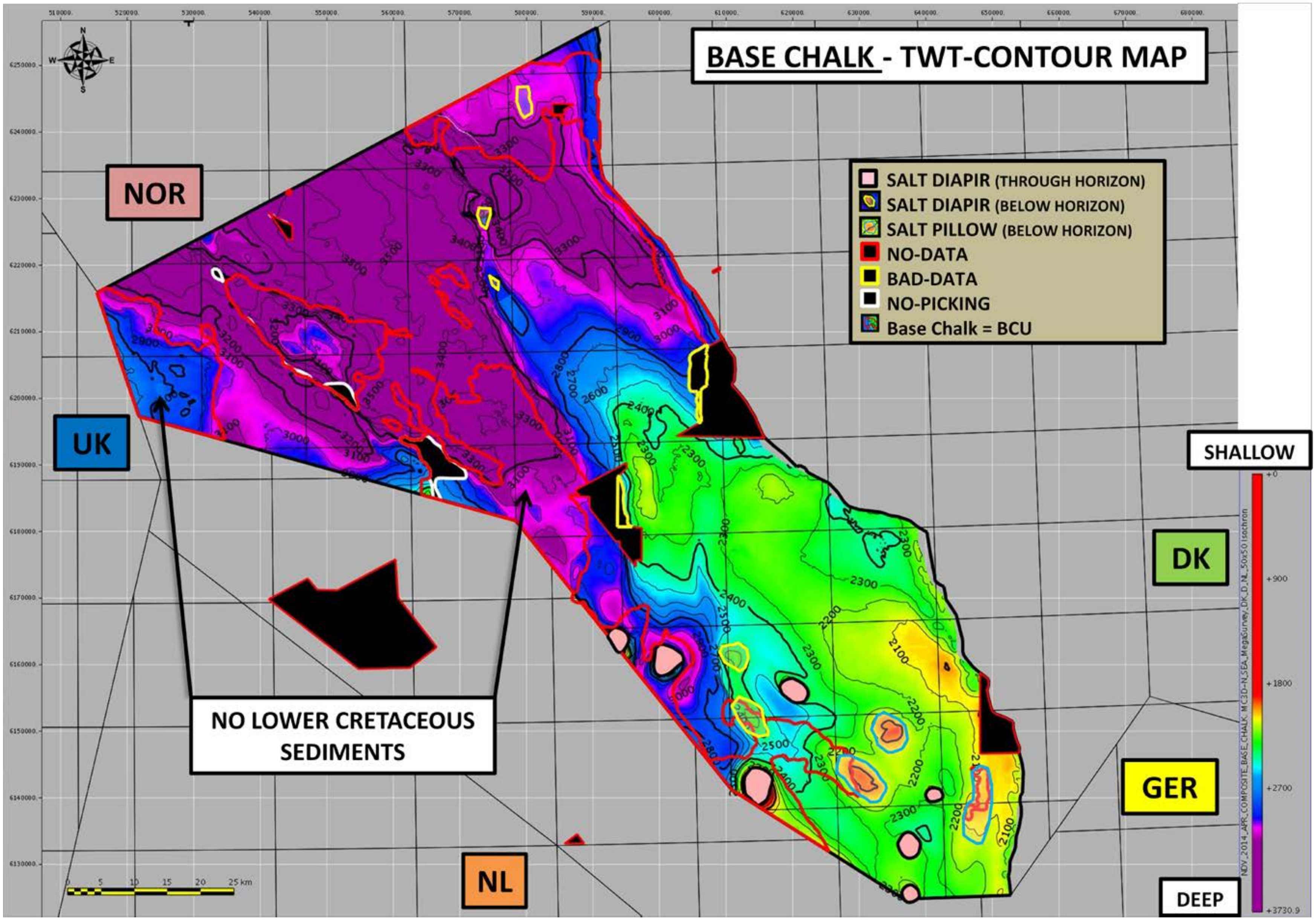


Figure 5.1.2: Base Chalk – TWT – contour map showing the elevation of the layer and the presence of the salt structures within the Danish Central Graben. The red polygons define the areas where the Base Chalk horizon acts as the BCU (SISMAGE).

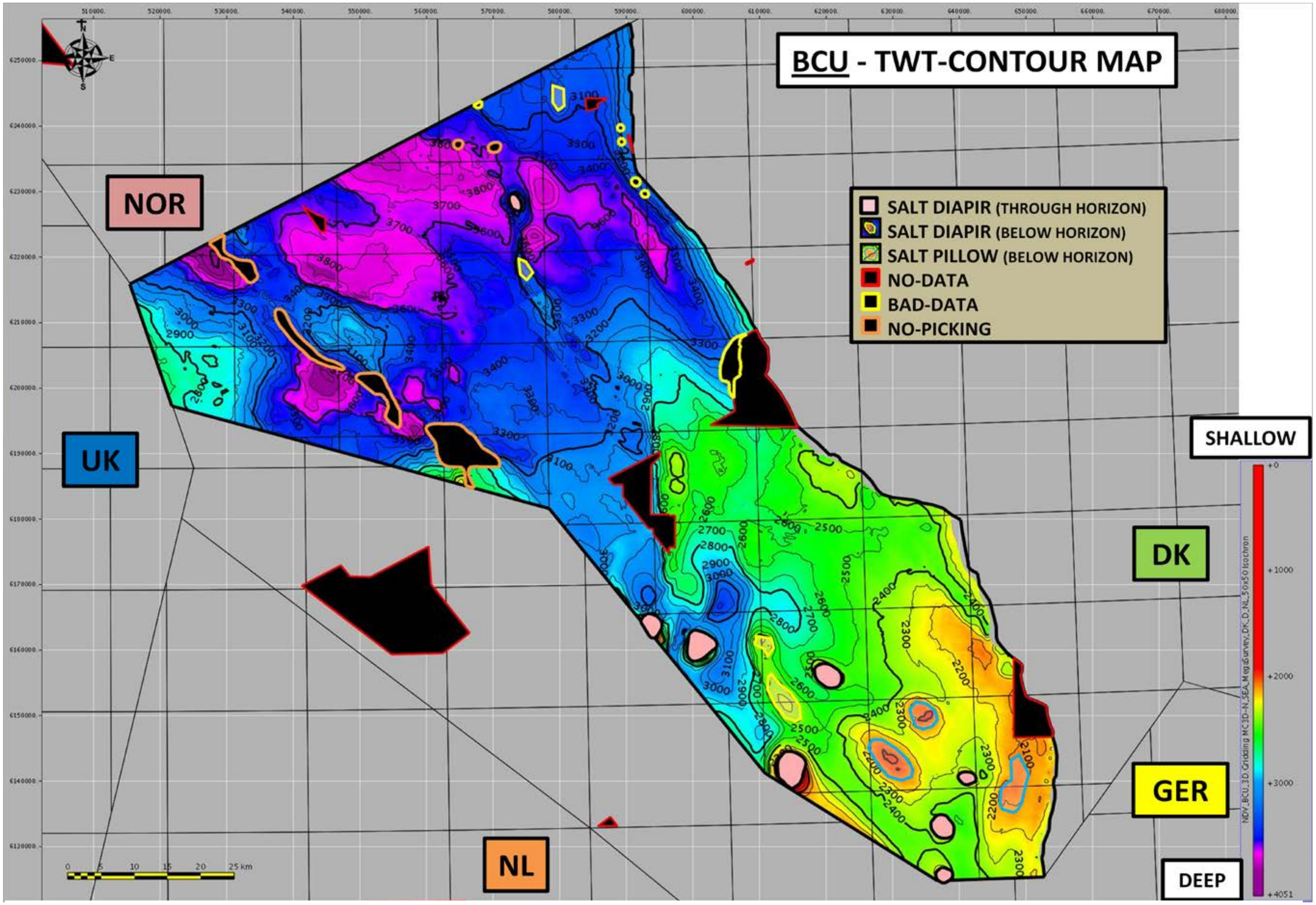


Figure 5.1.3: BCU– TWT – contour map showing the elevation of the layer and the presence of the salt structures within the Danish Central Graben (SISMAGE).

5.2 TWT-grid with coherency maps in the Danish Central Graben

In the figures 5.2.1 to 5.2.3 one can see the same TWT-grid without the contour lines as in the previous figures that are plotted above the corresponding Top Chalk-, Base Chalk- and BCU coherency maps. The many black features seen in the maps, corresponds to a variety of structural and stratigraphic elements. By viewing them together with the TWT grid, it gives us a detailed description of what kind of elements that have affected the horizon. For example, the many salt structures are all combined with a lot of minor faults that are caused as a result of the halokinesis. Other faults are observed at places where tectonic uplift has affected the area and other interesting features are seen in the brown outlined areas in the maps. The ones in the Top Chalk map in Figure 5.2.1 are areas that occur at the top and sides of slightly tectonic uplifted regions, where the seismic horizon can be compared with a bumpy road (See Figure 5.2.4). From a geological point of view, one might interpret these features as re-deposited chalk masses that are a result of mass-movements mechanisms (See sub-chapter 2.5.4). They are located close to the Coffee Soil Fault, so it is possible that big slumps of chalk could have moved downslope from the top of the Ringkøbing-Fyn-High. Similar features are seen around some of the salt structures and can likewise be interpreted as re-deposited chalk that has moved downslope because of the piercing salt movement.

Other brown outlined areas are seen in the Base Chalk map in Figure 5.2.2. The observed features are quite messy, which mainly corresponds to the bad picking as a result of bad data. The cause for the bad data in this area is a result of its location directly in line with the Valdemar Field. Gas seepage as led to some distortion of the data which has made the picking difficult. Similar features are seen on the Inge High and Mid North Sea High structures. Here the messy data corresponds to the many structural features present in these areas. It is therefore important that one should not trust the coherency maps too much, since artificial features could be present and blind the interpreter.

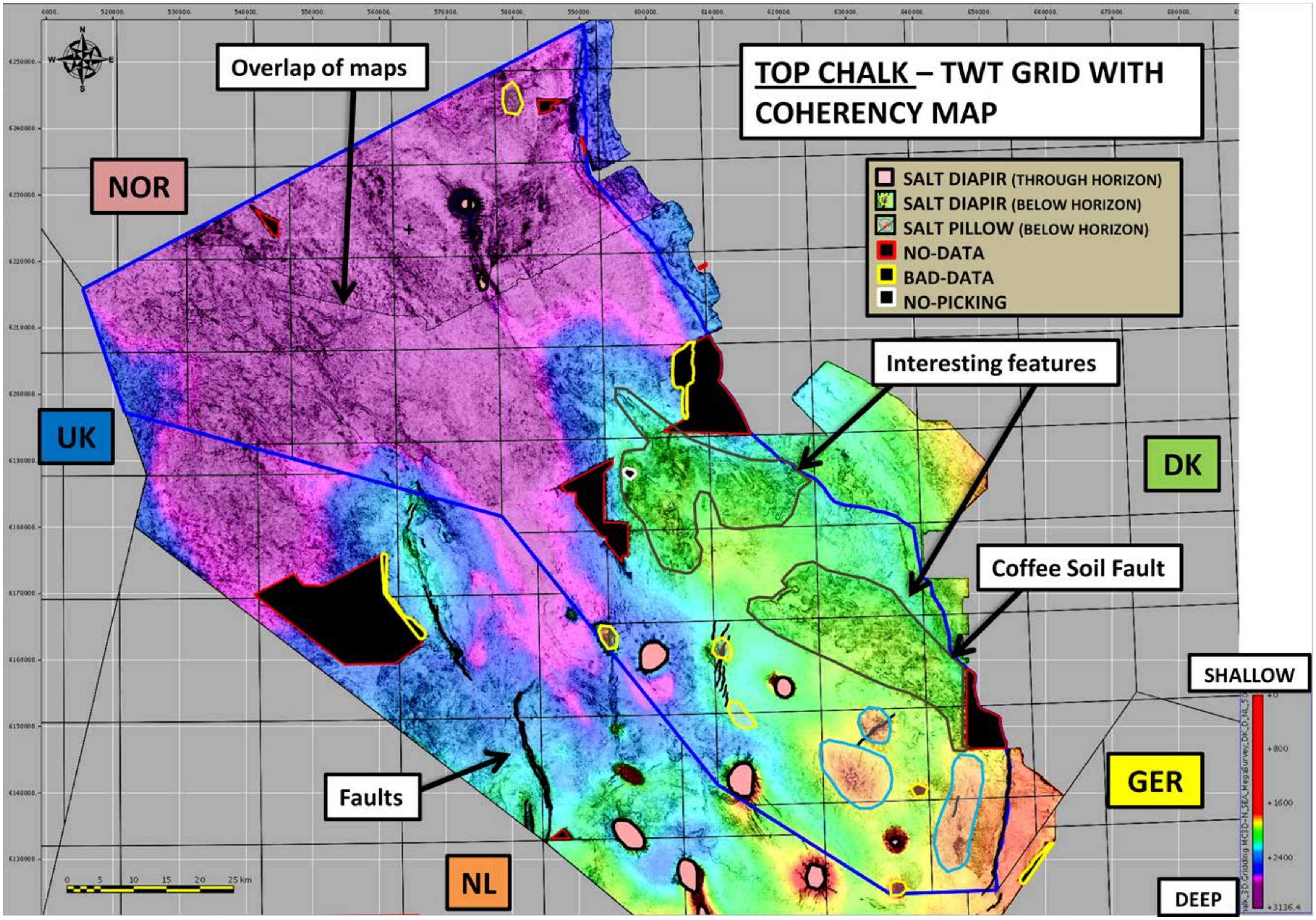


Figure 5.2.1: Top Chalk – TWT grid with coherency map showing the presence of structural and stratigraphic elements within the Danish Central Graben (SISMAGE).

Not many features are seen within the Salt Dome Province for the Base Chalk and BCU map, other than the faults that are caused as a result of the halokinesis. The same counts for the middle area of the NW part of the Base Chalk map. This indicates a relatively flat deposition of chalk on top of the Lower Cretaceous sediments in a quiet environment, where not many faults have penetrated the layer and the layers might be somewhat unfractured (See Figures 4.2 & 4.3).

The same degree of improvement concerning the details at which the structural elements can be seen within the graben is observed in the coherency maps. Again the structures become more clearly when going to further depths and the boundaries of the main highs and grabens become quite clear within the BCU and Base Chalk maps compared to the Top Chalk map. No real structures can for example be seen in Top Chalk map, other than a lot of features that correspond to minor faults, which again gives a hint about the structural complexity further down below. It is also interesting to compare the locations of the chalk field discoveries in Figure A in appendix B with the presence of faults in the Base Chalk and BCU maps. Almost all the fields are found on top of these faults, with the exception of Halfdan, so there is clearly a trend present.

In the NW part of the maps, one can see where my maps overlap with the one from Philip Straw's. The straight black line referred to as "overlap of maps" is thereby an artefact that does not represent any structural or stratigraphic feature.

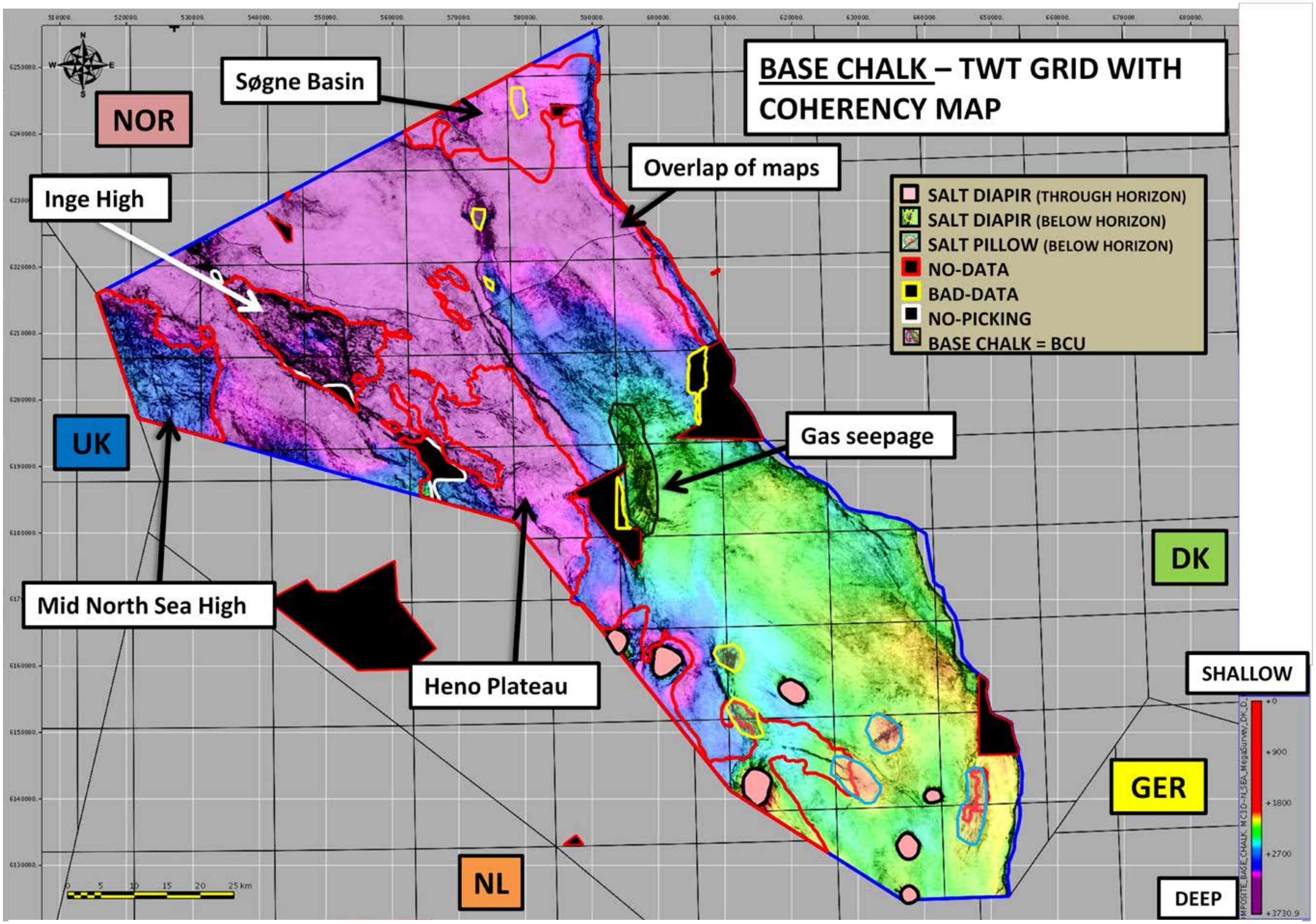


Figure 5.2.2: Base Chalk – TWT grid with coherency map showing the presence of structural and stratigraphic elements and where the Base Chalk = BCU within the Danish Central Graben (SISMAGE).

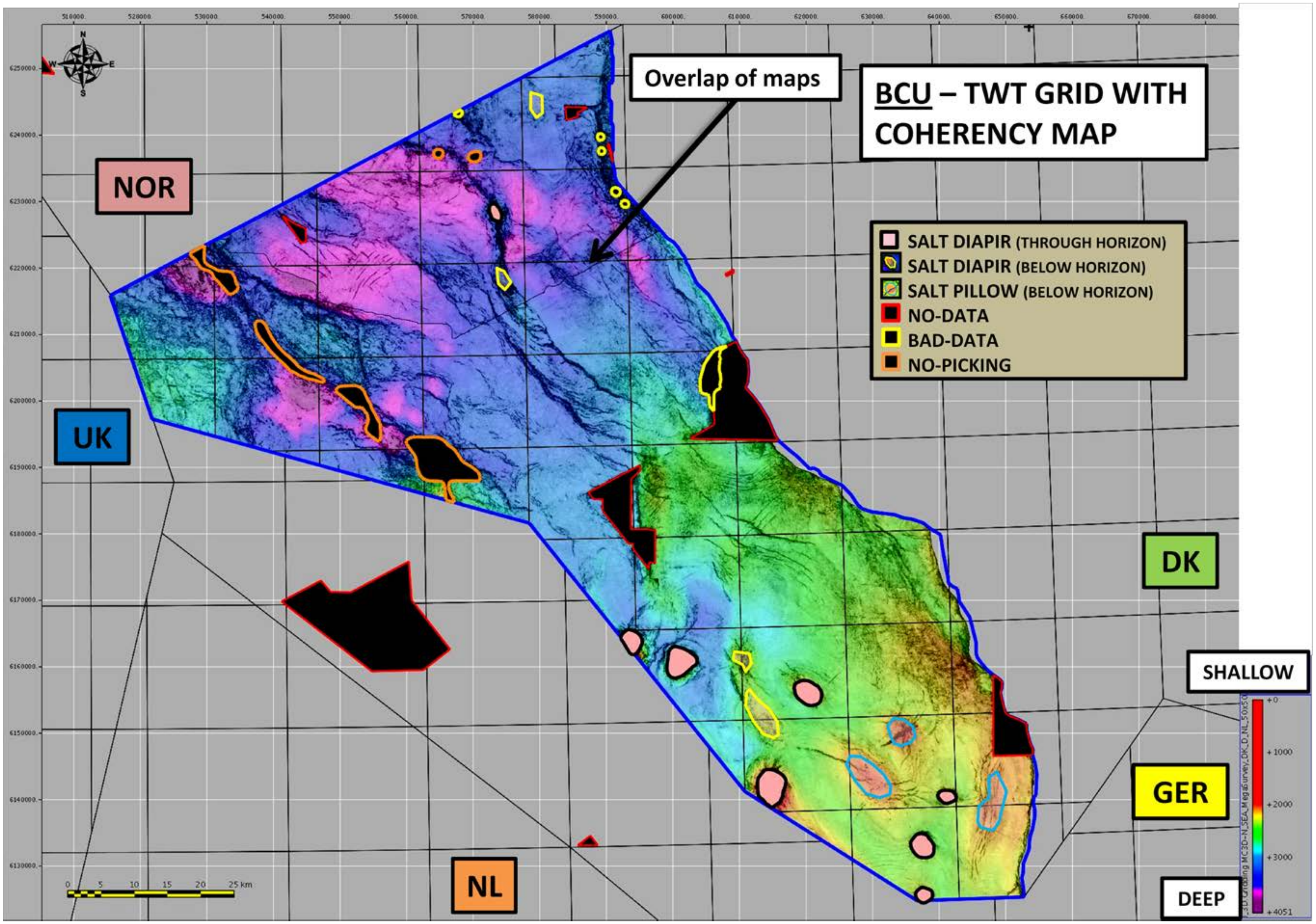


Figure 5.2.3: BCU – TWT grid with coherency map showing the presence of structural and stratigraphic elements within the Danish Central Graben (SISMAGE).

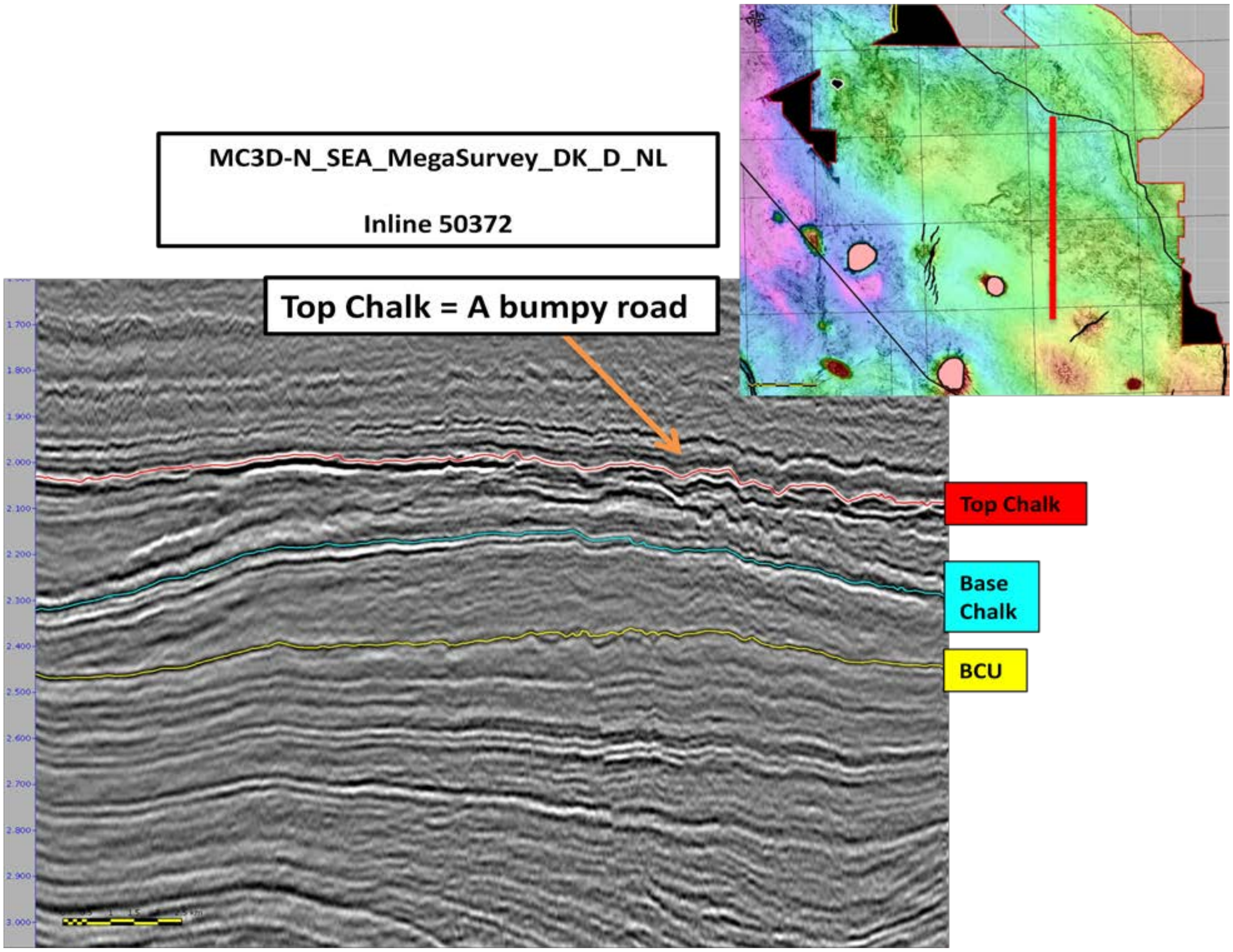


Figure 5.2.4: Seismic section of an inline through the interesting features seen in Figure 5.2.1. Top Chalk reflector follows a bumpy road (SISMAGE).

5.3 Amplitude maps in the Danish Central Graben

An amplitude map for the three horizons can be seen in the figures 5.3.1, 5.3.3 and 5.3.4. Before explaining the map corresponding to the Top Chalk layer, it is important to remember that the amplitudes seen in the map correspond to chalk, which means that one should be cautious when interpreting them. This is because chalk consists of a lot more factors that could be the cause for the corresponding amplitudes compared to for example sand. In sand the sudden change in amplitude over an area can usually be explained by the change in fluid saturation, however, in chalk there are several more factors that could be the cause for the sudden amplitude change, such as compaction, fractures, porosity, mud content, fluid saturation, diagenesis effects etc. Having this in mind one could try to find a pattern for the different amplitudes seen in the map.

Some degree of similarity in the amplitude change occurs at the different salt structures. It changes from slightly strong amplitudes to slightly weak amplitudes within these areas. As mentioned before, many of these regions correspond to HC discoveries, where the amplitude change could be explained by the change in fluid saturation from water to HCs (See Figure A in appendix B).

The amplitude map could also be used to identify structural elements, since the seismic reflection is typically weakened along structural lineaments, such as faults. However, in our case no detailed structural map is provided and no real pattern can be identified for which amplitudes characterize the transition from highs to lows. Some indications are seen at the Heno Plateau but it is not definite. Another reason for some of the amplitude changes can be explained by the merging characteristic of the seismic data itself. This can be seen in Figure 5.3.2 where the strength of the amplitude suddenly changes at the transition from one dataset to another. This again shows that one should be careful trusting the amplitude map for chalk.

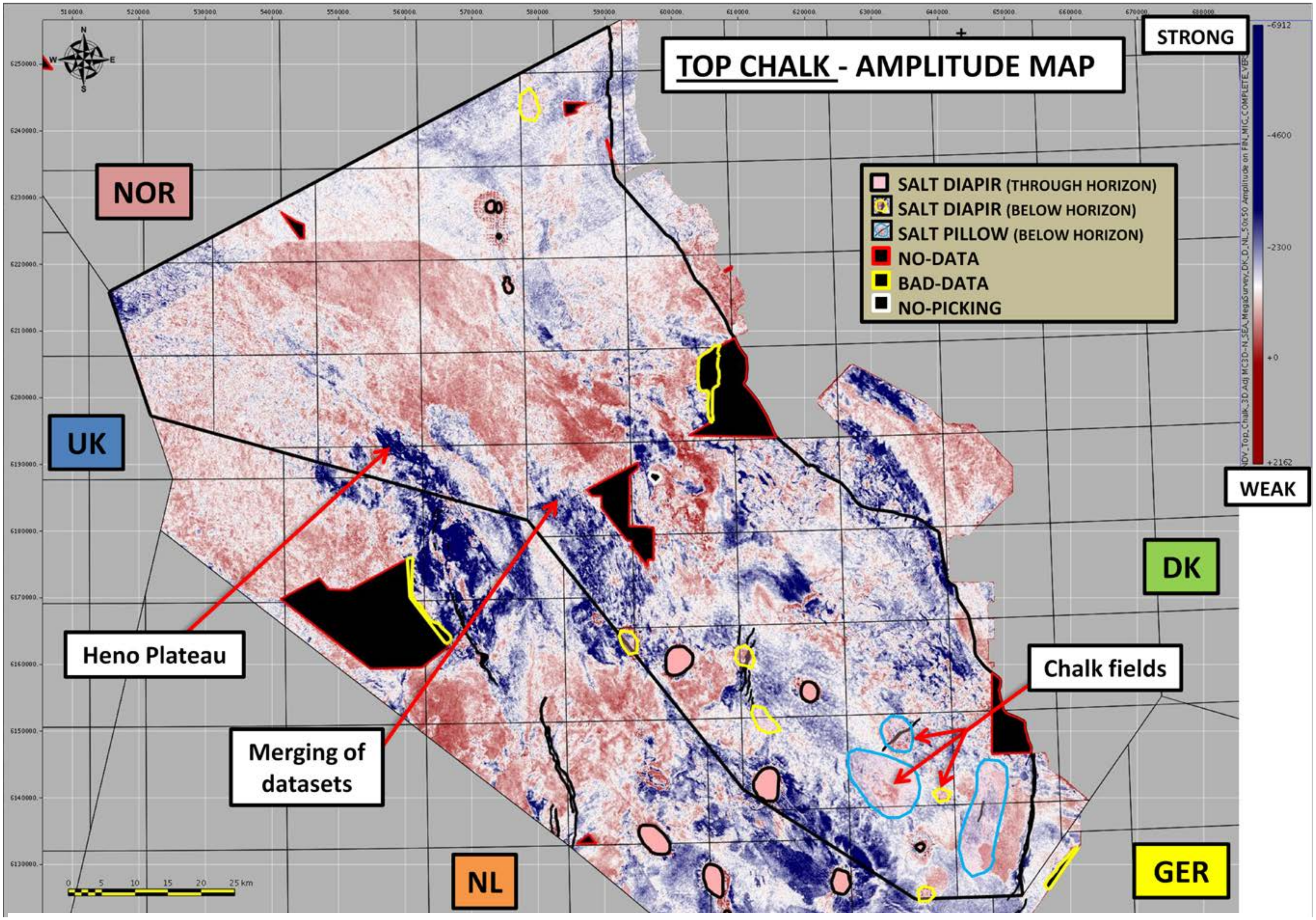


Figure 5.3.1: Top Chalk – amplitude map showing how the strength of the amplitude changes throughout the Danish Central Graben (SISMAGE).

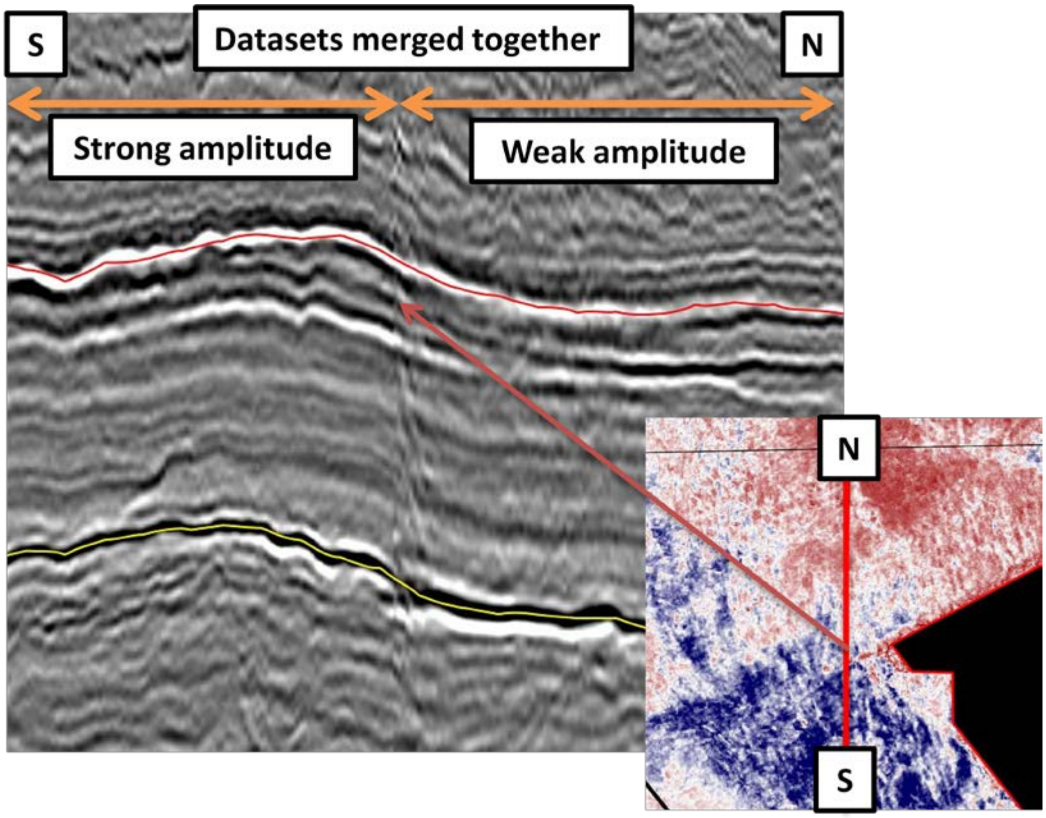


Figure 5.3.2: Shows the effect in amplitude change, when two datasets are merged together (SISMAGE).

The amplitude map for the Base Chalk horizon seen in Figure 5.3.3 can mostly be used to differ between the highs and lows. Some highs, such as the Heno Plateau, Inge High and Mid North Sea High show some signs of having strong amplitudes, whereas mostly weak amplitudes characterize the Tail End Graben. This is mainly because the Base Chalk horizon represents the BCU at the highs, which means that the transition goes from chalk to Jurassic shales, instead of chalk to Lower Cretaceous sediments. However, the pattern is not that trustworthy, since the Gertrud and Feda Grabens show the opposite effect. The salt diapirs do as well, but this is mostly because the marker weakens in amplitude atop these structures.

The marked oval circle in the map corresponds to the Valdemar chalk field, which contains both gas and oil at the Lower Cretaceous level. The picking of the horizon in this area was not easy, because of the presence of many weak amplitudes due to the gas seepage. However, there is one small area within the field that shows strong amplitudes that likely corresponds to the bright spot here, which is caused by the presence of gas.

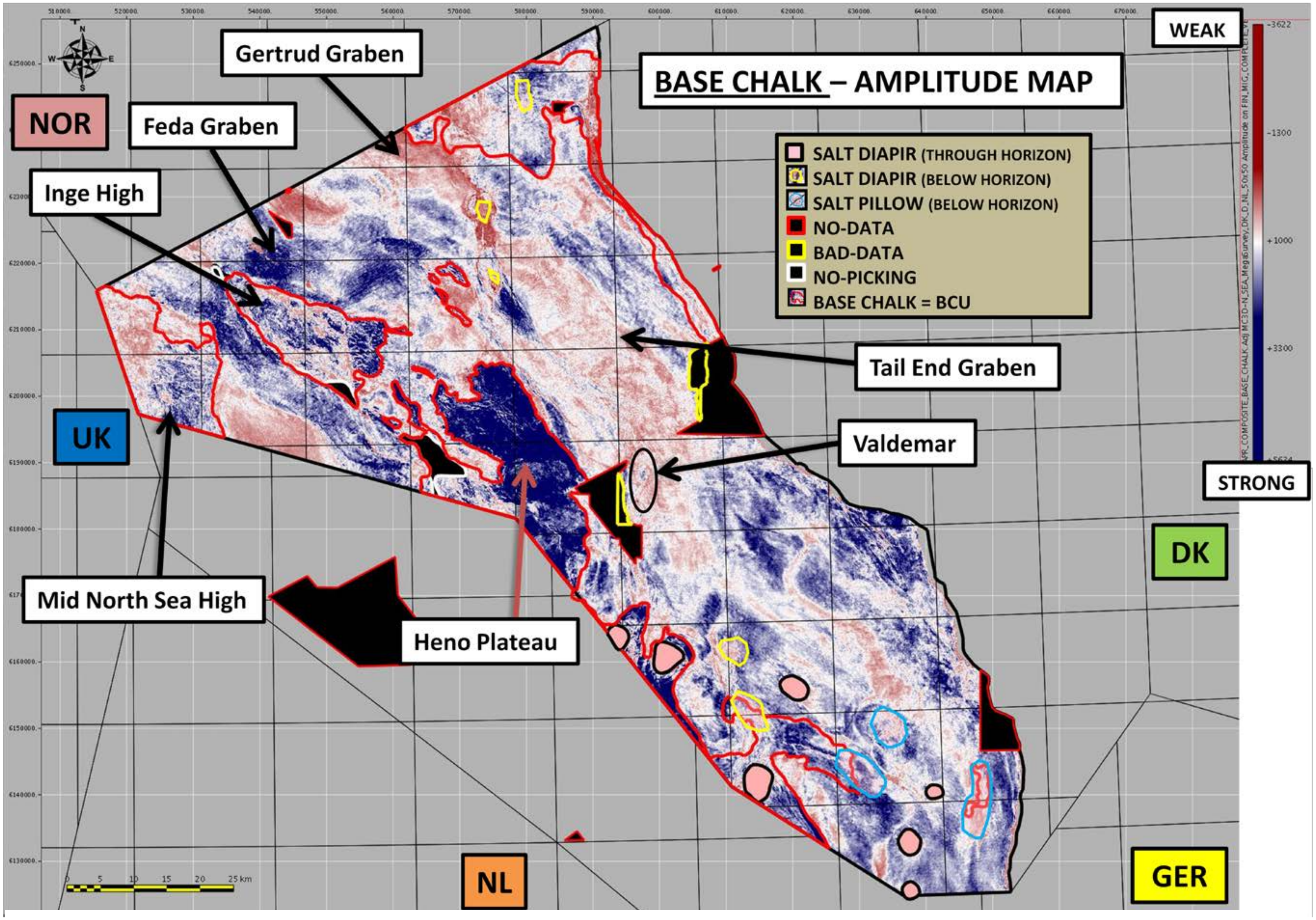


Figure 5.3.2: Base Chalk – amplitude map showing how the strength of the amplitude changes throughout the Danish Central Graben (SISMAGE).

In the amplitude map corresponding to the BCU in Figure 5.3.3, the outlines of some structures can be recognized. The Heno Plateau and Mid North Sea High give of strong amplitudes, which could mean that the BCU lies directly on top of Rotliegend rocks. The Tail End Graben consists of weaker amplitudes, as do the Gertrud and Feda grabens. The Salt Dome Province is on the other hand almost divided into two with strong amplitudes close to the German border and weak amplitudes near the Coffee Soil Fault. One explanation for this is that the difference in acoustic impedance between the Lower Cretaceous rocks to the Jurassic rocks is almost the same creating weak amplitudes. Another thing is that the interpretation in the weak amplitude area was more difficult, bringing us to the question of how trustworthy these amplitudes are.

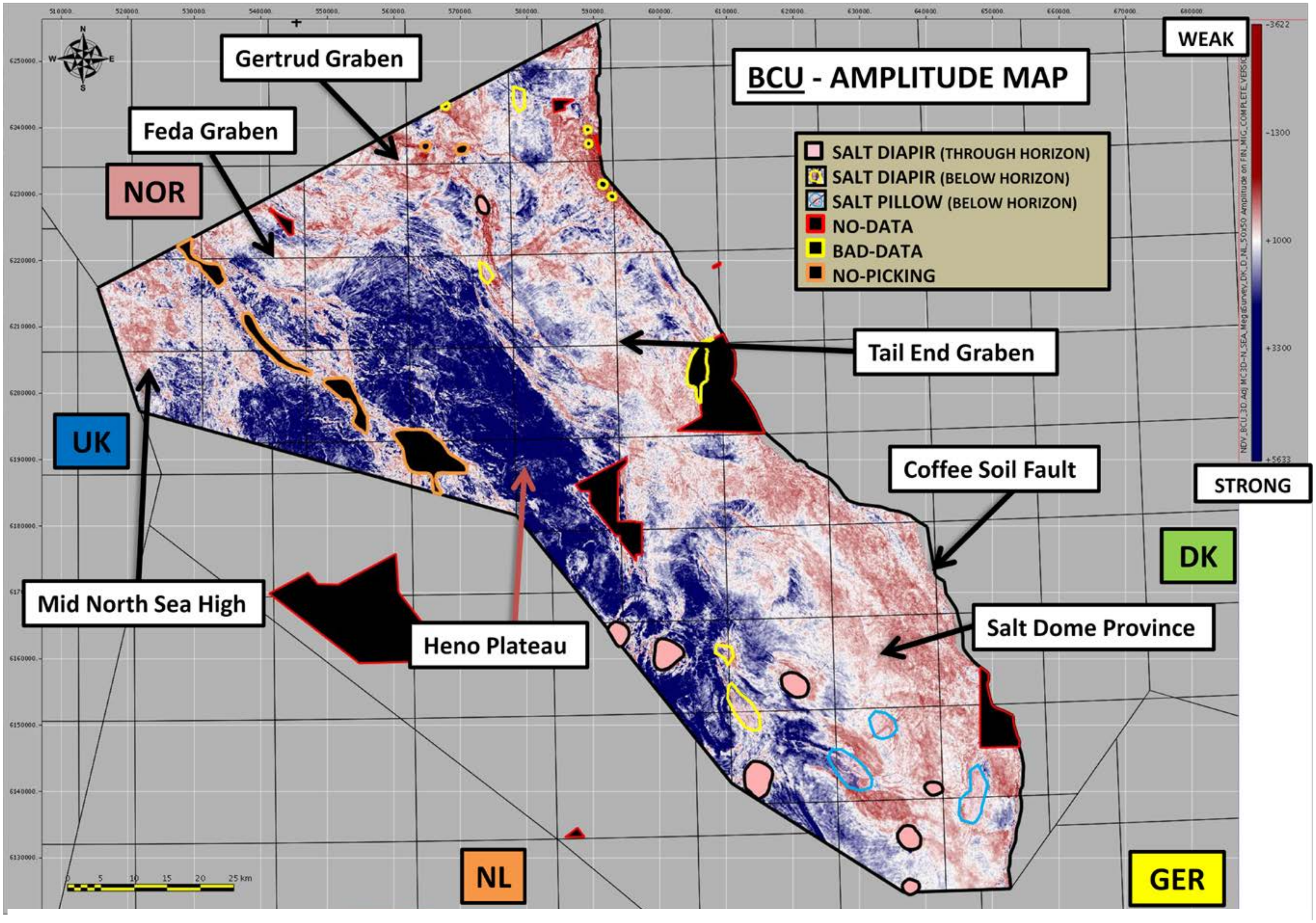


Figure 5.3.3: BCU – amplitude map showing how the strength of the amplitude changes throughout the Danish Central Graben (SISMAGE).

5.4 Thickness maps in the Danish Central Graben

A TWT thickness map for the Chalk layer and the Lower Cretaceous sediments across the Danish Central Graben can be seen in the figures 5.4.1 and 5.4.2. The thickness in chalk varies between 0-1150 ms, which corresponds to thicknesses of 0-2645 m, when using an average velocity of 2300 m/s for chalk (Holt & Bauer, 2013). The layer is practically present throughout the whole graben with the exception of where salt diapirs have pierced through the layers. However this is not the case for every salt diapir seen as a pink polygon. Some of these diapirs could have chalk on top of them, but the data has been so much distorted that I couldn´t follow them here.

As expected the chalk layers have the largest thicknesses within the grabens, since they provide the most accommodation space and are less exposed to erosion then the highs. The vice versa effect is therefore seen on top of the highs, such as the plateau´s, ridges and salt structures, where the chalk layers are at their thinnest.

Considering the locations of the HC discoveries with respect to the chalk thicknesses, most of them are found within rather thin sections of chalk (See Figure A in appendix B). This gives us an impression of how slow the HC migration must be through unfractured chalk, since no considerable amount of HCs has been found within thicker section of chalk. By saying this, one should of course consider the presence of potential traps within these thicker sections first in addition to the sealing capacity of the overlaying rock. The Halfdan field is based on this principle, where the discovered HCs are believed to have moved away from a structural trap due to late structural tilting (See sub-chapter 6.5). However, because of the low permeability and unfractured chalk the HCs have not been able to migrate that far and are therefore found within a pocket in the chalk layers.

The Lower Cretaceous sediments vary in thicknesses of 0-1100 ms, which correspond to around 0-2200 m, when using an average velocity of 2000 m/s for the shales mostly present in these sediments (Holt & Bauer, 2013). The layer is absent at the Inge High, Heno Plateau and Mid North Sea High, part of the Søgne Basin and within part of the Salt Dome Province. This seems logical because of the increased exposure to erosion on top of these structures.

The same principle seems to explain the thickness of the layer at the HC field locations as with the chalk layer. The Lower Cretaceous sediments are also quite thin at most of these positions.

By comparing both maps the trend seen in each one of them is quite similar, where both layers increase in thickness at the grabens and thin in thickness at the highs. The maps give therefore a good impression of where the main structural elements are located within the graben.

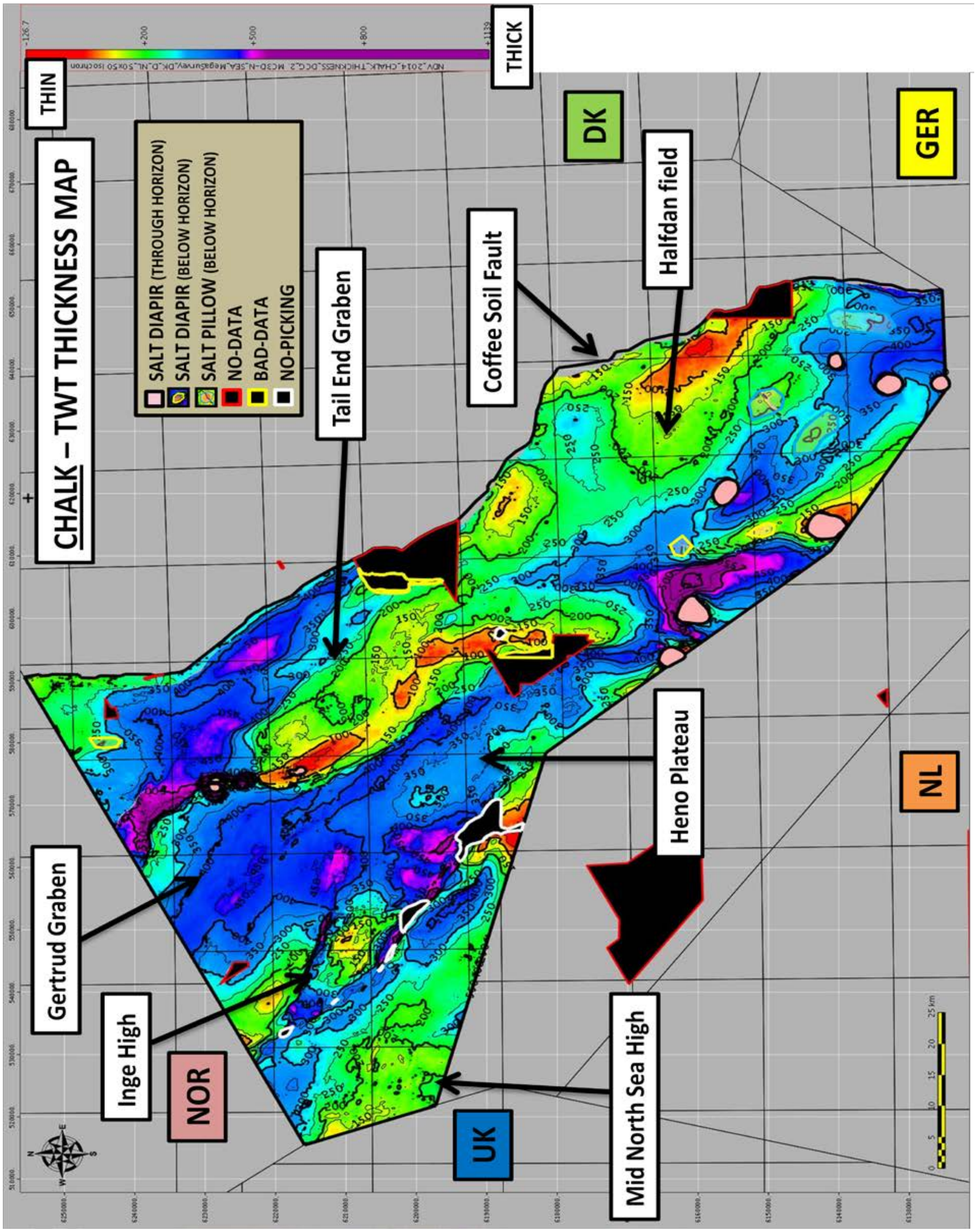


Figure 5.4.1: TWT – Thickness map for the chalk layer across the Danish Central Graben (SISMAGE).

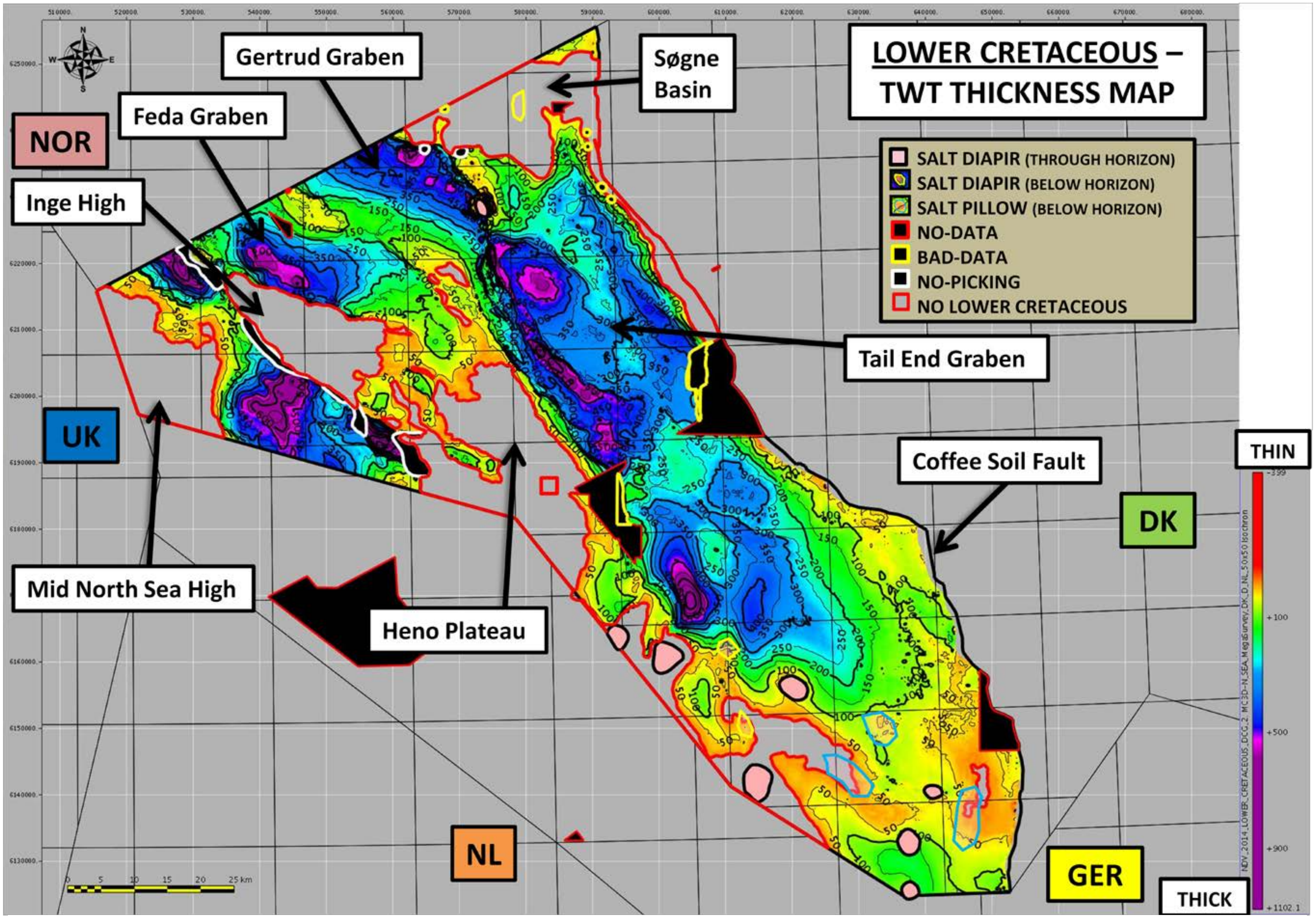


Figure 5.4.2: TWT – Thickness map for the Lower Cretaceous layer across the Danish Central Graben (SISMAGE)

5.5 Maps of the Dutch Central Graben

Similar maps as the ones in the previous subchapters are done for the Dutch Central Graben, by the senior geophysicist Philip Straw. These maps are found in the figures B to H in appendix B. Only maps for the two chalk markers are included, so no BCU maps will be seen here. A short interpretation of the maps is found below.

5.5.1 TWT-contour maps

The TWT-contour maps for the Top Chalk and Base Chalk can be seen in figures B and C in appendix B. The main Top Chalk horizon is found at depths of 1500-2600 ms, where large salt diapir structures have led to some exceptions. The same counts for the Base Chalk horizon, which is mainly located at depths of 1600-3100 ms. The two horizons, give therefore a similar impression based on the elevation variation throughout the graben.

The Top Chalk horizon corresponds also here to the top of the Ekofisk Formation across the better part of the graben. The Base Chalk horizon is on the other hand represented by either the top of the Lower Cretaceous Greensand Formation, the Upper Holland Marl Member or Zechstein salt.

The purple outlined black polygons correspond to where chalk is absent as a result of erosion. The Jurassic rocks are therefore directly overlain by the Tertiary sediments. Again some structural closures can be seen in the Top Chalk map, where the Hanze Field has led to a discovery, whereas the other noticeable salt diapir in the map corresponds to a dry well. The dark green outlined black polygon in the Base Chalk map corresponds to an area where the Base Chalk horizon is absent. However, the Top Chalk is present here, which means that a Base Chalk should also be here. The chalk thickness map in figure H in appendix B tells us on the other hand that the chalk is very thin here, meaning that the seismic resolution is not detailed enough to capture the two reflectors. It instead only captures one reflector, which corresponds to the Top Chalk horizon.

5.5.2 TWT-grid with coherency maps

The structural and stratigraphic features for the Top & Base Chalk horizon in the Dutch Central Graben can be viewed in the figures D and E in appendix B. Both maps give a relatively clear few of the faults present in the graben and the same structural outline of these elements is seen in both cases. The Base Chalk map is on the other hand filled with some more features, which seems reasonable since it is located at deeper depths and more affected by the underlying structural elements. Also here the salt structures are combined with minor faults surrounding the diapirs.

Some form of stratigraphic features within the orange outlined polygons can be seen in the southern and northern part of the map, which gives a similar impression as the chalk slumps viewed in Figure 5.2.1. Again they could have moved downslope from the fault or from the piercing salt structures.

The area where the Base Chalk horizon is not present marks a lot of black features within the Top Chalk map. No real tectonic event other than the quiet deposition of sediments has happened here, so the marked are is therefore quite misleading and one should be cautious to trust it.

5.5.3 Amplitude maps

The amplitude maps for the Top and Base Chalk horizon can be seen in the figures F and G in appendix B. In the Top Chalk map the weak amplitudes are found on top of the salt structures, in the area where no Base Chalk is present and across the southern part of the graben. A line that marks the distinct change from weak to strong amplitudes when moving from south to north looks on the other hand quite suspicious and not very trustworthy. However, when comparing it with the coherency map in Figure D in appendix B, there is also observed a change, where more features cover the area to the south than the north. The many features could therefore be responsible for the weak amplitude effect in the south.

The middle and north part of the graben is mostly covered by strong amplitudes, meaning that not many structural or stratigraphic elements have affected the Top Chalk horizon here. This is in a way verified by the corresponding coherency map, which only shows a few features in these areas.

The Base Chalk amplitude map shows a more consistent amplitude change throughout the area, without abrupt changes. Again the areas on top of the salt structures are seen as weak amplitudes, whereas the remaining areas are seen as relatively strong amplitudes. The marked area in the map, which is represents weak amplitudes, is not caused by any salt structure. It corresponds on the other hand to a tectonic uplifted area. Here the uplifted area has caused the formation of faults within the Base Chalk horizon, which likely correspond to these weaker amplitudes. Compared with the coherency map in Figure E in appendix B this adds up.

5.5.4 Thickness map

A TWT thickness map of the chalk layer within the Dutch Central Graben is seen in Figure H in appendix B. It has a large thickness variation of 0-1650 ms, which is around 0-3795 m, when using an average velocity of 2300 m/s for chalk (Holt & Bauer, 2013). However, the main thickness of chalk across the graben is seen as a thin cover that is around 100-200 m, where the exceptions are observed further to the north and at a little area to the west.

The marked Hanze Field is found within a relatively thin chalk layer on top of a salt diapir that is surrounded by thicker layers of chalk to the north and south. This scenario is also seen on the Danish Central Graben at several occasions and has likewise led to many chalk discoveries. Looking further, there are on the other hand not many other places in the Dutch Central Graben that has the same properties other than the field that is marked as a “dry well”. This could be the reason for why no other discoveries have been made atop the other salt structures. Anyway, the proven HC discoveries are again found in connection with thin chalk layers.

6. Petroleum system analysis

The following chapter gives a petroleum system analysis of one chalk field within each of the five categories of chalk fields discovered in the Danish Central Graben (See Table 3.2). In addition, I have included the Hanze Field from the Dutch Central Graben. An overview of the seismic cross-sections that are used to describe the fields is seen in Figure 6.1.

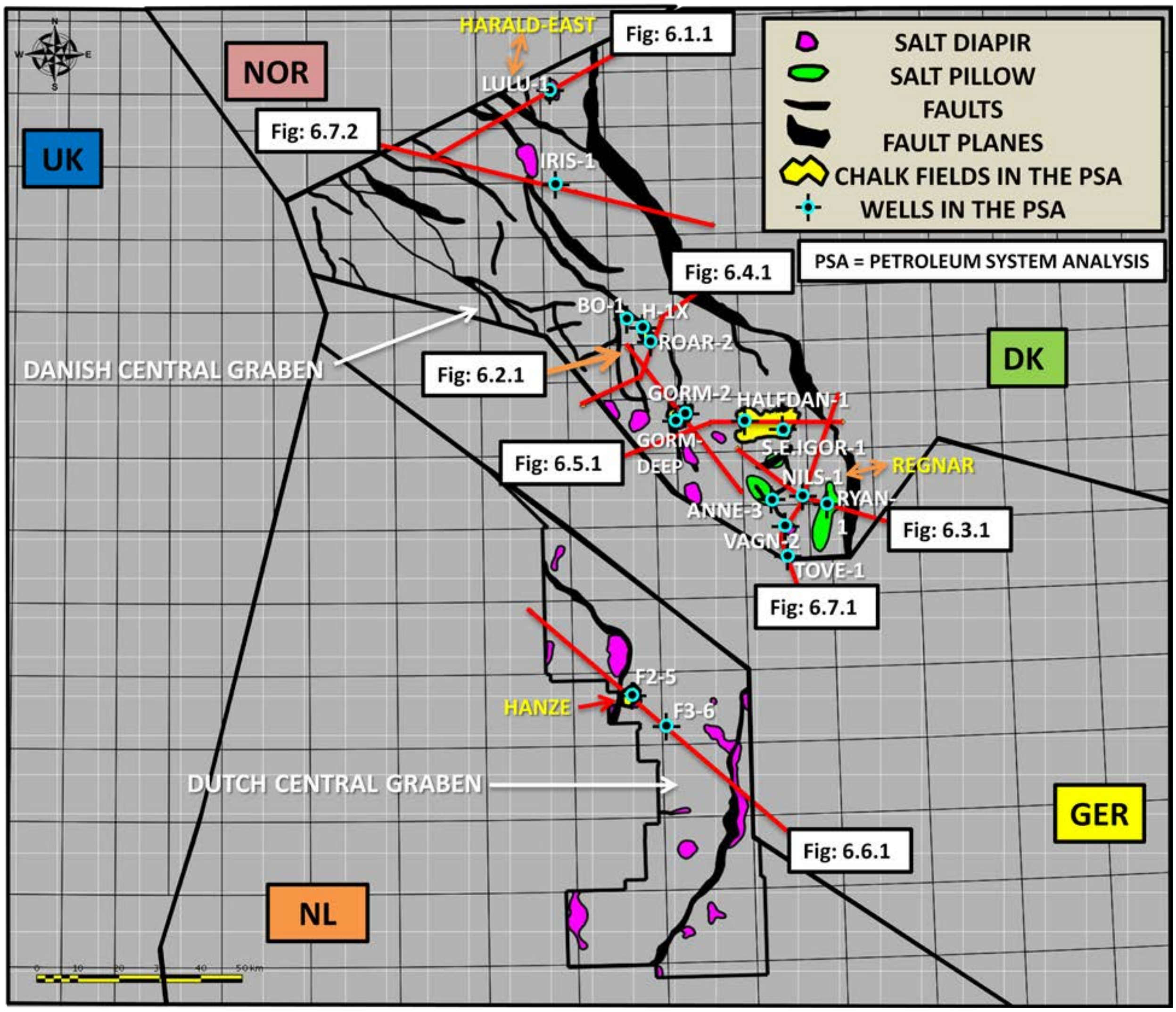


Figure 6.1: Shows an overview of the chalk fields that are considered in the petroleum system analysis and the wells that are used during this analysis. The different red lines correspond to the seismic cross-sections used during the analysis to describe the fields (SISMAGE).

6.1 Harald East Field

The Harald East Field is part of the larger Harald Field, which is also comprised of the Harald West Field. Both fields are gas accumulations with minor oil production, but are found in different reservoir rocks and geological ages. The eastern part is found in chalk that ranges from the Upper Cretaceous to Danian age, whereas the western part is found in Jurassic sandstones (ens.dk(2)). The western part is therefore out of the scope of this thesis. The east field was discovered in 1980 by the Lulu-1 well and contained around 25 billion normal cubic meters (Nm^3) of gas in reserves. Results from the well showed favourable production properties in the Danian chalk and indicated the Maastrichtian interval to be in an oil-water zone, which should produce water-free HC if a more favourable structural position could be obtained[4]. The reservoir itself is located at a depth of 2700 m below the sea surface and has been producing since 1997. In 2012 the remaining reserves were estimated to be 3 billion Nm^3 of gas (ens.dk(2)).

The Harald East Field is located within an anticlinal structure that is positioned above a salt diapir (ens.dk(3)). The diapir is a result of the halokinetic movements that happened after the deposition of salt during the Zechstein age, 250 million years ago. It is believed that after this deposition, the salt has been liquefied by the increasing pressure and weight of the overlaying sediments. This has led to a process resulting in salt pillows that intruded vertically into the chalk layers and formed salt diapirs. Such a salt diapir has in this case led to the formation of a bulge in the chalk layers at the Harald East Field, leading to a dome structure that traps the oil (ens.dk(3)).

The reservoir rock, seal rock and overburden rock are characterized as being post-rift sediments, meaning that the piercing of salt and the formation of the trap must have happened during post-rift tectonic events, such as the Laramide or Sub-Hercynian pulses. The source rock was deposited during the syn-rift period of sedimentation.

Petroleum system cross section

Figure 6.1.1 shows a cross-section through the Harald East Field, where the different elements that make up the petroleum system are seen in the colour scale. The source rock in the system corresponds to the Upper Jurassic Kimmeridgian Bo Member, which is something that can be seen from the high GR response in the composite well log of the Lulu-1 well seen in Figure B in

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[4] From the Completion Report of well Lulu-1, obtained from www.geus.dk

appendix A. The high responses can be observed just below the BCU and correspond to typical source rock material that contains poorly fossiliferous marine claystones, which are deposited in a marine environment with restricted circulation and anoxic conditions[4]. In the seismic, the interpretation of the source rock is found only at the top of the salt structure. This interpretation is based on a rough estimation, since the source rock is not seen as a distinct marker. The interpretation is also in part based on the distribution of the source rock seen in Figure 2.5.1, which actually indicates an absence of the Bo Member here. I.e. I have been careful in extending it too much to either the SW or NE direction.

The section shows the vertical migration paths from the active source rock through the Cretaceous rocks. Fractures within the chalk are proven from the core-sections taken from the completion report of the well and are a result of the salt tectonics[4]. The fractures have likely improved the HC migration upward, where it has been captured within the four-way dip closure at the top chalk layers. The associated small TWT-contour map in the section shows this structural closure represented by the field. Since the source rock distribution through the Søgne Basin is unknown, one could expect lateral HC migration as seen from the figure. Most of the HCs would probably end up within the Harald East Field, but places like the Mandal High and on top of the Ringkøbing-Fyn-High are also valid places for HCs to have accumulated after their migration. This is proven by the many discoveries found within Palaeocene fields in the Siri Trend that are charged by HC migration from the Central Graben.

The composite well log of Lulu-1 also marks the presence of Palaeocene shales on top of the chalk, which have formed a seal to complete the trap[4]. As seen from Figure 6.1.1, this seal can be followed throughout the whole section, and opens up the possibility for lateral HC migration through the chalk on top of the Ringkøbing-Fyn-High.

There are no gas anomalies viewed on top of the field within the Tertiary layers; however a DHI in the form of a phase reversal can be seen at the Top Chalk horizon overlaying the structure. Since the Harald East is a gas field, the phase reversal is likely caused as an effect of the decreasing acoustic impedance in the chalk.

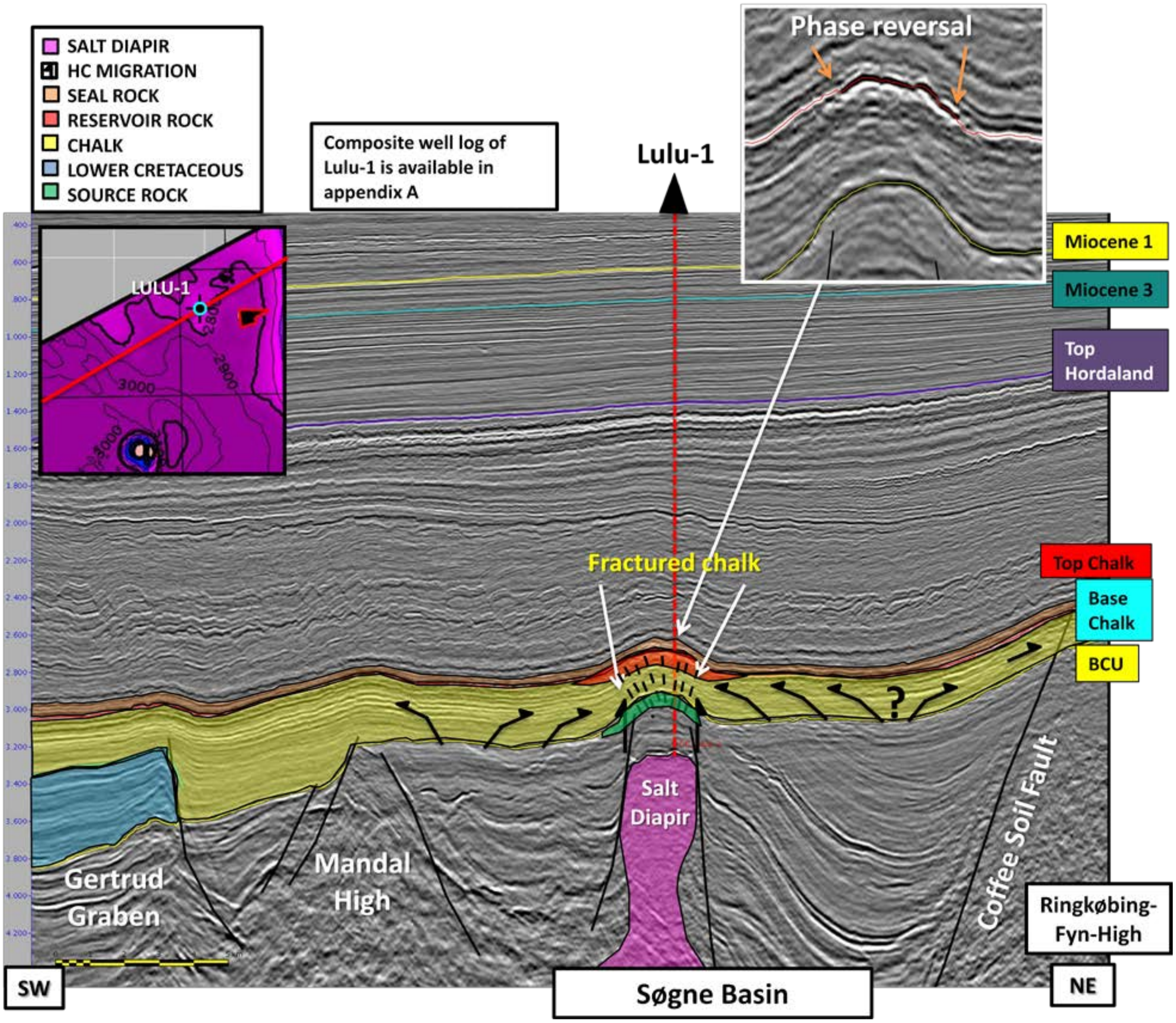

Figure 6.1.1: Seismic cross-section through the Harald East Field, showing the various elements and processes that make up the petroleum system. Notice the phase reversal at the Top Chalk (SISMAGE).

The interpreted reservoir rock shows the area of where the HCs are likely to be located. However, this marked area is also based on a rough estimation and since no distinct flat spot can be seen that would mark the gas-water-contact (GWC), an outline of the field is hard to mark on the section without going into further detail.

6.2 Gorm Field

The Gorm petroleum system was discovered in 1971 by the Gorm-1 well and contained around 410 million barrels of oil equivalent (MMBOE). It is found at a depth of 2100 m below the sea surface, where the age of the reservoir rock ranges from Upper Cretaceous to Danian chalks (ens.dk(2)). The Gorm-2 well considered in this section was drilled with the objective to test the chalk reservoir producibility on the higher eastern fault block of the structure and to evaluate the presence of a gas cap. Since the well was drilled in a crestal position on the fault block, a gas cap was not believed to be present, which was also the case since no gas cap was observed in the well[5]. The field itself has been in production since 1981 and in 2012 it was estimated that around 34 MMBOE was still left in the field (ens.dk(2)).

The Gorm Field is also found within an anticlinal structure that is induced through Zechstein salt tectonics. The salt is part of a major halokinetic area, known as the Salt Dome Province, which extends from the southern portion of the Tail End Graben across the German North Sea sector and into the Dutch waters[5]. The structure itself is located in the Tail End Graben, and the same procedure of liquefied salt moving upwards to form a salt diapir that bulges the chalk layers to form a dome structure that again traps the oil is therefore likely to have happened also in this case. However, the structure differs from the Harald East structure, because of the addition of a major fault that divides the field into two reservoir blocks. Numerous other minor faults that cut the top of the chalk layer are also present[5]. However, they are too small to notice clearly on the seismic.

During the Tertiary until present day the field has been exposed to subsidence and continuous deposition of sand and clay. It is therefore surrounded by basement rock below the field and alternating clay and sandstone deposits above the field (ens.dk(3)).

<u>Petroleum system cross section</u>

The seismic cross-section through the Gorm Field can be seen in Figure 6.2.1. The charging of the field is likely to have happened in the same way as the Harald East Field, with vertical migration that is improved by the fractured chalk on top of the salt structure. The well-recovered

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[5] From the Completion Report of well Gorm-2, obtained from www.geus.dk

cores from the chalk section all give the indications of minor to moderate fractures, which have provided a good porosity and permeability[5].

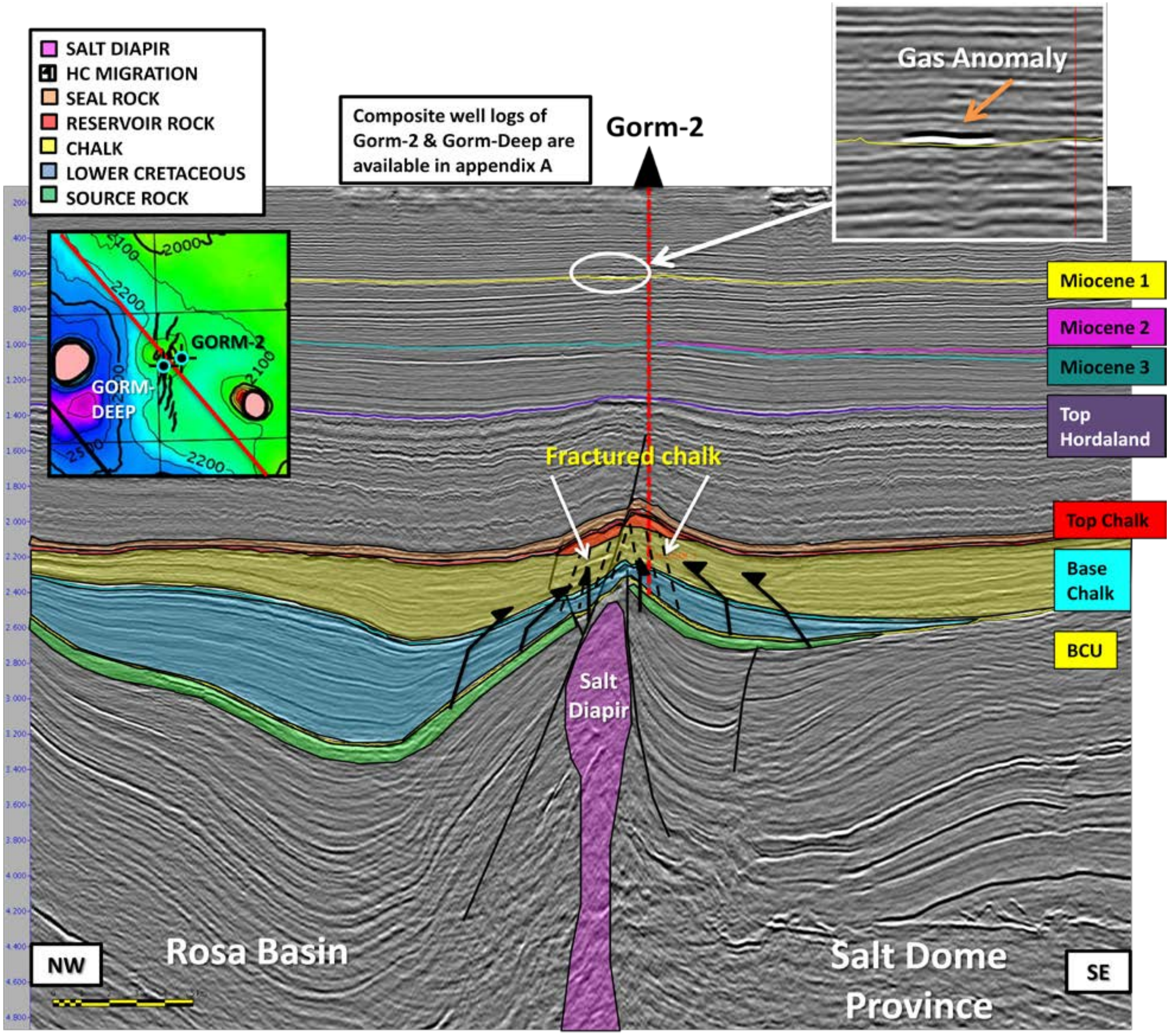

Figure 6.2.1: Seismic cross-section through the Gorm Field, showing the various elements and processes that make up the petroleum system. Notice the gas anomaly further above within the Tertiary layers (SISMAGE).

It can be seen that the major fault divides the field in two, where its presence stops a bit below the Top Hordaland marker. This means that it probably took place sometime close to the beginning of the Neogene age around 30 million years (Ma) ago as a result of the piercing salt diapir. As mentioned earlier, the presence of the fault leads to the separation of the field into two reservoir blocks. The two blocks have on the other hand a similar oil-water-contact (OWC), making us believe it is one block. However, when the well Gorm-2 was drilled, this line of thought was neglected, since a drill-stem test (DST) identified one of the blocks being a saturated reservoir, while the other block was an under-saturated reservoir. I.e. it indicated two separate reservoirs[5]. The fault also contributes to the HC migration and acts as a part of the trap. Even though only one major fault is seen in the seismic, the TWT-contour map shows several more that cross the structural closure of the field in a NNE to SSW direction.

The Gorm-2 well seen in the figure does not go all the way down to the Jurassic layers, so no indication of a source rock can be seen in its composite well log in Figure J in appendix A. However, I have included the composite well log of the Gorm-Deep well in the same figure, and here the Bo Member can be seen by its characteristic increase in the GR log. The Gorm-Deep well is located pretty near the Gorm-2 well, but cannot be seen in Figure 6.2.1. Again the distribution of the source rock is interpreted just below the Lower Cretaceous and throughout the Rosa Basin and in part of the Salt Dome Province. The Gorm Field is the only apparent four-way-dip-closure within the chalk that is present in the section, so most of the HC migration has likely moved vertically upward and accumulated within the trap.

The primary objective of the Gorm-Deep well was to explore the HC potential of the Middle Jurassic Haldager Formation beneath the Gorm chalk structure, while the secondary objective was to evaluate the reservoir properties of the Danian-Maastrichtian chalk in the down-flank position. The results indicated that no reservoir was found in the Jurassic, but very good reservoir properties with an average of 80 % oil saturation and around 33-35 % porosity was found at the flanks of the chalk field[6]. The flanks of the HC discoveries and prospects should therefore not be disregarded when drilling for oil, since they prove to be valuable places in the field to recover HCs from.

The seal is again marked by Palaeocene Shales as seen from the composite well log of Gorm-2. In addition there is indicated an oil-water-contact (OWC) on the log, but trying to find this on the seismic is not that that easy. There is a small indication of a flat event, but it is not very clear. A gas anomaly is on the other hand seen within the Tertiary layers and contributes to the validity of the petroleum system.

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[6] From the Completion Report of well Gorm-Deep, obtained from www.geus.dk

6.3 Regnar Field

The Regnar Field was discovered in 1979 by the Nils-1 well and contained around 6 MMBOE. The age of the reservoir rock originates from the Upper Cretaceous and the reservoir itself is found at a depth of 1700 m below the sea surface (ens.dk(2)). Results from the well Nils-1 indicate that the chalk from the Lower Palaeocene and Upper Cretaceous is very hard and stylolitised due to high diagenetic pressure. The layer rests directly on top of Upper Permian dolomitic limestone and the thick sequence of Upper Cretaceous chalk that is recorded elsewhere in the region was either deposited and then eroded or it was never deposited[7]. The reservoir itself has been producing since 1993 and in 2012 the remaining reserves in the field were estimated to be zero, so production has been suspended (ens.dk(2)).

The HC accumulation in the Regnar Field is also the result of a closure that has formed within the chalk through the piercement of a salt diapir. However, it differs from the Harald East and Gorm fields in terms of how much the salt diapir has pierced through the underlying layers. In this case the diapir has pierced a lot further going through the BCU and connecting directly with the overlying chalk. Its influence has even extended well into the overlying Tertiary clays and possibly into the Quaternary[7]. The chalk is therefore heavily fractured and brecciated, where the amount of effective fracturing is related to the hardness of the rock. This has resulted in favourable reservoir conductivity at some places in the field[7]. In terms of reservoir structure, the Regnar field is comparable to the Skjold, Rolf, Dagmar and Svend fields, which are all heavily fractured reservoirs as a result of being positioned above salt diapirs that have pierced through the underlying layers.

Petroleum system cross section

A view of the petroleum system corresponding to the Regnar Field is observed in Figure 6.3.1. The system is quite similar compared to both the Gorm and Harald East fields, but there are some differences between them that give them their own characteristic. As mentioned, the piercement of the salt diapir is more drastic, where the overlying chalk is heavily fractured and the salt diapirs influence has possibly reached the layers belonging to the Quaternary. (Notice the slight uplift in the Miocene 1 horizon). One can see that the data is distorted on top of the salt structure,

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[7] From the Completion Report of well Nils-1, obtained from www.geus.dk

which corresponds to a gas chimney where gas could have leaked out through the heavily fractured overlaying layers.

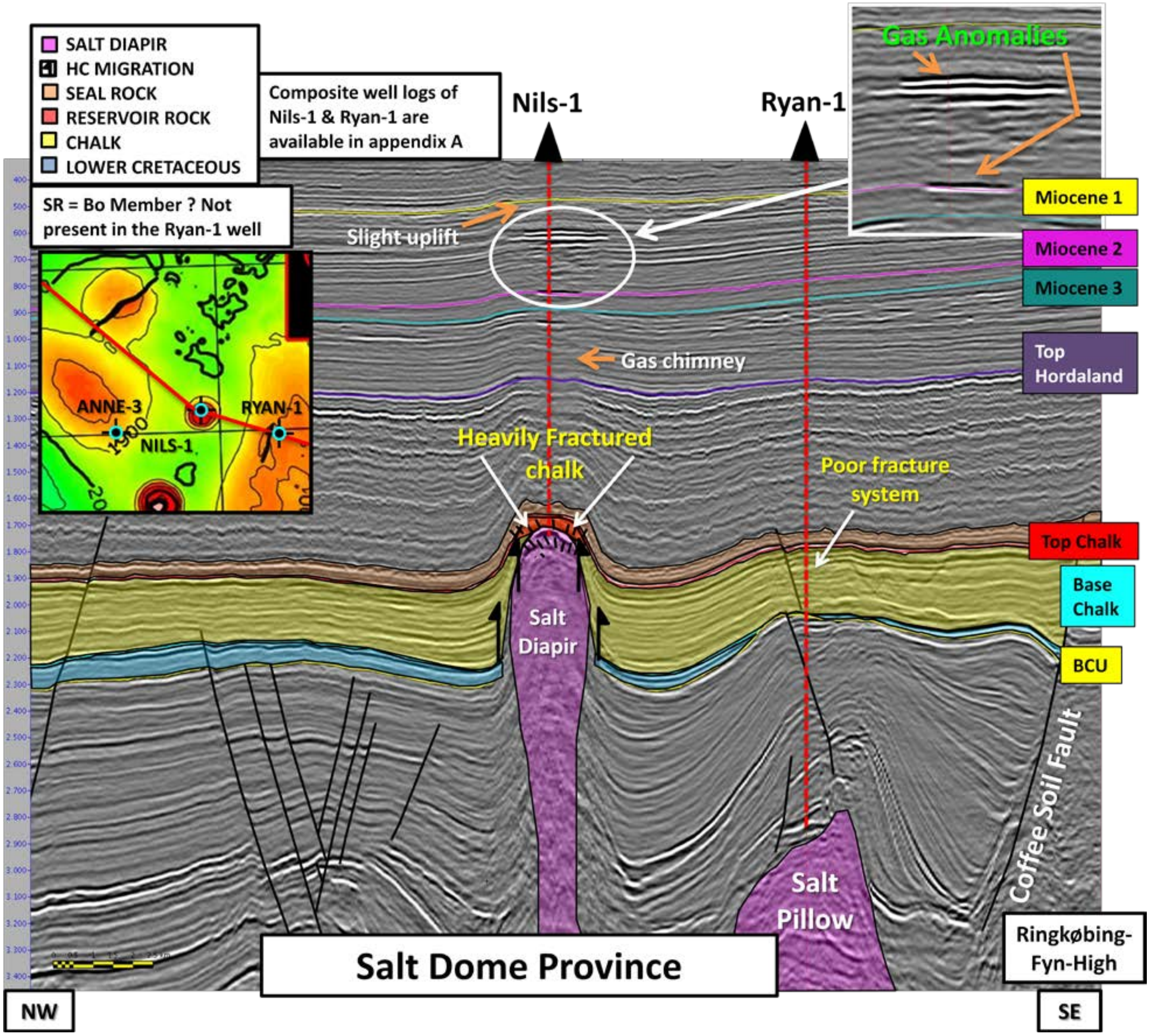

Figure 6.3.1: Seismic cross-section through the Regnar Field, showing the various elements and processes that make up the petroleum system. Notice the degree of the salt piercement (SISMAGE).

No source rock is interpreted in the section, which basically means that they are not encountered by the two wells, Nils-1 and Ryan-1 (See Figures F and I in appendix A). However, we know that there are economical HC accumulations on top of the salt diapir, which means that a source rock should be present. In Figure 2.5.1, the Bo Member is encountered in the Anne-3 well, which is the well that comes closest to the Regnar Field (See TWT-contour map in the figure). It is therefore likely to believe that the Regnar Field is also charged by these source rocks, since no other significant source rock has confirmed its presence here (Ineson et al, 2003).

One thing that is more certain though, is that the HCs have likely migrated upward by using the flanks of the salt diaper. The diaper represents also the most apparent four-way-dip-closure within the chalk, so most of the generated HCs would accumulate here. The other possibility could be within the chalk layers on top of the salt pillow. However, the Ryan-1 well has concluded that the encountered chalk corresponds to a fairly tight dense section with a poor fracture system. A poor reservoir quality is therefore found in this section, something that is backed up by the core analysis[8]. Other possible traps, like the ones created by the faults further down in the Jurassic section or traps formed in some other way, should always be kept in the back of the mind. In this case no other discovery was made, other than the one represented by the Regnar Field. It is therefore valid to assume that most of the HC migration from the Bo Member has accumulated above the salt diapir.

The core description and production tests performed within the Nils-1 well indicate that the HCs are essentially produced from the fractures that are a result of the almost catastrophic deformation of the Danian and Maastrichtian objectives[7]. This field represents therefore one of many similar petroleum systems, where a lot of uncertainties are associated with the fracture production. In other words an exact economic analysis of the field is unclear, since future methods could increase the production from these fractures.

A seal consisting of Palaeocene Shales is interpreted throughout the whole section and can be seen in the composite log of both wells. Strong gas anomalies are also found within the Tertiary layers and mark the underlying structure as an interesting feature. Wherever gas anomalies are present, HCs are involved. However, it’s up to us to define if the prospect responsible for these anomalies is of economical value or not.

A seismic to well calibration is done for the Nils-1 well and can be seen in Figure 6.3.2. The Top Balder, Top Chalk and Zechstein markers are defined on the figure, together with the seven logs, represented by the GR, density, velocity, Acoustic Impedance (AI), resistivity, synthetic traces

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[8] From the Completion Report of well Ryan-1, obtained from www.geus.dk

and the real seismic traces. The synthetic traces have been shifted with 14 ms down to better fit the various logs and the seismic and the resulting correspondence between them seem to be quite good. The observed interpretation also agrees more with the synthetic than with the seismic. However, there are some irregularities within the main chalk layers, when comparing the synthetic with the seismic traces. It is important to notice that the seismic on top of the salt diapir is quite distorted, so any detailed interpretation is hard to perform here. The seismic to well calibration also becomes difficult here.

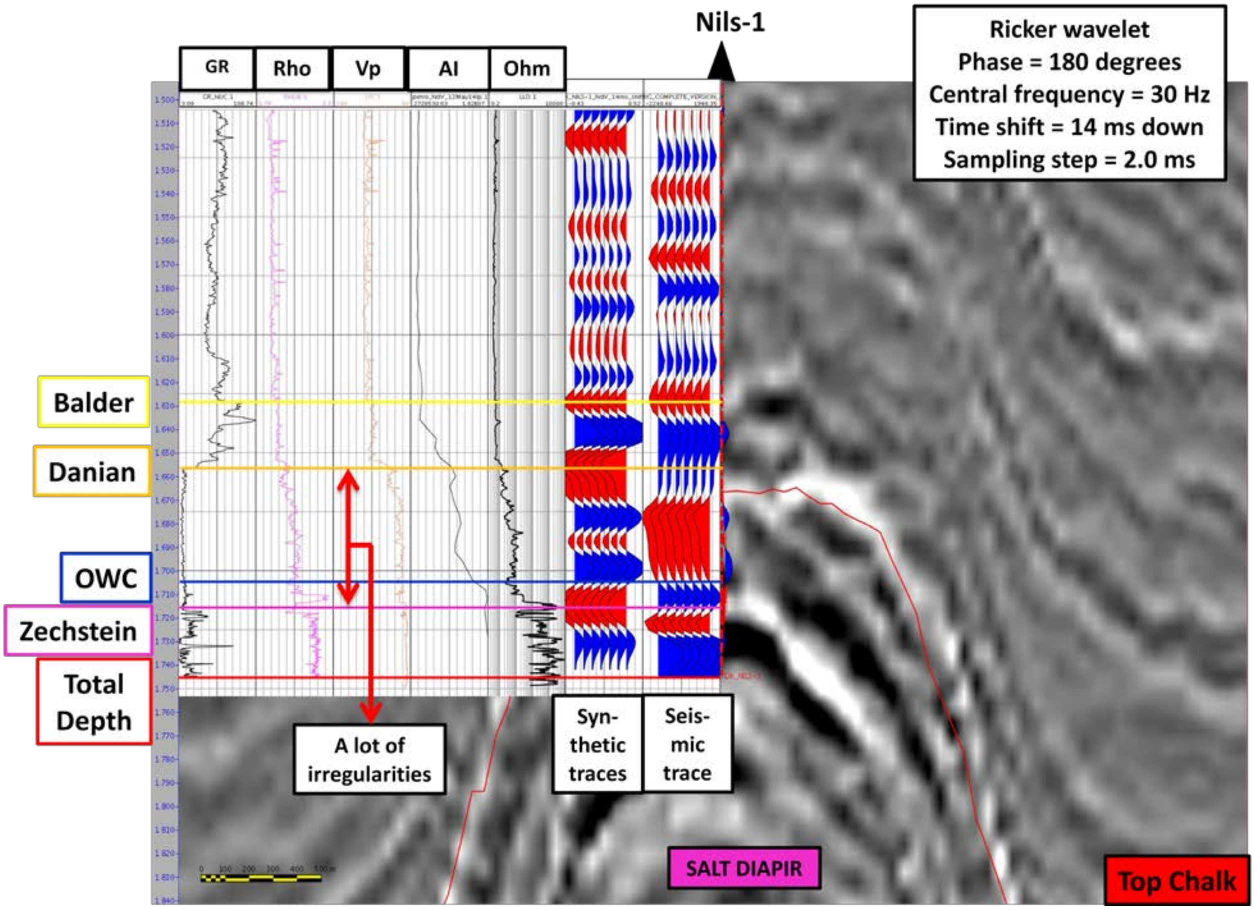

Figure 6.3.2: Shows the seismic to well calibration of well Nils-1 going through the Regnar Field on top of the salt diapir (SISMAGE).

An OWC is included in the logs of where I think it is located. I based this interpretation mostly on the resistivity log, since this will show increased values in areas containing HCs. The resistivity log shows a small decrease at the marker, before it increases strongly when entering the salt, so it is not based on any clear evidential material.

6.4 Roar Field

The Roar Field is a gas accumulation containing condensate that was discovered in 1968 by the H-1X well. The reservoir is located at a depth of 2025 m below the sea surface, where it consists of the reservoir rock chalk that ranges in the geological ages from Danian to Upper Cretaceous. When discovered it measured a reserve of 15 billion Nm^3 of gas (ens.dk$^{(2)}$). The results from the Roar-2 well, which is considered in this section, are encouraging in terms of the measured gas column as well as the gas composition. The well has also identified reworked masses of Maastrichtian chalk at the base of the Danian sequences, something that coincides with the interesting features interpreted as chalk slumps in Figure 5.2.1[9]. The field itself has been producing since 1996 and measured a remaining reserve of 0.3 billion Nm^3 of gas in 2012 (ens.dk$^{(2)}$).

The Roar Field is found within a small anticlinal closure known as the Bent structure, which is created by tectonic uplift. The structure itself is located within the depocentre known as the Roar Basin, which is believed to be one out of three separate depocentres that were developed after the Tail End Graben ceased to exist as a coherent structural element during the Early Cretaceous (Japsen et al, 2003). Results from the well H-1X indicate that the Danian to Upper Cretaceous chalk section has a good reservoir characteristic that is highly fractured and has a large porosity[10]. The tectonic uplift might be the cause for these fractures and it could also have triggered the gravity mass-movements of chalk that has led to areas of reworked masses (Japsen et al, 2003).

Post-rift sediments that consist of alternating layers of clay, sand and shale have later on been deposited on top of the structure.

Petroleum system cross section

The seismic cross-section that shows the tectonic uplifted area corresponding to the Bent structure can be seen in Figure 6.4.1. A large anticlinal structure can be seen in the section, which extends over the entire Tail End Graben. However, the Roar Field does not correspond to such a large area, but is located within the small closure represented by the marked red area. The extend

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[9] From the Completion Report of well Roar-2 & 2a, obtained from www.geus.dk

[10] From the Completion Report of well H-1X, obtained from www.geus.dk

of the structural closure that corresponds to the Roar Field can be seen in the TWT-contour map in the section. One can see that I have interpreted the source rock below the Lower Cretaceous section. They are again represented by the Upper Jurassic Bo Member, but are not found in the Roar-2 well, since it doesn´t go past the BCU (See Figure K in appendix A). There is on the other hand a nearby well called for Bo-1X that shows the presence of these source rocks again[11] (See Figure K in appendix A and Figure 6.1). Since the Roar Field is located on top of thick Jurassic successions, I believe the source rock to be present here and have based my interpretation on this. In addition one can see that the source rocks distribution in Figure 2.5.1 covers the Roar Field.

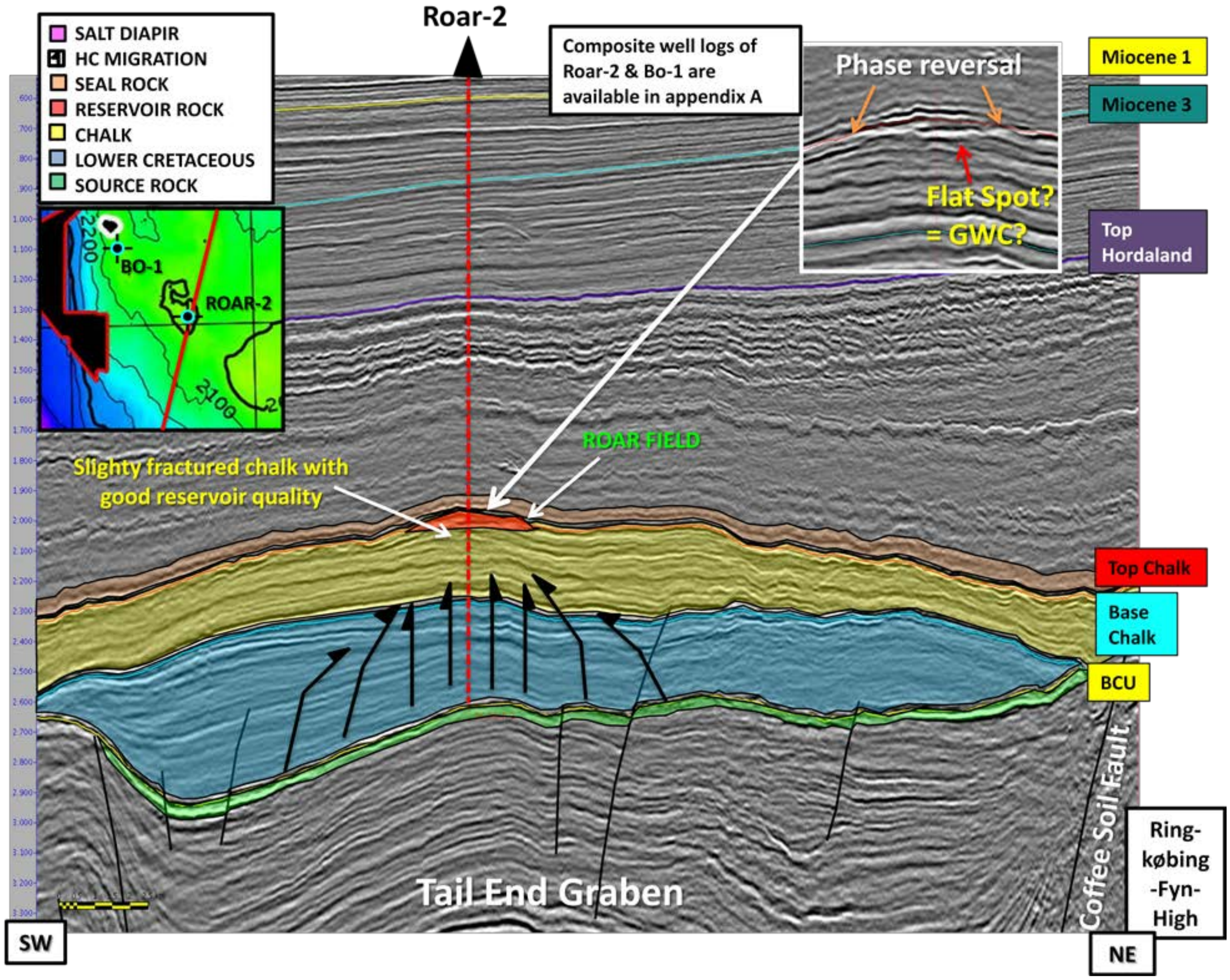

Figure 6.4.1: Seismic cross-section through the Roar Field, showing the various elements and processes that make up the petroleum system. Notice the small anticlinal closure representing the field and the absence of gas anomalies further above within the Tertiary layers (SISMAGE).

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[11] From the Completion Report of well Bo-1X, obtained from www.geus.dk

The HC migration has likely moved vertically upward through the thick Lower Cretaceous and chalk layers. Results from the core descriptions describe the chalk layer to be slightly fractured throughout most of the subdivisions, so HC migration would have been possible here. The Lower Cretaceous is on the other hand mostly comprised of calcareous claystone and limestone with some interbedded sandstone intervals. These layers will not prevent all the HC migration from moving upwards, but at some place possible traps could be generated. The secondary objective of the Roar-2 well was therefore directed onto the Lower Cretaceous limestones and marls[9].

The marked close-up seen in the section gives a closer view of the main reservoir marked by the red coloured area. Since the Roar Field is a gas field, a phase reversal just as the one seen at the Harald East Field can be observed at the Top Chalk horizon. This adds up quite well seen from the calibration performed in this well (See Figure 6.4.2), where the Top Chalk marker represented by the Danian is seen as a weak amplitude response marked by the opposite polarity. In addition a faint flat spot that marks the GWC of the reservoir can be seen on the seismic and is strengthened by the calibration. Again the GWC marker is set with the help of the resistivity log, but a clear AI increase that correlates to a strong positive reflectivity kick can also be observed. Both these features represent valid DHI´s that strengthen the validity of the petroleum system. The Base Chalk horizon also correlates well with the synthetic trace, which is marked with an opposite polarity kick than the GWC. This is reasonable since gas to water represents an increase in AI, while chalk to Lower Cretaceous sediments represents a decrease in AI.

The Roar-2 composite log marks the presence of Palaeocene shales on top of the chalk. These shales have acted as a good seal for the Roar Field, which can be seen by the lack of gas anomalies and shallow gas further above within the Tertiary layers. I.e. no gas has leaked out of the field, which means the seal is airtight.

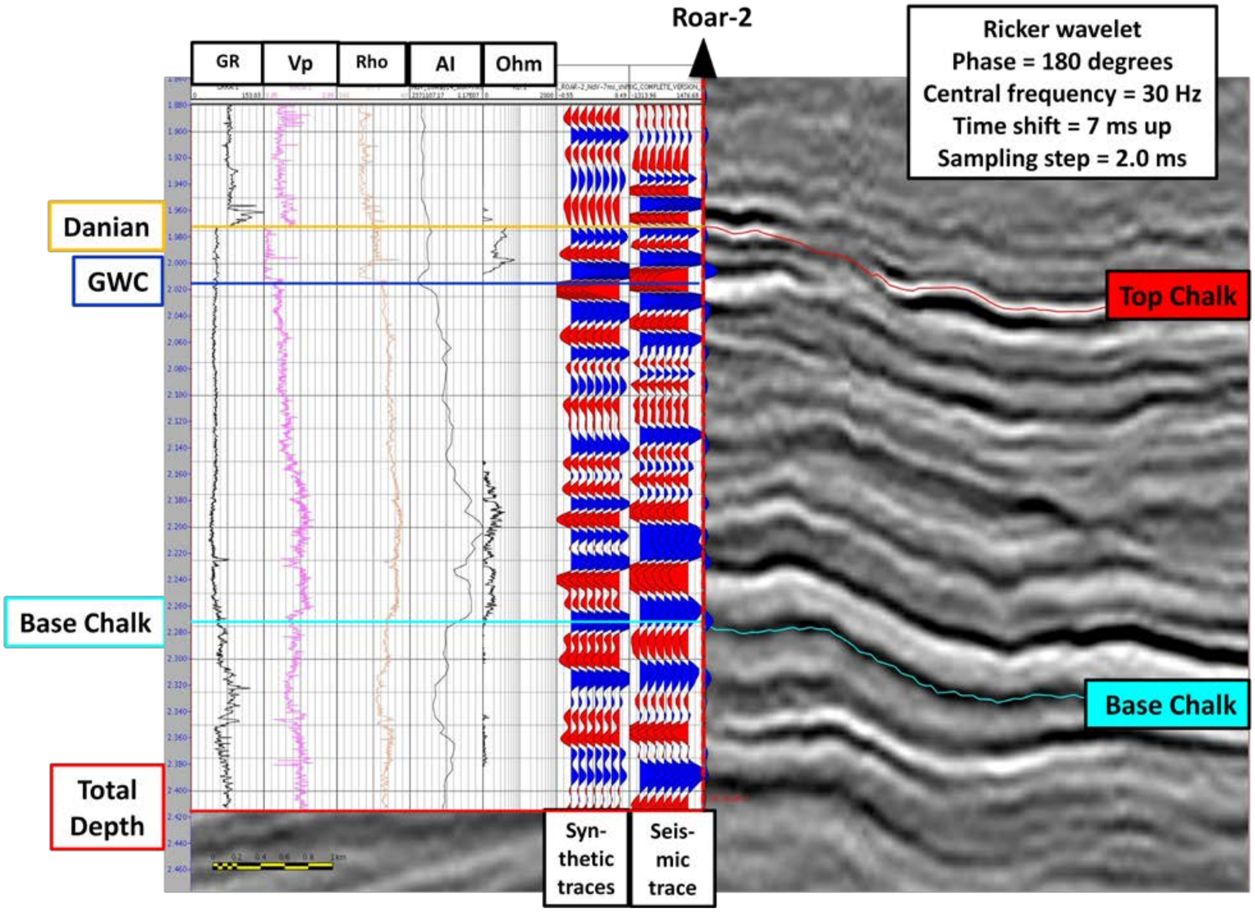

Figure 6.4.2: Shows the seismic to well calibration of well Roar-2 going through the Roar field. Notice the GWC correspondence in the logs and the seismic (SISMAGE).

6.5 Halfdan Field

The Halfdan Field was discovered in 1998 and is comprised of the Halfdan, Sif and Igor areas. The field contains a continuous HC accumulation and has been producing since 2000. The age of the reservoir rock ranges from Upper Cretaceous to Danian, where the SW part of the field primarily contains oil in the Maastrichtian layers, while the areas toward the north and east primarily consist of gas in the Danian layers. The reservoir is found at a depth of 2100 m below the sea surface and was estimated to contain reserves of 630 MMBOE and 32 billion Nm^3 of gas at the year of discovery (ens.dk$^{(2)}$). The Halfdan-1X (HDN-1X) well considered in this section, was drilled with the objective to appraise the reservoir properties and HC potential of the Maastrichtian reservoir in the area. Results from the well indicated a 75 meters thick oil column comprised within laminated chalk with argillaceous material and a low permeability[12]. In 2012 an estimation of the reserves concluded that there was still 277 MMBOE and 8 billion Nm^3 of gas left in the field (ens.dk(2)).

The accumulation of HCs within the Halfdan Field is found within a pocket in the chalk layers, which constituted a structural trap in earlier geological times. The trap was a result of the extensive rifting and the formation of the graben system during the Jurassic. During this time source rocks were deposited and later overlain by the Cretaceous and Tertiary sediments when the extension ceased and subsidence dominated (Albrechtsen et al, 2001). Through these years the structural trap has gradually disintegrated due to later movements in the subsoil, which has led to the migration of oil away from the trap in a SE direction. However, the HCs have only managed to migrate over a short distance due to the low permeability of the reservoir. The chalk and surrounding layers of the Halfdan Field are therefore characterized as being unfractured and almost not affected by any structural movements throughout the years (ens.dk(3)). The Halfdan Field lies hereby on the western flank of an inversion ridge and is not confined within a structural closure (Albrechtsen et al, 2001).

Petroleum system cross section

The cross-section of the seismic random-line that crosses through the Halfdan Field can be seen in Figure 6.5.1. The line crosses through the Danish Central Graben in a slightly SW to W direction and shows us that the field is located within the middle of the Tail End Graben, just north of the Salt Dome Province (See Figure 6.1). The general position of the field gives an indication of the low degree of tectonic activity that has affected the area, which in turn is something that is highly connected with the reservoir properties (Albrechtsen et al, 2001). The reservoir itself is for example comprised of unfractured low permeability chalk, since no major tectonic events have affected the chalk in this area, compared to the previous described chalk reservoirs. Almost flat deposition of chalk and Lower Cretaceous shales dominates the area, where a few to almost none of the faults affect the reservoir domain. However, one distinct feature that also describes the general trapping mechanism of the Halfdan Field can be seen in the section. This feature is represented by the up-dip thinning and pinch-out of the chalk layer, which is caused by late structural tilting. The main HC bearing section is located within such a pinch-

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[12] From the Final Well Report of well HDN-1X, obtained from www.geus.dk

out of the Maastrichtian chalk that thins towards the Tyra-Igor inversion Ridge. (See the structural outline of the field in the associated TWT-contour map in the section.)

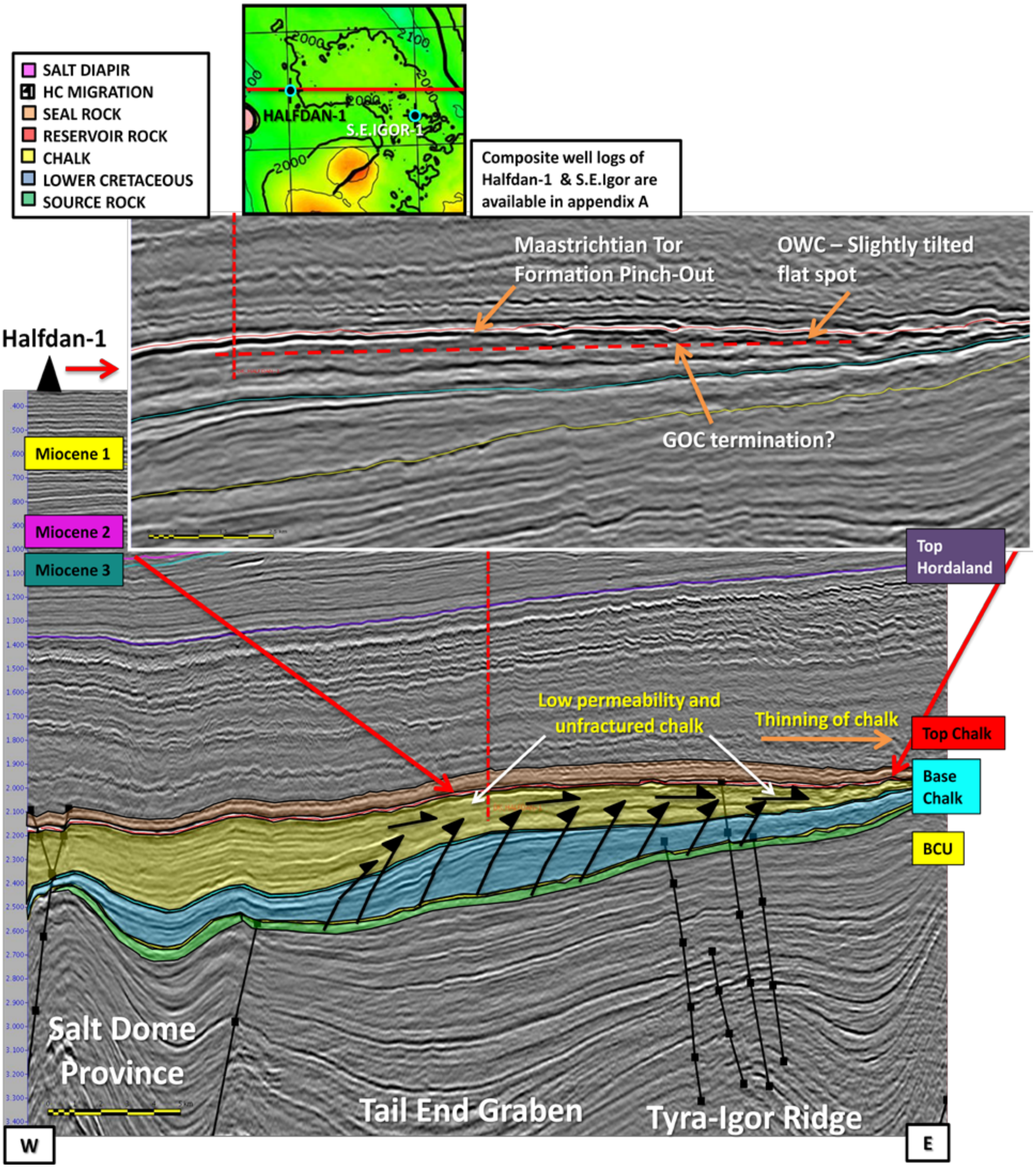

Figure 6.5.1: Seismic cross-section through the Halfdan Field, showing the various elements and processes that make up the petroleum system. Notice the stratigraphical closure represented by the pinch-out in the chalk layer and its tilted flat spot (SISMAGE).

The source rock responsible for charging the Halfdan Field is represented by the Bo Member and is interpreted along the entire Tail End Graben. Again the interpretation is based on the marked presence of these source rocks within a nearby well that is not seen in the section, namely the S.E. Igor-1 well[13] (See Figure L in appendix A). The well that on the other hand can be seen in the section, Halfdan-1, doesn't go deep enough to encounter the source rocks. However, based on the results from S.E. Igor-1 I believe the source rock to be present here

The charge history of the Halfdan Field is as of today still poorly understood, but it is believed to have occurred through several stages of HC migration. These stages are represented by rapid fluid pulses entering the field through a relatively deep-seated fracture system (Albrechtsen et al, 2001). The first migration has likely occurred during the Eocene to early Oligocene, when the Halfdan structure was still part of a four-way dip closure present at the Top Chalk. The porosity at this time was considered to be high due to the shallow burial depths, which means that the fluid migration processes could have been significantly faster compared to the present day migration velocities in the chalk. The structural closure has later on during the Oligocene and Pliocene gradually disappeared, because of the rapid subsidence that took place. This resulted into the oil migration away from the field (Albrechtsen et al, 2001). The HC migration changed on the other hand its direction into the Halfdan Field during the Pliocene, because of the rejuvenation of the inversion along the Tyra-Igor Ridge that dramatically changed the basin configuration (Albrechtsen et al, 2001)(Figure 6.5.2). At the same time rapid sedimentation and subsidence occurred, which resulted into several large fluids volumes being expelled from the deepest part of the basin. This has resulted into a complex fluid distribution within the Halfdan Field, where evidence from the pressure gradients confirms that the fluids have not reached equilibrium. I.e. oil is still migrating at some places without being trapped (Albrechtsen et al, 2001). However, since the fluid entry pressures are very high for the chalk compared to other reservoir rocks and the general permeability is low, this has resulted in very slow migration velocities, when measured in geological time (Albrechtsen et al, 2001).

I have tried to describe these migration patterns within the sections, but they are of course based on what's known about them. Therefore, they don't represent a final answer.

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[13] From the Completion Report of well S.E. Igor-1, obtained from www.geus.dk

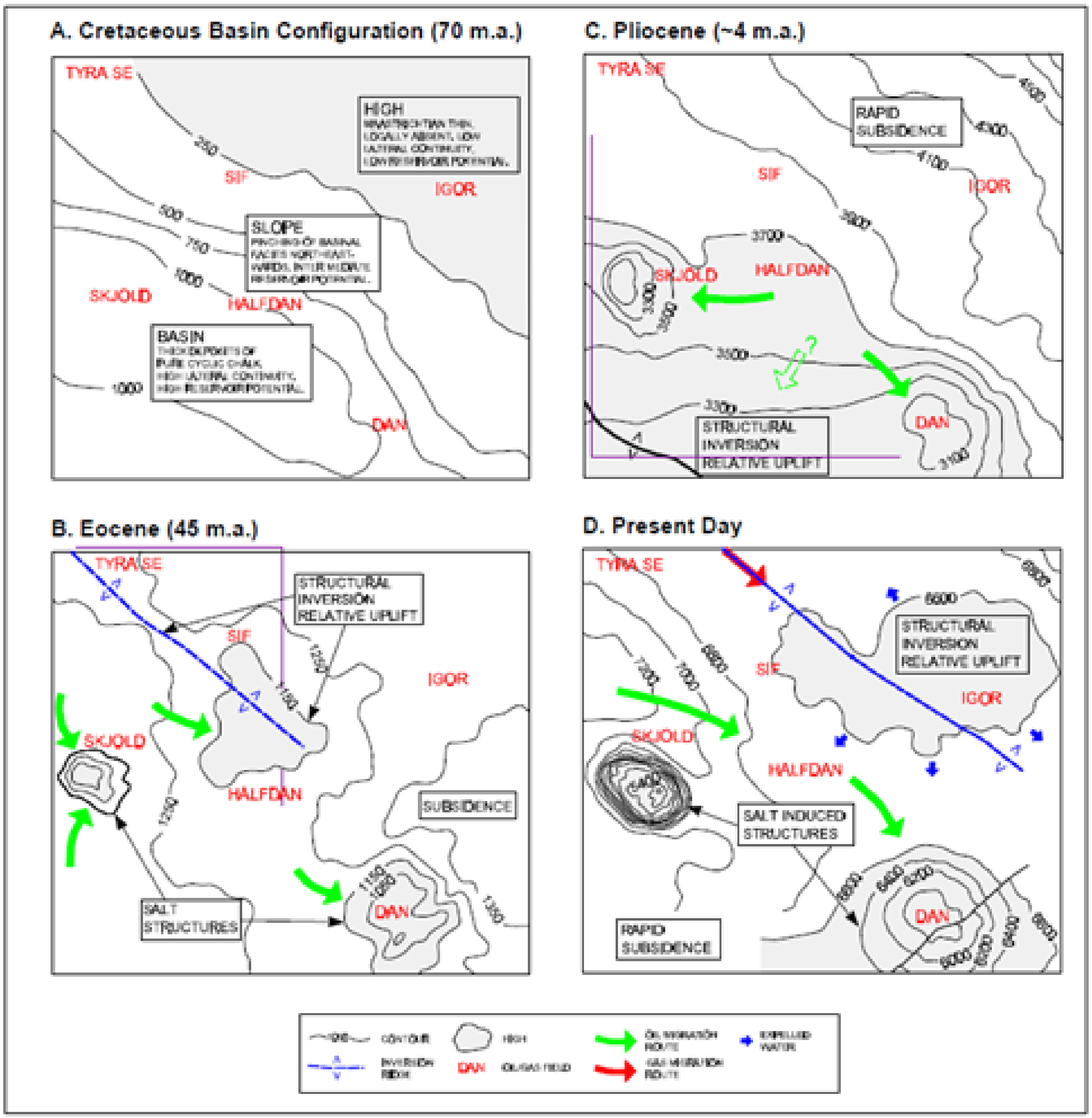

Figure 6.5.2: Shows the structural evolution and migration history within the Halfdan area (Albrechtsen et al, 2001).

In the zoomed-in area on the Figure 6.5.1, we can see the pinch-out of the Top Maastrichtian Tor Formation when going west. Below this white reflector a vague tilted flat spot can be seen, which likely corresponds to the OWC. It terminates almost at the end of the section. There should also be a GOC present, just below the Top Chalk horizon, since there have been indications of gas in the Halfdan Field. Both these contacts are better viewed in the corresponding well calibration observed in Figure 6.5.3 Here it can be seen that the GOC is found just at the top of the chalk layer, represented by a strong positive kick. A very dim reflector represents on the other hand the OWC, where the marker is located at a strong decrease in resistivity. Two internal chalk horizons and the overlaying Balder horizon can also be seen in the calibration and it looks like the synthetic traces are very well calibrated with the corresponding seismic responses seen on the seismic. The calibration provides us thereby with a lot more information than only looking at the seismic or well data separately.

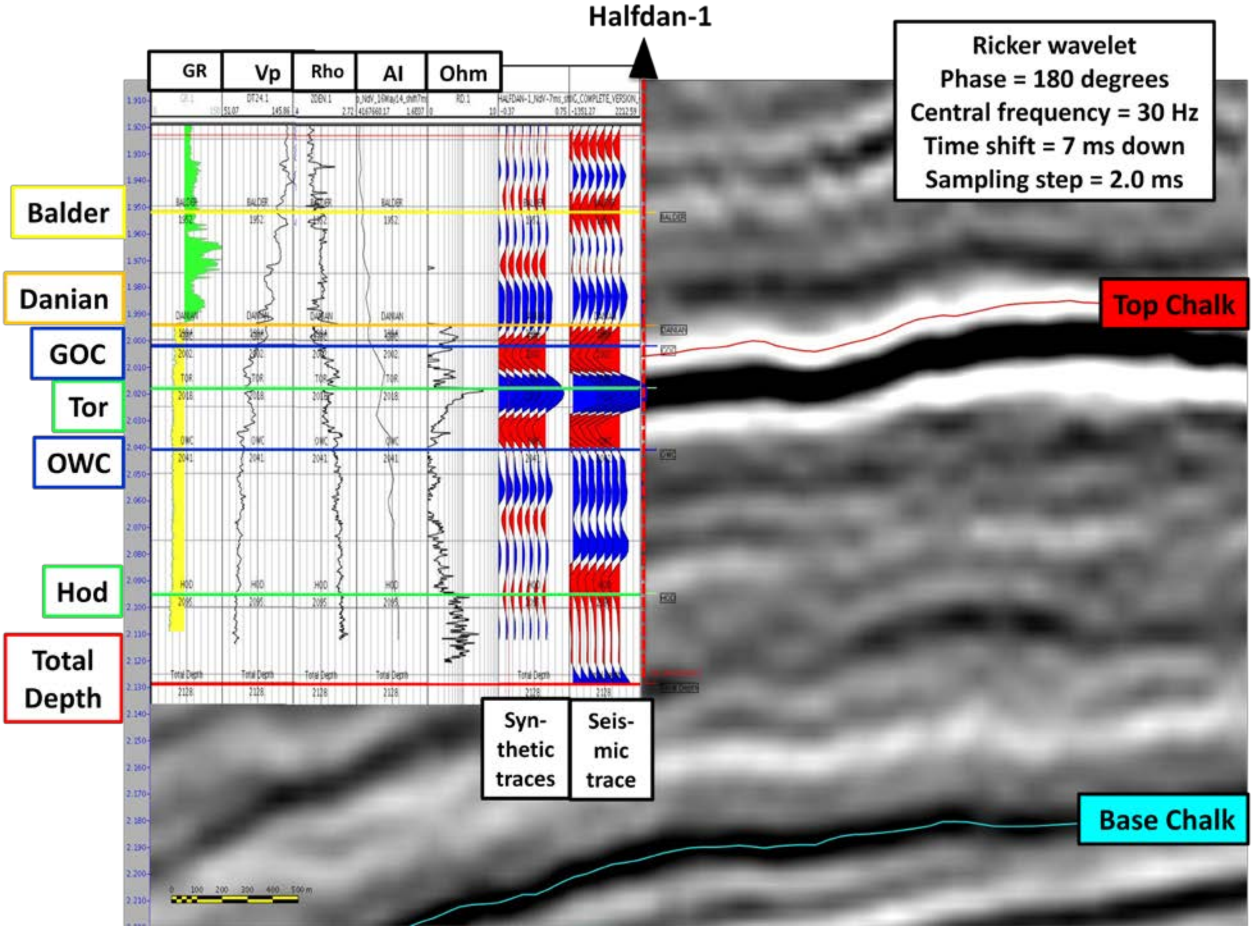

Figure 6.5.3: Shows the seismic to well calibration of well Halfdan-1 going through the Halfdan Field. Notice the GOC, OWC and the correspondence in the logs and the seismic (SISMAGE).

The seal is interpreted throughout the whole section and corresponds to the Palaeocene Shales (See Figure L in appendix A). The shales contribute to trapping the complex fluid distribution within the field, but are not enough for the HC accumulation to reach a state of equilibrium. Main reasons such as the relatively poor flow properties in the tight chalk and the capillary hysteresis effects prevent this state of equilibrium from happening (Albrechtsen et al, 2010).

To summarize it is evident that the Halfdan Field is an extremely important discovery, since it gives an example of a stratigraphically and dynamically confined HC find, where no structural trapping is involved (Albrechtsen et al, 2001). It therefore represents the future of HC exploration within the chalk layer of the whole North Sea area.

6.6 Hanze Field

The Hanze Field is located in the Dutch offshore sector and was discovered in 1996. It contained a total reserve of 34 MMBOE and around 1 Nm^3 of associated gas (Guasti et al, 2010). The age of the reservoir rock ranges from Upper Cretaceous to Danian, were the main reservoir is located in the Ekofisk Formation and in the Maastrichtian part of the Ommelanden Formation. The reservoir is characterized as being naturally fractured; having a clean porosity and is located at a depth of 1340 m below the sea surface (Guasti et al, 2010). As of today the field is still producing.

The Hanze Field is situated directly above the salt of a major salt diapir (Figure 6.6.1), where the trap is formed as an anticlinal structure (Guasti et al, 2010). It resembles the Regnar Field on the Danish sector and its formation has likely occurred through the same tectonic events as the Harald East, Gorm and Regnar fields. The field is overlain by hydraulically sealing Lower Tertiary shales, where the overburden rocks consist of alternating shale and sand layers throughout the Tertiary and Quaternary (Guasti et al, 2010). The reservoir-, seal- and overburden rock are considered as post-rift sediments, while the source rock is classified as being syn-rift.

Petroleum system cross section

A cross-section of the Hanze Field can be seen in Figure 6.6.1. The various elements that make up the petroleum system are very similar to the Harald East, Gorm and Regnar fields, where the main difference is in the source rock, which is represented by the Posidonia Shales in this case. This is proven by the distinct marker seen in the figure, as well as the marked section in the composite well log corresponding to well F3-6 in Figure H in appendix A. The source rock is mainly confined to the thick Jurassic sections in the middle of the Dutch Central Graben and could be followed throughout the section. A lot of the HC migration has therefore occurred vertically at the side of the salt structure, where the presence of faults has contributed as an extra help to the migration. The HCs are likely to be captured on top of this salt structure, if the right properties are in place, which is the case for the Hanze Field. However, it is possible to imagine other HC migration pathways, concerning the distribution of the Posidonia Shales. There are many faults present that could provide other pathways to the chalk layer and the thin chalk within the graben could also provide possibilities for stratigraphic trapping. One should on other hand be careful with these traps, since they could have many spill points and generally act as a poor trap. In addition, the Jurassic section is very thick in the graben and it could therefore be more reasonable to look for HCs that are originated from the Posidonia Shales in the Jurassic layers. This theory is strengthened where thicker chalk layers are present, since the Lower chalk in these areas can act as a seal. If Jurassic sand sections directly underlie these layers, possible petroleum prospects could be identified, when the other elements of the petroleum system are in place.

As mentioned earlier, the field is directly overlain by Lower Tertiary shales, classified as the Lower Palaeocene Landen Formation that belongs to the Lower North Sea Group (See Figure G in appendix A). The layer provides a tight seal in this case, with the help of a fault on the left side. It is present throughout most of the graben and can also be seen in the composite well log corresponding to well F3-6.

No real DHI can be observed within the reservoir rock that could give us an indication of the field's size. A large gas anomaly is on the other hand seen above the field within the Tertiary layers.

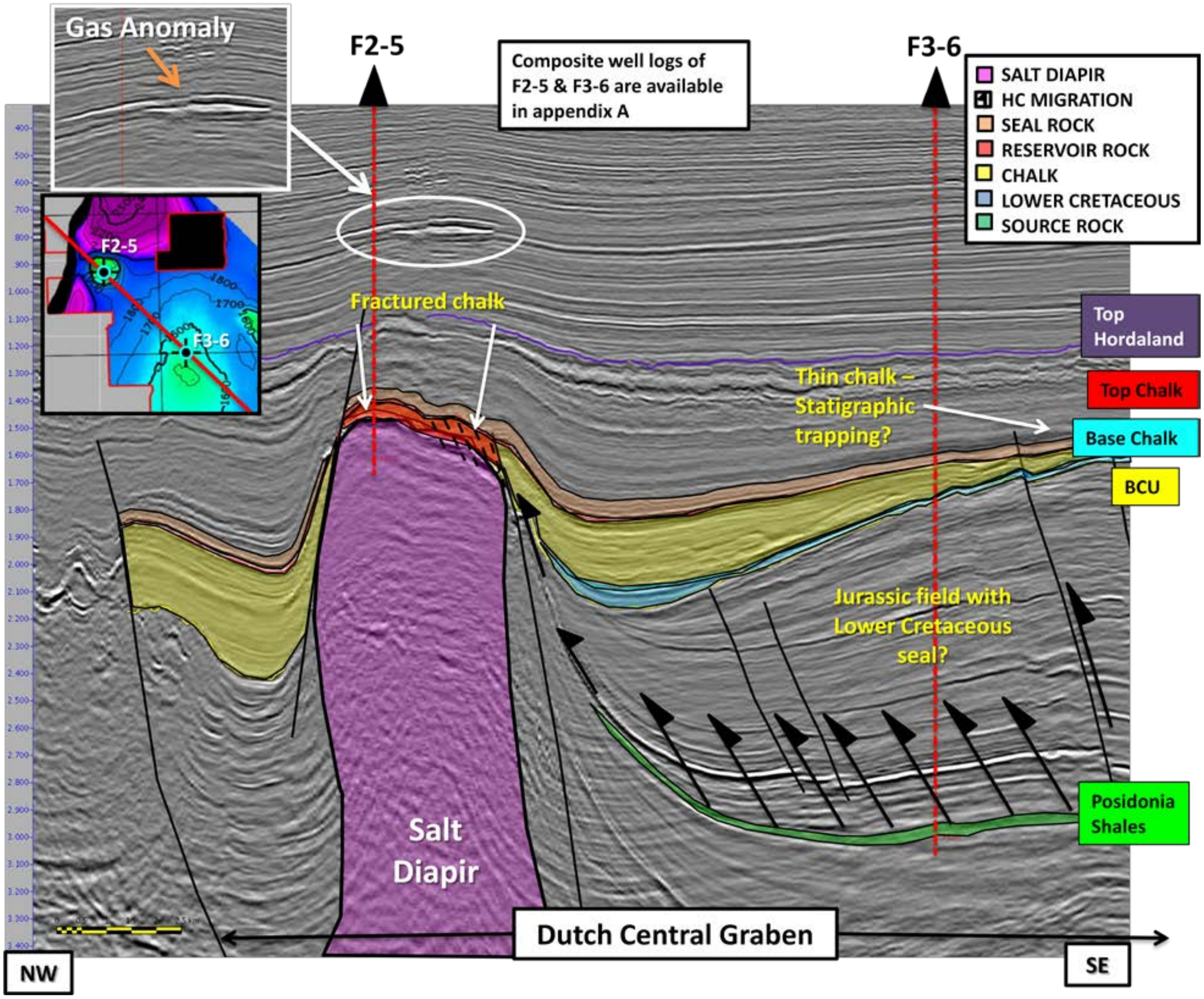

Figure 6.6.1: Seismic cross-section through the Hanze Field, showing the various elements and processes that make up the petroleum system. Notice the presence of the Posidonia Shales (SISMAGE).

6.7 Dry wells

6.7.1 Wells Tove-1 and Vagn-2

In Figure 6.7.1, three interesting structures created through salt tectonics can be seen. From a first look, without knowing if the structures have been drilled or not, they look like very promising prospects. One can notice that the salt structures provide nice four-way dip closures within the chalk and possible HC migration pathways at the flanks. It is likely to assume that the chalk is fractured on top of the structures, as a result of the halokinesis, which in turn could provide nice reservoir properties. A seal is also present throughout the whole section and all three prospects strengthen their validity with the presence of gas anomalies further above within the Tertiary layers. Other explorers have thought the same thing, which has therefore led to the drilling of all three structures. However, only the Regnar Field has led to an economical discovery. Why?

Results of the well Tove-1

When Tove-1 was drilled, the primary objective in the well was the Danian to Maastrichtian chalks. Approximately 60 meters of scattered HC shows were encountered, mostly associated with fractures and with fractured chert and argillaceous laminae[14]. This led to the execution of two production tests, where test no. 1 was performed on the Maastrichtian and test no. 2 on the Danian (See Figure M in appendix A). Test no.1 concluded an average of 1561 barrels of oil per day (BOPD), while test no. 2 had an average of 1621 BOPD. The well was plugged and abandoned in 1978, summarizing the prospect of having a questionable commercial significance, although the well was in a favourable structural position. Further evaluation of the prospect should be considered through improved seismic re-analysis and reserves determination[14].

So even though HC shows were encountered, no economical value could be extracted from the prospect. The core descriptions from the well where all cut in the Danian-Maastrichtian chalks and describe it as being highly fractured with pure and moderately hard compactness. Because of the chalks fractured nature and the shallow closure in the Tertiary, it indicates that there was probable late Tertiary salt movement. This movement could be the cause for making the trap less functional, which in turn has led to possible spill points and leaky traps[14].

Results of the well Vagn-2

The primary objective of well Vagn-2 was based on the Danian to Maastrichtian chalks, with no secondary objectives expected. The extracted cores, starting from the top chalk layer, indicated poor to fair oil shows throughout the chalk layer that were scattered and generally only associated with fractures. The logs also indicated the matrix of the objective zones to be water wet. Still, based on the HC shows in the fractures, open-hole testing was conducted to evaluate any possible fracture potential (See Figure M in appendix A). These tests revealed that there were no signs of oil in the Maastrichtian and that the production was too low to measure within the Danian. So

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[14] From the Completion Report of well Tove-1, obtained from www.geus.dk

from the wells optimum structural position and the negative results it was considered that additional drilling on the Vagn prospect is not warranted thus leading to its plugging and abandonment in 1978[15].

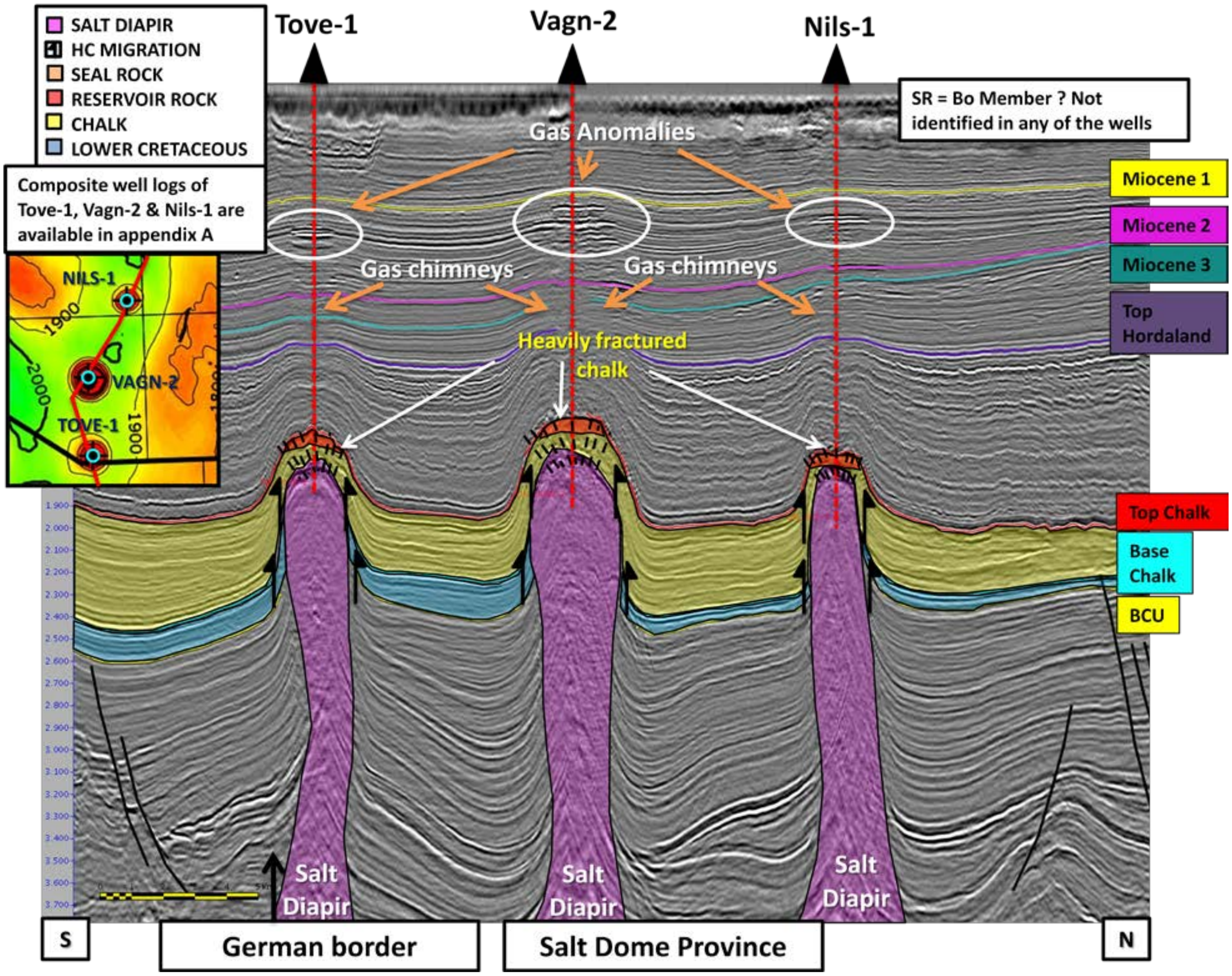

Figure 6.7.1: Seismic cross-section through the dry wells Tove-1 & Vagn-2 compared to the economical discovery found by well Nils-1. Notice the extreme degree of salt piercement which influence affects layers as far as the Quaternary (SISMAGE).

Trying to explain the paucity of HC shows indicated by the well one needs to consider the structure into further detail. It appears that the structure is a result of late salt movement, which has caused considerable fracturing within the primary objective. This extensive fracturing and the addition of having a shallow closure, has allowed most of the HCs to escape, at least partially, to

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[15] From the Completion Report of well Vagn-2, obtained from www.geus.dk

the overlying beds. The shallow closure has also possibly caused a bathymetric expression on the sea floor during the Tertiary, which has resulted in the deposition of shallow sands that later on have trapped the gas. As we know, this gas can be seen in the form of strong anomalies on the seismic[15].

6.7.2 Results of the well Iris-1

The well Iris-1 is located on top of a tectonic uplifted area that represents a large anticlinal structure (Figure 6.7.2). The anticlinal outlines of the four-way dip closure are best represented by the Base and Top Chalk horizons, which also represent the secondary objectives of the well. The primary objective was to test the Upper Jurassic sands[16].

The well encountered some signs of HCs that occurred in the chalk, but the fracture porosity in this area is not well developed. The reservoir properties are therefore not optimal, which seems logical considering that the tectonic activity in this area has been low. The composite well log in Figure N in appendix A also indicates the absence of the Bo Member, since no distinct increase in the GR log can be noticed. It is therefore uncertain, if any source rock is present in this area that could have charged the closure within or below the chalk. However, another structural closure more to the left on the section is represented by the Svend Field. This field corresponds to a discovery that is similar to the Regnar field and is charged by the Bo Member source rock. A source rock is therefore close by, so the closure penetrated by well Iris-1 should not be disregarded so quickly. However, the possibility of finding HC in the chalk within this area is extremely low, most importantly because of the poorly developed fracture porosity.

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[16] From the Completion Report of well Iris-1, obtained from www.geus.dk

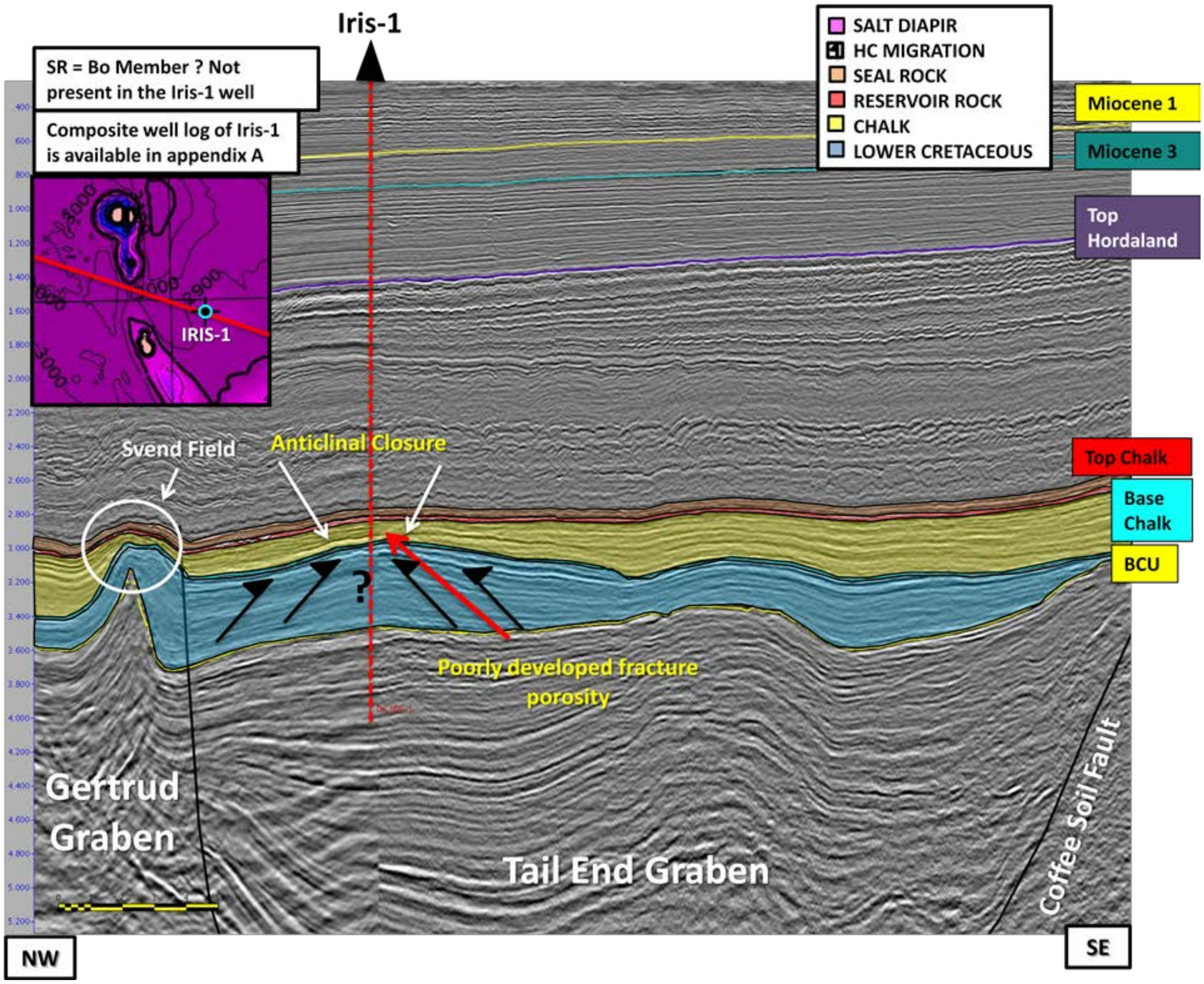

Figure 6.7.2: Seismic cross-section through a similar anticlinal uplifted area found at the Roar Field, showing the dry well Iris-1. Notice the absence of the Kimmeridgian Clay source rocks, the Bo Member (SISMAGE).

7. Remaining prospectivity analysis

7.1 Interesting locations

Most of the discovered chalk fields are located within the Salt Dome Province in the southern part of the Danish Central Graben (See Figure A in appendix B). All the structural closures have been drilled here and what´s left is to find similar stratigraphically confined HCs like the Halfdan Field. It would also be interesting to understand why some of the drilled structural closures are dry. The locations of the seismic sections seen in the sub-chapters 7.1.1 and 7.1.2 correspond to the red lines found in Figure I in appendix B.

7.1.1 Drilled structural closures

Inge High

The NW part of the graben shows surprisingly few discoveries, limited to the Harald East, Svend and South Arne fields (Figure A in appendix B). There is yet to be made a chalk discovery to the far west, which in turn marks an interesting area. The source rocks are present here as seen in Figure 2.5.1 and the highs provide possibilities for structural closures (See Figure 5.1.1). There are a lot of Jurassic faults here that provide nice migration pathways and the area contains places with thin chalk that correspond to nice reservoir properties (See figure 5.2.2, 5.2.3 & 5.4.1). In this part of the graben I want to look closer at the Inge High structure, which has been drilled by the Inge-1/P-1X and Isak-1 wells.

Inge-1/P-1X:
The primary objective in this well was to test the pre-chalk section, while the Danian chalk was considered as a secondary objective. No shows of HCs were encountered and the chalk itself was very tight and hard with no cavities or fractures[17].

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[17] From the Completion Report of well Inge-1/P-1X, obtained from www.geus.dk

Isak-1:

As a primary objective, the well was to test the HC potential in reservoirs of the Upper Jurassic Heno Formation, but also at any other level. A secondary objective was based on acquiring data on the reservoir quality and stratigraphy of the Chalk Group. Results showed a water bearing chalk with poor porosity and very weak shows[18].

Both wells can be seen in the seismic section in Figure 7.1.1. Even though the corresponding completion reports show negative result, I will not be so quick as to disregard this structure. This is primarily because of the well locations relative to the main structural closures, which can be seen from the small TWT-contour map in the section. The map shows us that the line goes through the upper left “corner” of the structure, which represents the main accumulation points. The other part of the structure is on the other hand not drilled and a seismic section through this region can be seen in Figure 7.1.2. Through looking at this figure, I would like to think about the possibility of stratigraphic HC trapping. The reason for this is based on the NE to SW thinning of chalk layers and the indication of some reflection terminations of the internal chalk layer horizons. These terminations could provide stratigraphic traps and prevent the HCs from migrating all the way to the main accumulation point. This could in turn be a possible explanation for the dry wells in Isak-1 and Inge-1/P-1X. In addition, the presence of reworked chalk is indicated by erosion and re-deposition of the underlying Maastrichtian chalk[17]. This means that the porosity is higher than when the chalk would not have undergone a re-depositional process. The play becomes therefore more and more similar to the Halfdan Field (Bramwell et al, 2001).

There are no distinct DHI’s found within or above the chalk layers. This could be interpreted in two ways. Either there are no HCs here, so no gas seepage is observed or there are HCs here and the overlaying seal is airtight. As we have seen from the Harald East and Roar fields in chapter 6, it is no obligation to have gas chimneys or shallow gas anomalies on top of the fields to have HCs present.

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[18] From the Completion Report of well Isak-1, obtained from www.geus.dk

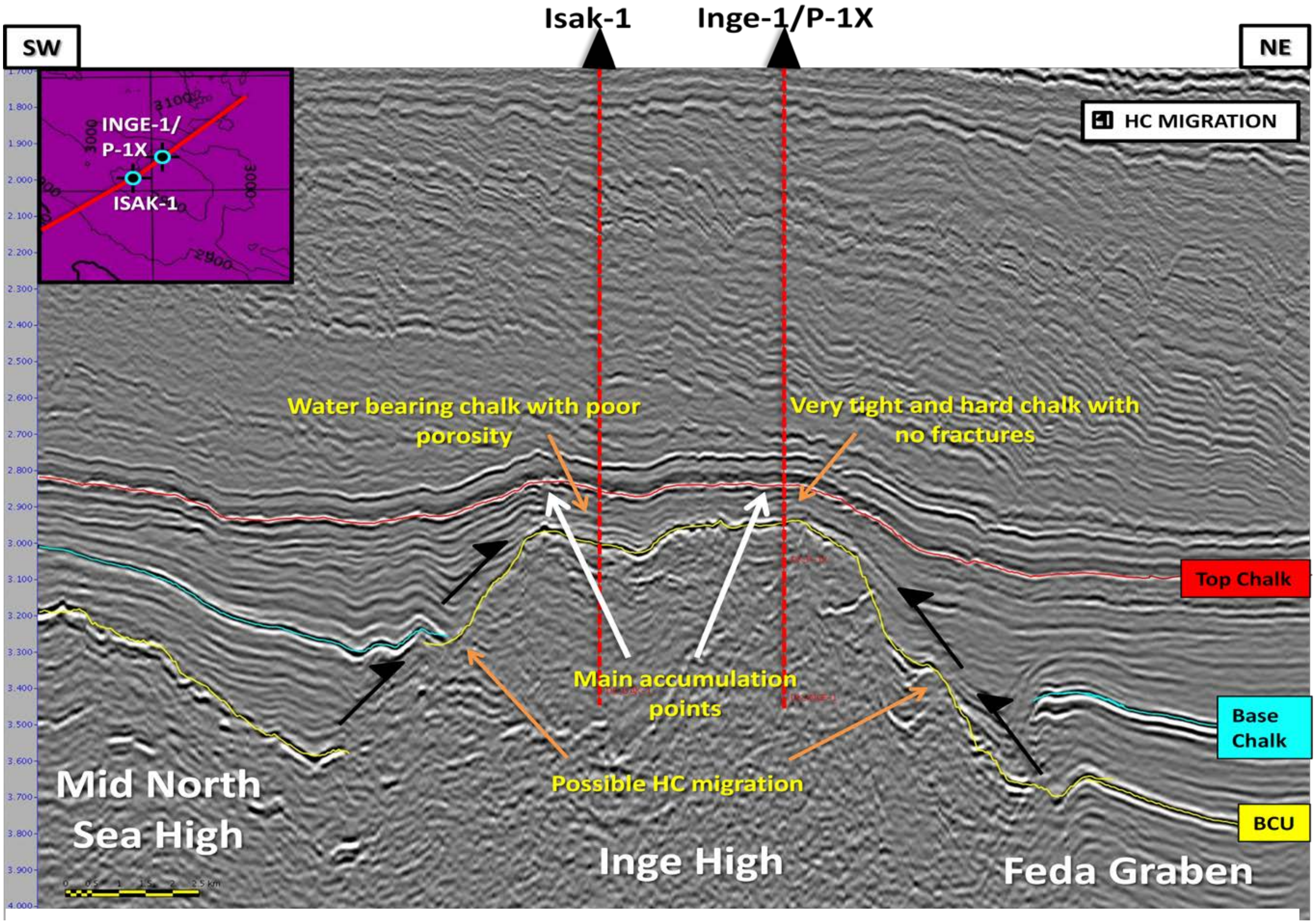

Figure: 7.1.1: Seismic cross-section of the random-line through the NW part of the Inge High structure that shows the projection of the two wells, Isak-1 and Inge-1/P-1X (SISMAGE).

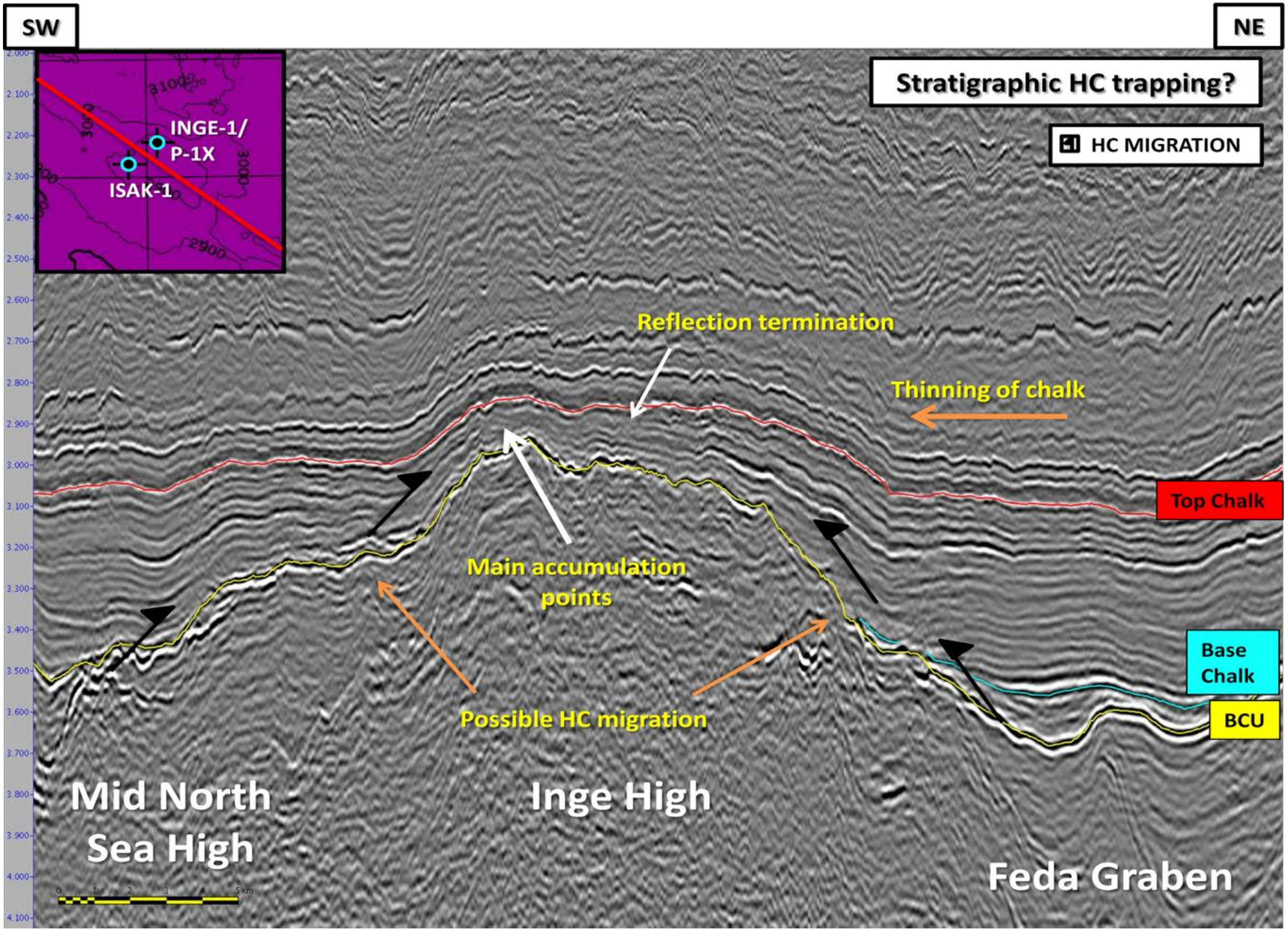

Figure: 7.1.2: Seismic cross-section of the random-line in a NW to SE direction over the Inge High structure. Notice the reflection termination and thinning of chalk that could provide stratigraphic trapping of HCs (SISMAGE).

Per-1:

Another interesting structural closure is located just outside the Danish Central Graben on top of the Ringkøbing-Fyn-High (Figure 7.1.3). Considering the contour-line that marks the structural closure on the attached TWT-contour map, it is a big closure and only drilled by one well. The primary objective of the well was to test the low amplitude anticline at the chalk level, with a secondary objective directed to the Lower Cretaceous sands. Poor to fair oil shows were found in the chalk, but cores indicated that all zones in the well were water wet. The Ekofisk and Maastrichtian indicated positive porous reservoir characteristic, but the DST indicated no flow. Based on these negative results, the well concluded that additional drilling on this prospect is not warranted pending more favourable seismic or other information[19].

Personally I think this prospect should not be neglected so easily, since the majority of elements and processes that make up the petroleum system are in place. There are on the other hand some aspects that make the prospect less likely. The first thing one notice is the lack of source rocks on the seismic within the Tail End Graben, which is confirmed by the rocks distribution seen from Figure 2.5.1. Secondly, no shallow gas anomalies are observed above the structure and thirdly in some places the structural closure is in direct contact with the Jurassic source beds, which might have led to migration away from the prospect.

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[19] From the Completion Report of well Per-1, obtained from www.geus.dk

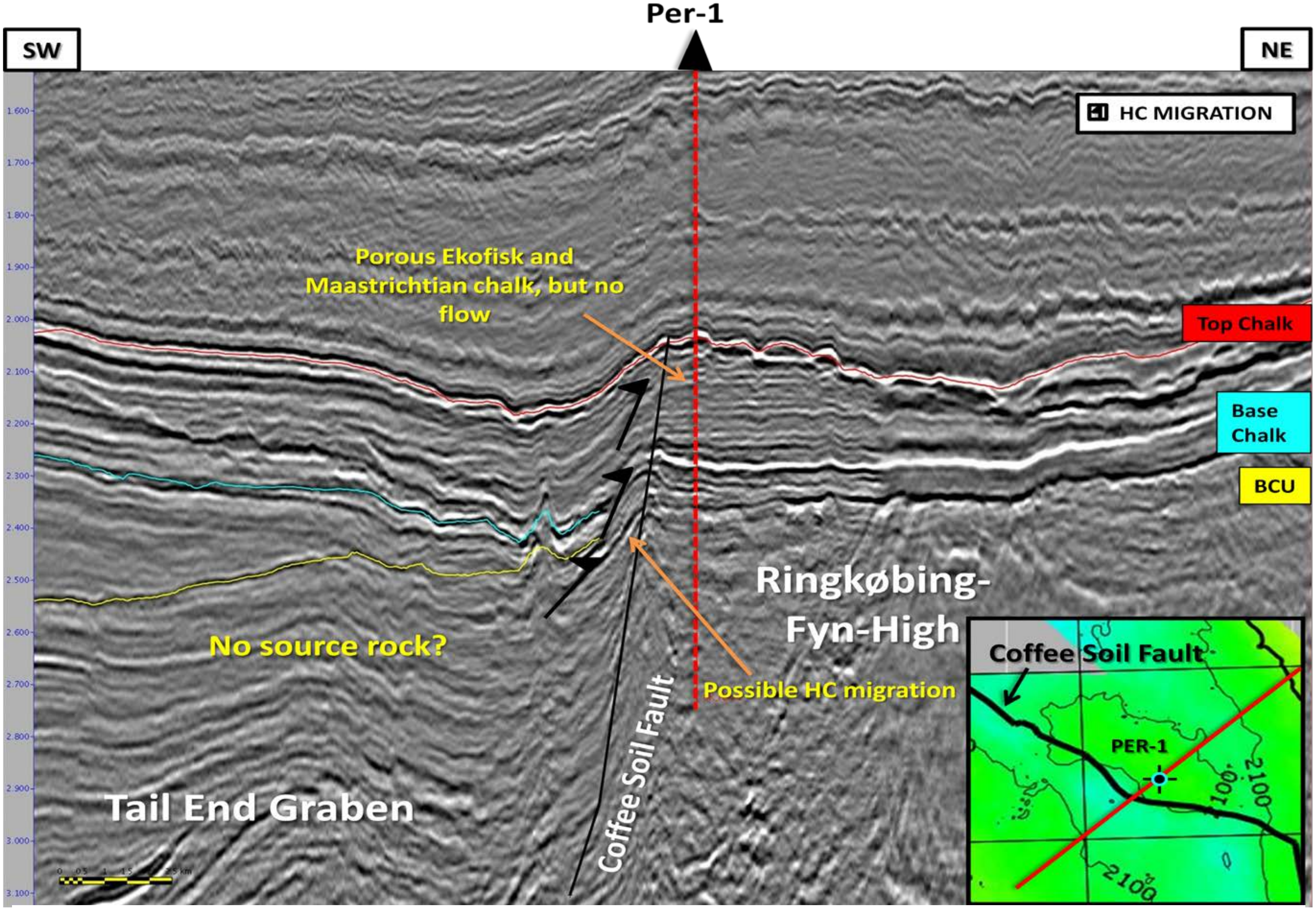

Figure: 7.1.3: Seismic cross-section of the random-line through the structural closure that is drilled by the Per-1 well (SISMAGE).

7.1.2 Undiscovered stratigraphically trapped HCs

Another example of stratigraphically confined HCs can be seen in Figure 7.1.4. The prospect is located north of the Regnar Field and shows similar petroleum play characteristics as the Halfdan Field. As stated in chapter 6.5, the presence of source rocks has been identified by the nearby S.E. Igor-1 well, which can be seen on the attached TWT-contour map (Figure L in appendix A). A pinch out of the chalk layers can be seen moving north and a distinct reflector termination is marked on the section. This geometry symbolizes the possibility for a stratigraphic trap.

The area has on the other hand been neglected based on the results from the S.E. Igor-1 well. This well's primary objective was to test the Danian chalks, which showed poor oil shows and no moveable HCs were indicated. The core descriptions also presented poor reservoir conditions, since the chalk was massive and hard, with no fractures[13]. However, the well was drilled as early as in 1983 and since the Halfdan Field wasn't discovered until 1998, a similar find could be discovered here.

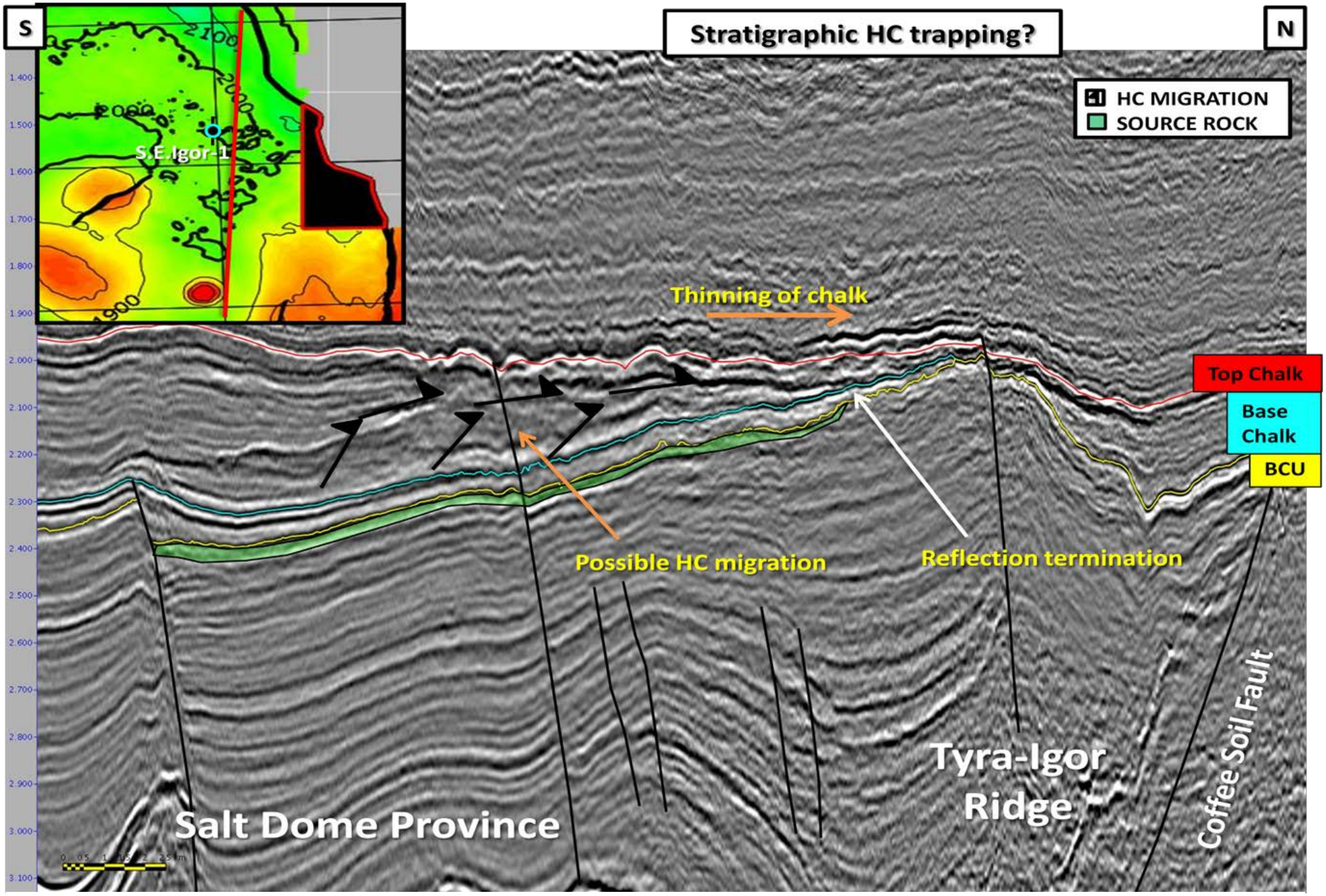

Figure: 7.1.4: Seismic cross-section of an inline through a possible stratigraphic trap near the S.E.Igor-1 well (SISMAGE).

7.2 Extracted amplitude maps

7.2.1 Danish Central Graben

In figures 7.2.1 and 7.2.2 one can see the maps that represent the extracted maximum amplitude anomalies that are found between the Miocene 1 and 3 markers and the Miocene 3 and Top Hordaland markers, throughout the Danish Central Graben. In the bottom left corner of the figures a seismic section can be seen, which shows the typical strong anomalies that correspond to the strong red amplitudes that are seen in the map. These amplitudes represent in most cases shallow gas anomalies and the maps give us thereby an overview of which chalk discoveries are found in combination with these features. One must on the other hand be careful in interpreting every red area as gas anomalies, since the thickness between the two markers at which the maximum amplitudes are extracted is pretty thick. Optimally one should decrease this thickness, so that one is certain which strong amplitudes correspond to which amplitude anomaly in the seismic.

By looking at Figure 7.2.1 together with the map that shows the location of the chalk fields in Figure A in appendix B, one can see that most of the fields are found in connection with strong amplitudes. However, this does not apply for all fields, since the Harald East, Roar, Dan, Tyra, Tyra SE and Halfdan are found in areas corresponding to weak amplitudes. The Harald East and Dan field also break the tendency of having gas anomalies in fields located atop salt structures, while Roar, Tyra and Tyra SE do the same for the fields at tectonic uplifted areas. In addition the strong amplitudes do not always represent an economical discovery as seen in the Tove-1 and Vagn-2 wells.

Some interesting places that show high amplitudes values, but do not correspond to any discovery are marked on the map. One such place is at the Per-1 well location. However, I believe the anomalies seen from the seismic correspond to some sedimentary effect instead of gas. If this was not the case, it could be seen as an extra indication for the presence of HCs at the Per closure. Another observation is the lack of strong amplitudes in the entire NW area, which doesn’t help us much in giving me some hints to look at specific places for the remaining HCs in this area.

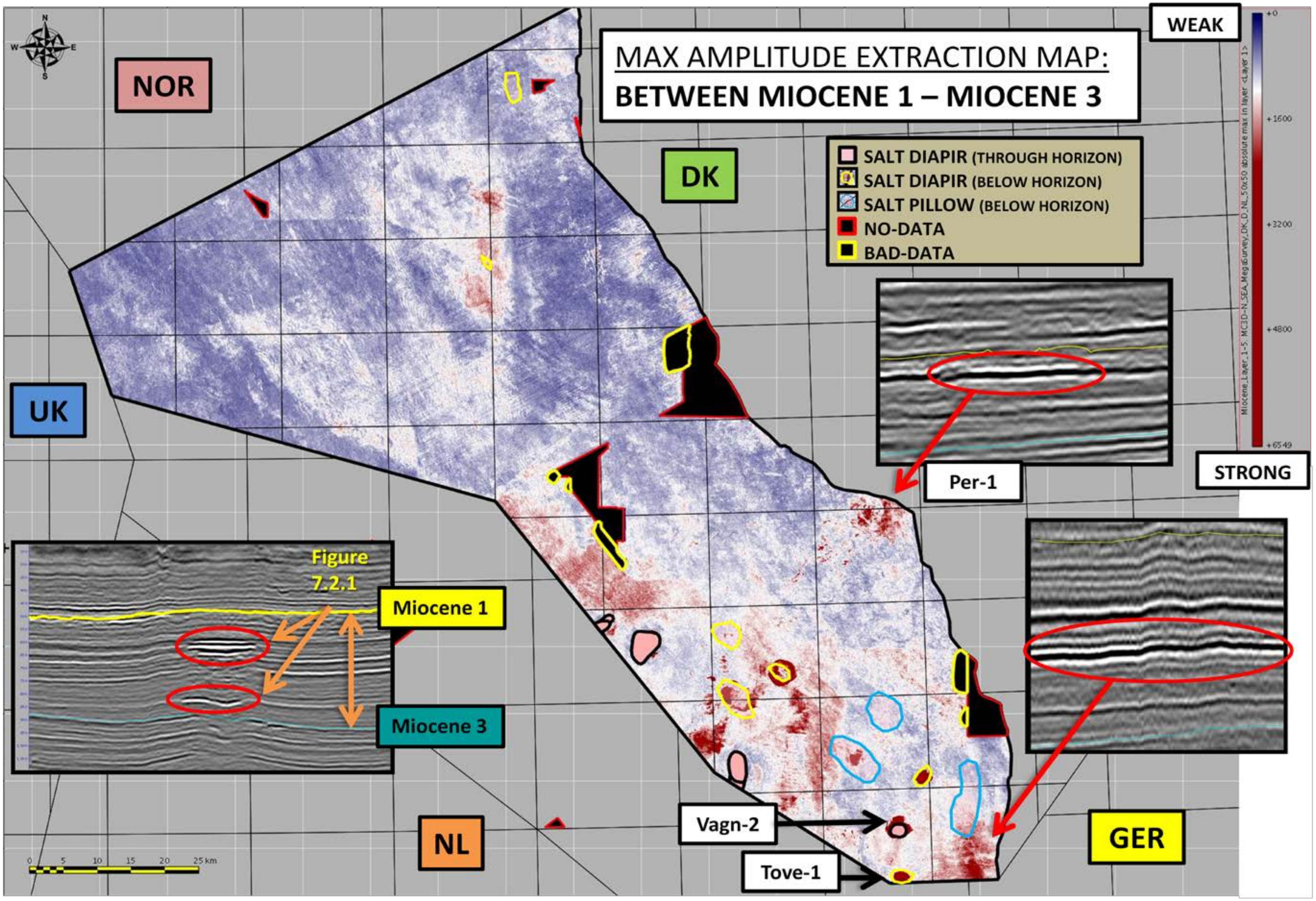

Figure 7.2.1: Overview of the strong amplitudes present between the Tertiary Miocene 1 and 3 horizons (SISMAGE).

The Figure 7.2.2 gives mostly the same representation of strong and weak amplitudes throughout the graben as the previous one. Small changes are seen on top of the salt structures, which are represented by weak instead of strong anomalies. This is because gas chimneys are often found on top of the salt diapirs before going over into the shallow gas anomalies seen in Figure 7.2.1. The amplitudes in gas chimneys are usually very weak and distorted and that's why the area on top of Vagn-2 and Tove-1 are represented by weak amplitudes.

One major difference is represented by the strange elongated features marked throughout the whole map. I first thought they could maybe be an acquisition footprint, but since the data consist of a merge of many data sets where the boat has moved in various directions it couldn't be this, since all the features have the same NW to SE direction[20]. From the seismic section seen on the right hand side in the figure the features seem to correspond to very small prograding clinoforms. So it's a depositional effect that causes the anomalies, where no gas effect is involved.

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[20] Discussions with senior geophysicist Philip Straw, TOTAL E&P Norway AS.

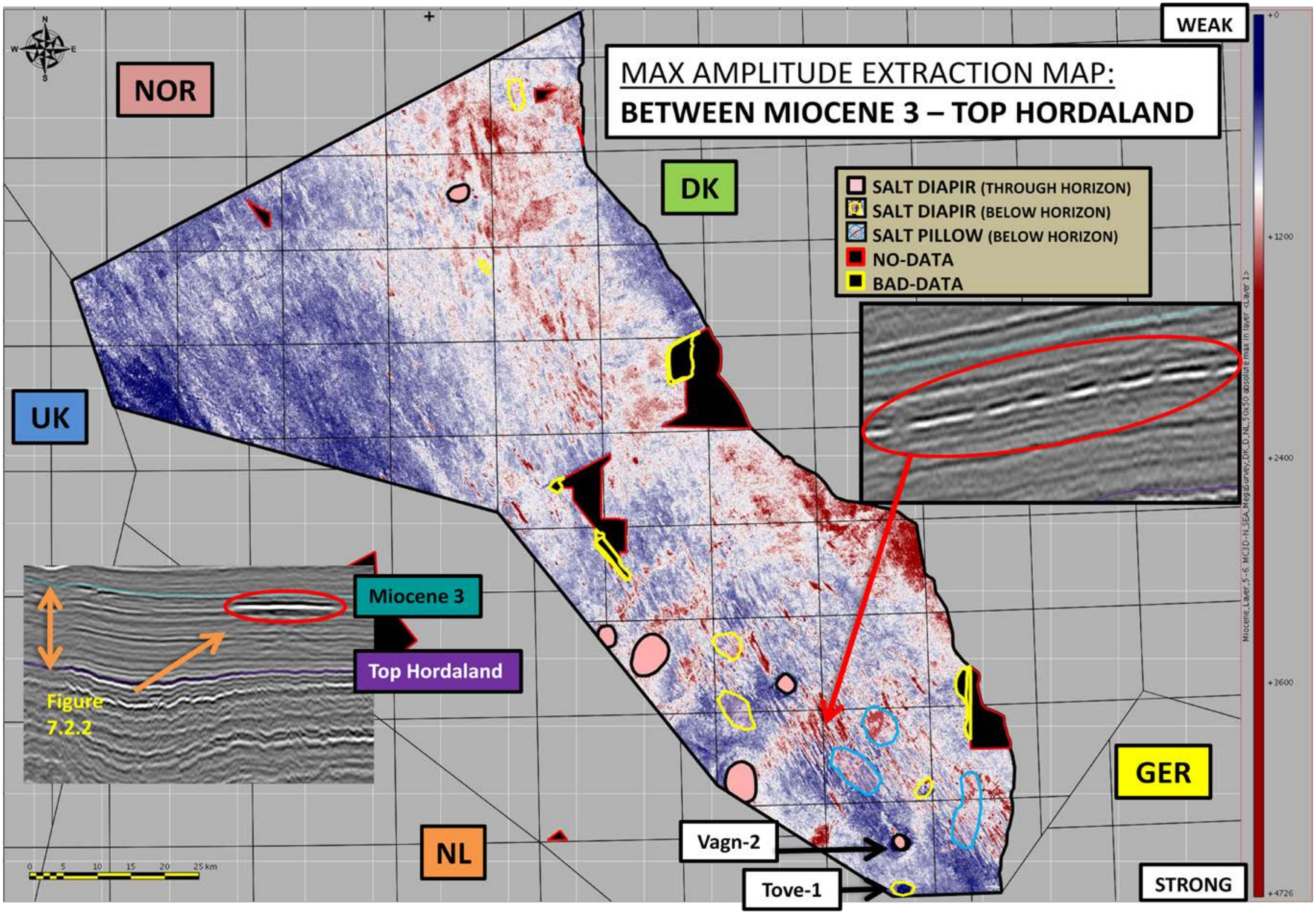

Figure 7.2.2: Overview of the strong amplitudes present between the Tertiary Miocene 3 and Top Hordaland horizons (SISMAGE).

7.2.2 Dutch Central Graben

A map of the shallow bright spots across the Dutch Central Graben can be seen in Figure 7.2.3. The map is made by someone else in a program called, ArcGIS. By comparing the map with Figure A in appendix B, one can see the strong correlation of salt diapirs with the occurrence of shallow gas anomalies. This does not come as a surprise, since the salt structures often deform the overlaying layers in such a degree that gas seepage can easily migrate upwards, when a known source rocks that has generated the gas is present further down below. However, the Hanze Field is the only chalk field found in combination with a bright spot, since the other anomalies correspond to either dry wells or are a result of other HC fields found at other depths. No distinct correlation can therefore be drawn between the occurrence of bright spots and the presence of chalk fields.

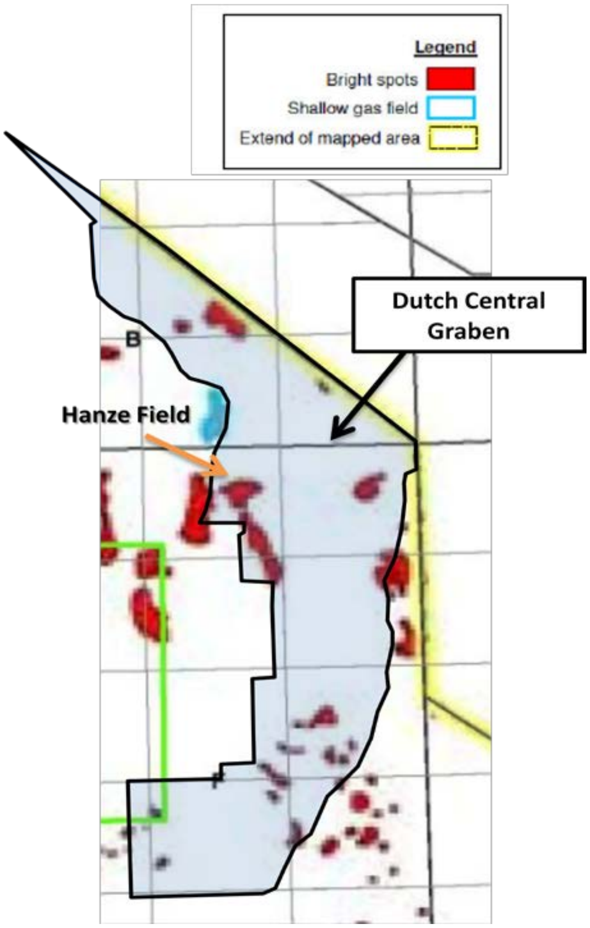

Figure 7.2.3: Shows the distribution of shallow bright spots throughout the Dutch Central Graben (Map is taken from ArcGIS).

8. Discussions

8.1 Quality of methods

8.1.1 Seismic interpretation

The seismic interpretation that was performed during this thesis has been a useful tool to understand the petroleum system of the chalk fields in the Danish and Dutch Central Graben. It has provided me with good view of the “big picture” concerning the distribution of the chalk layer in the two grabens. However, by interpreting only the Top & Base Chalk horizons, no detailed information about the subdivision of the chalk layer is obtained. The main reason for why this is not done is the lack of time available to achieve this. The second reason is the degree of complexity found within the Chalk Group in the Danish Central Graben compared to the Dutch Central Graben[21]. To interpret these subdivisions on a detailed scale would require an experienced geophysicist and a lot of time. For future studies, I would therefore like to recommend that such a project should be conducted, since the achievement of a detailed stratigraphic subdivision of the chalk could lead to several more interesting HC-producing intervals. Van der Molen (2004) has done this for the Chalk Group in the Dutch North Sea sector and GEUS is planning to do this for the Danish North Sea sector during the next years.

8.1.2 Well interpretation, correlation and calibration

The main correlation and calibration of wells by using logs that are loaded into the interpretation software, SISMAGE has not received as much attention as it should have. The main reason for this is the lack of wells within the area of interest and the late receiving of newly bought wells. To make up for this a lot completion reports have been studied and have been useful in the understanding of the changing thicknesses of the formations across the graben. They have also been very helpful in identifying the presence of the source rocks, where these are identified by a distinct property in the composite well log.

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[21] Discussions with senior geophysicist Philip Straw, TOTAL E&P Norway AS.

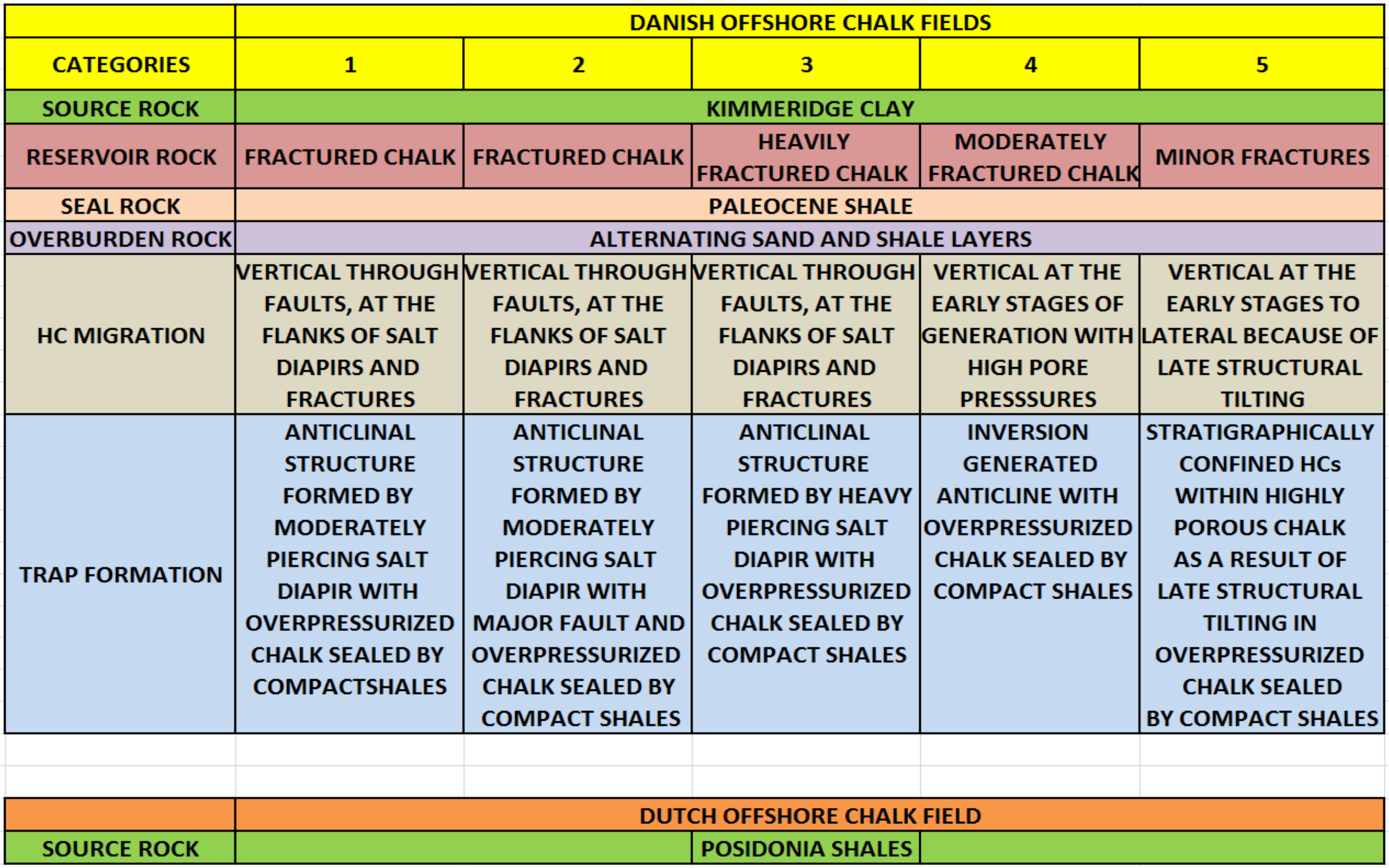
8.1.3 Maps

The generation of the maps that was performed has been helpful in giving a topographical and structural overview of the subsurface in the Danish and Dutch Central Graben. They have increased my understanding of where the discovered chalk fields are located in terms of structural position, thickness distribution of the chalk and Lower Cretaceous layers and amplitude anomalies. As a consequence of these terms, a remaining prospectivity analysis could be performed, where similar undrilled areas are brought forth.

8.2 Petroleum systems of the Danish and Dutch Central Graben

The results of the petroleum system analysis of the discovered chalk fields in the Danish and Dutch Central Graben, divide the fields into five categories (See Table 3.2). The selection of these categories are mostly based on the structural or stratigraphic characteristic of the reservoir, where three of them are found in combination with halokinesis, one within structures caused by tectonic uplift and one where the structure purely marks the stratigraphic trapping of HCs. Table 8.1 shows the similarities and differences between the five categories.

To be able to discuss the results of all the processes and elements that make up the petroleum system, it is important to do this in combination with the syn- and post-chalk depositional and structural evolution of the Danish and Dutch Central Graben. This is because the structural events represent a key aspect of making the chalk petroleum system in the Central Graben work. They are responsible for fracturing or modifying the chalk morphology; they have impacted the burial history, affected the maturation of the source, controlled the trapping of migrated HCs and are responsible for the chalk porosity and permeability relationships (Bramwell et al, 1999).



	DANISH OFFSHORE CHALK FIELDS				
CATEGORIES	1	2	3	4	5
SOURCE ROCK	KIMMERIDGE CLAY				
RESERVOIR ROCK	FRACTURED CHALK	FRACTURED CHALK	HEAVILY FRACTURED CHALK	MODERATELY FRACTURED CHALK	MINOR FRACTURES
SEAL ROCK	PALEOCENE SHALE				
OVERBURDEN ROCK	ALTERNATING SAND AND SHALE LAYERS				
HC MIGRATION	VERTICAL THROUGH FAULTS, AT THE FLANKS OF SALT DIAPIRS AND FRACTURES	VERTICAL THROUGH FAULTS, AT THE FLANKS OF SALT DIAPIRS AND FRACTURES	VERTICAL THROUGH FAULTS, AT THE FLANKS OF SALT DIAPIRS AND FRACTURES	VERTICAL AT THE EARLY STAGES OF GENERATION WITH HIGH PORE PRESSSURES	VERTICAL AT THE EARLY STAGES TO LATERAL BECAUSE OF LATE STRUCTURAL TILTING
TRAP FORMATION	ANTICLINAL STRUCTURE FORMED BY MODERATELY PIERCING SALT DIAPIR WITH OVERPRESSURIZED CHALK SEALED BY COMPACTSHALES	ANTICLINAL STRUCTURE FORMED BY MODERATELY PIERCING SALT DIAPIR WITH MAJOR FAULT AND OVERPRESSURIZED CHALK SEALED BY COMPACT SHALES	ANTICLINAL STRUCTURE FORMED BY HEAVY PIERCING SALT DIAPIR WITH OVERPRESSURIZED CHALK SEALED BY COMPACT SHALES	INVERSION GENERATED ANTICLINE WITH OVERPRESSURIZED CHALK SEALED BY COMPACT SHALES	STRATIGRAPHICALLY CONFINED HCs WITHIN HIGHLY POROUS CHALK AS A RESULT OF LATE STRUCTURAL TILTING IN OVERPRESSURIZED CHALK SEALED BY COMPACT SHALES

	DUTCH OFFSHORE CHALK FIELD				
SOURCE ROCK			POSIDONIA SHALES		

Table 8.1: Shows the various differences and similarities between the 5 categories of chalk fields discovered within the Danish Central Graben. The only Dutch producing chalk field is included as a category 3 field.

Danish source rocks

The composite well-log interpretation and the research of various articles mark the principal source rock in the Danish Central Graben as the Bo Member within the Upper Jurassic Farsund Formation (Ineson et al, 2003). Proof of its existence throughout the graben is indicated by the high GR values that are marked in some of the composite well-logs (See appendix A). It is on the other hand important that one doesn´t interpret all the high GR values as the “hot shales” source rocks, since these values could represent normal shales. For example in places where the Lower Cretaceous Shales are absent or very thin, the chalks could go directly into the “hot shales”, since they are found just below the BCU. However, since one normally has a GR increase when moving from chalk into the shales, one should be careful to indicate the GR increase as “hot shales”, since they could represent normal shales in these situations (See Figure C in appendix A). The source rock is also found at a deep burial depth throughout the graben, as illustrated by several of the seismic sections in chapter 6. It is therefore reasonable to assume that the source rock has been mature enough to generate HCs, something that is proven by the many discoveries.

The identifications of the Bo Member within this thesis are purely based on the distinct GR increase, since they don´t represent a distinct reflector in the seismic. No information has on the other hand been gathered about the source rock quality of the member at the various wells. I have therefore assumed that the quality has been good enough wherever the source rock was present and that it has been the main source for charging the nearby chalk fields. This is something that should be checked when more well data becomes available, since it could create sources of error. It might even lead to indications of other source rocks that could have charged the fields.

Dutch source rocks

As mentioned by De Jager & Geluk (2007), the HC results in the chalk section of the Dutch Central Graben are related to the Posidonia Shale distribution. This is made clear by the Hanze Field discovery in the vicinity of the Posidonia Shale marker in figures 4.9 and 6.6.1. However, since the main source rock north of the Dutch sector corresponds to the Upper Jurassic Kimmeridge Clay, one has to wonder why this is not the case in the Dutch Central Graben. The main explanation for this is the loss of its kerogenous content when entering the Dutch North Sea sector (De Jager & Geluk, 2007). Since the Posidonia Shale Formation is also only restricted to

Late Jurassic basins such as the Dutch Central Graben, it is without a doubt the source rock that has charged the Hanze Field and the still undiscovered chalk discoveries.

According to Guasti et al. (2010) a late HC generation phase from the Posidonia Shale is crucial for the success of the chalk play. This contradicts what observed at the Hanze Field which in fact has received a lot of its HC accumulation from an overspill of an existing oil reservoir in the Upper Jurassic Graben sand. Therefore, there is no major late phase of oil generation, just leakage from the original one.

In the rest of the discussion I will treat the Dutch petroleum system as a category 3 field, so except from the difference in source rock in the two grabens, the rest of the elements and processes of the petroleum system analysis are very similar to each other.

HC migration and reservoir characteristics

The halokinetic and tectonic movements during chalk deposition have had a direct influence on its facies distribution. Many syn-sedimentary faults that cut the base of the chalk are therefore identified in the seismic sections. These faults represent the main structural features that have provided the most obvious and natural pathways for HC migration to occur from the source rock to the chalk reservoirs (Bramwell et al, 1999). The HC migration is therefore mostly represented by vertical migration occurring along major faults provided by the salt induced structures in the first three chalk field categories (Figures 6.1.1, 6.2.1 & 6.3.1).

In the fourth category, the migration has also occurred mostly vertical, but not along any major faults (Figure 6.4.1). This brings us to a migration that has occurred during the early stages of generation and expulsion between the source rock and the chalk, when high pore pressures and a well-preserved porosity to permeability system existed. No major faults were therefore necessary to initiate vertical migration (Bramwell et al, 1999). The migration must on the other hand have been slow, because of the thick Lower Cretaceous and chalk layers and because of the low permeability nature of chalk. The probability for long-distance migration seems therefore small and the fact that the reservoir is positioned directly above the source rock comes therefore as no surprise. This could symbolize a characteristic feature for the fields in category 4 and be a necessary condition for their existence (Vejbæk et al, 2007).

The charging of the Halfdan Field viewed in Figure 6.5.1 illustrates the several stages of HC migration. The migration has occurred through both vertical and lateral movements, where the first stage is marked by similar vertical fluid displacements as found within the Roar Field. As stated in the chapter 6.5, the Halfdan Field was first part of a structural closure; so primary migration has likely occurred when relatively high porosities and permeabilities existed as in the case of the Roar Field (Figure 6.5.2). These conditions preclude therefore the formation of a stratigraphic trap at the first stages of the HC migration (Bramwell et al, 1999). The inversion seen on the west side of the figure marks the later structural event that has led to the secondary HC migration stages, which are represented by lateral fluid movements. This late geologic evolution of the chalk has produced significant porosity layering, which has enabled the formation of secondary traps to form within diagenetic and stratigraphic seals (Bramwell et al, 1999). The lateral migration plays an important role in the HC distribution within the chalk and is restricted to individual pressure compartments. The marked distribution gives thereby a representation of the oil saturation within the field, which again will be a direct function of the porosity, permeability and capillary pressure (Bramwell et al, 1999).

Another main factor that plays a major role in the HC migration is the presence of fractures in chalk. This also counts for the HC production, since the fractures provide the main permeability pathways (Bramwell et al, 1999). Many of the figures in appendix A, mark the presence of these fractures in the upper chalk layers, where they range from being moderately to heavily fractured. The fractures are commonly seen in the first three field categories, where they are found on top of the salt structures as a result of the halokinesis. The degree of fracturing changes from being moderately fractured in the first category to heavily fractured in the third category. The fields represented by the third category, describe thereby a thin line between being an economical discovery or a dry well as seen in chapter 6.7. It depends on whether the fracture formation degrades the seal integrity or not. For example, in case of Tove-1 and Vagn-2 the salt diapir movements has likely led to heavily fracturing of both the chalk and overlying seal, which in turn has decreased the seals capacity and led to the apparent escape of HCs to the overlying layers[14,15] (Figure 6.7.1). It should therefore be said that a definite need to understand the salt movements timing and its relation to HC accumulation needs to be obtained from seismic evidence, to reduce the risk in drilling similar types of features in the future[15].

The timing of the fracture formation in chalk shows therefore a clear connection with the post-chalk structural evolution, where pulses of tectonic compression during the Eocene and throughout the Oligocene and Miocene have affected the chalk structures locally through diapirsm (Bramwell et al, 1999). This also counts for the category 4 fields where the fracture formation is a result of the inversion-generated anticlines. However, the fractures are defined at a much lesser scale compared to the salt generated fractures, mostly because of the difference in structural "violence" between the salt diapirs and the inversion anticlines.

In the Halfdan Field the chalks are also connected with the post-chalk structural events in terms of areas of reworked chalk. These reworked (allochthonous) chalks are namely a result of redistribution of primarily pelagic (autochthonous) deposited chalks by various processes like downslope mass flow movements, which again are caused by these syn-depositional tectonics (Abramovitz et al, 2013)(Figure 6.5.1). The results indicate on the other hand not many fractures in the field, which creates one of the main obstacles in obtaining an economical production. However, the fact that the reservoir is located within reworked chalk is better than in the case of a reservoir in pelagic chalk, since it is shown that re-deposited chalks are more likely to be fractured than pelagic chalks. Stratigraphic trapping should therefore theoretically work (Bramwell et al, 1999).

Rerservoir properties and seal and trap formation

The general preservation of porosity in chalk is also an important success factor in the chalk petroleum system and is highly connected to the diagenetic history of the chalk. The main factors controlling this preservation are the burial depth, HC saturation, the original depositional facies and the chalk overpressure (Bramwell et al, 1999). In terms of burial depth, the chalk discoveries in the Danish Central Graben are found in between a large variation of depths, ranging from 1500 to 2700 m (Figures chapter 4 and 6). Although this represents a range of depths of well over a 1000 m, there is no clear relationship between the burial depth and the porosity. I say this; because both the Halfdan Field located at a depth of 2100 m and the Kraka Field located at a depth of 1800 m, show similar porosity values throughout the chalk layers (Abramovitz et al, 2013). The main reason for this is according to Vejbæk et al. (2007) a combination of over-pressuring and early HC invasion that has preserved the quality of the reservoirs in their traps, despite the great depths at which some of the chalk fields are buried. This then brings us to the presence of high HC saturations in chalks that are often seen together with unusual high porosities. This could be a more distinct condition for the porosity preservation, but it is no guarantee since water wet chalks are also found within these chalks (Bramwell et al, 1999). However, all the field discoveries that have been considered in the petroleum system analysis show moderate to very good porosities, so to be able to locate such high porosity chalks is a method that should be further exploited for the future, since it is likely to find HCs here.

The third condition for porosity preservation again tells us that the reworked chalks constitute better reservoirs than pelagic chalks, which is seen at the Halfdan Field. Similar areas and additional areas such as the flanks of salt structures should therefore be more explored, since they represent such reworked chalk areas.

The last factor for maintaining the porosity in chalk is represented by the chalk overpressure. It is mainly caused by the overlaying seal and describes therefore the strong relation it has to the sealing mechanism and trap formation of the chalk reservoirs. It also emphasizes the importance of obtaining a model for the over-pressured hydrodynamic regime within the chalk, because the potential for subtle oil traps within the chalk is probably more dependent on the pressure regime than on any other parameter (Caillet et al, 1997). According to Vejbæk et al. (2007) the overpressure is therefore an important factor for the chalk play success in the Danish Central Graben. My results seem to agree, since the overlaying seal is practically represented by the same Paleocene shales throughout the better part of the graben. They are therefore interpreted above every chalk field considered in the petroleum system analysis and I can safely assume the same counts for all the other chalk fields in the graben (Chapter 6 figures). It is because of the rapid burial and compaction occurring after the chalk deposition that has caused the over-pressuring by effectively closing of the Chalk Group hydronamically from the Paleogene above (Vejbæk et al. 2007).

The seal also acts as one of the factors that control the trapping mechanism. It is therefore crucial to understand when the seal was deposited, when the seal started to maintain the chalk over-pressure and what kind of internal properties the seal consists of. This is because the concurrent timing of HC migration, entrapment and compaction together with the fracture and structural formations are critical for the classic chalk plays (Bramwell et al, 1999). To relate this to my results in the first three categories, a lot depends on the timing of the salt movements in relation to the HC accumulation. Salt moves as a result of tectonic activity, so to analyze the timing of the structural events in affiliation to the HC generation and migration is extremely important to determine if the prospect is a success or failure. I give these statements based on these points:

- Salt movement is mainly responsible for the fracture formation in chalk on top of salt diapirs. I.e. it determines if fracture formation is present went HC migration and accumulation occurs.
- Late salt movements could degrade the seal integrity leading to leaky traps and no economical HC discoveries (Tove-1 and Vagn-2).
- Salt movements are responsible for the major fault generations that provide the main HC migration pathways. I.e. it determines when HC migration will accumulate in potential overlaying traps, which provides us the opportunity to check if a seal is in place at this time and if over-pressuring was present in the chalk when oil entrapment took place.

The HC entrapment in the fourth category is based on when the tectonic uplift took place, relative to the timing of the HC migration and seal over-pressuring. This is because the uplift is responsible for the fracture formation and decides when good reservoir conditions are present in the chalk. The uplift movement also decides the tightness of the seal, by the degree it has been uplifted. If this is too drastic, potential fracture formation within the seal could be too much and lead to possible breach-points. Gas chimneys are in this case expected to be located on top of the field. If the movement on the other hand is to mild, the reservoir properties might be to bad and the structural closures become more unbelievable. The HC migration could in this case be located further down at other potential traps (Figure 6.7.2 and well Iris-1).

For a stratigraphic trap to work, the highest risked parameter is the efficiency of the top, bottom and lateral seals. The top seal is in general defined by the Paleocene Shales, the bottom seal by either chalk or Lower Cretaceous Shales, while the lateral seal may comprise a fault zone or a facies variation, juxtaposed against a chalk reservoir facies (Bramwell et al, 1999). This is shown for the stratigraphic trap formation within the Halfdan Field where the top and bottom seals are as mentioned above, while the lateral seal is comprised of the pinch-out of two major sequence boundaries (Figure 6.5.1). The lateral seal is on the other hand not completely optimal since the west side of the trap is not completely sealed and remains kind of “open”. Oil is therefore actively migrating towards the Dan Field as mentioned by Albrechtsen et al. (2001) (Part D in

Figure 6.5.2). The sealing potential for the Halfdan Field has therefore been strongly dependent on the low permeability and high fluid entry pressures in the chalk that have prevented the HCs from migrating away. A subtle stratigraphic trap is therefore a combination of having all the right elements and processes of the petroleum system in place, in addition to its dependence on the right pressure conditions, hydronamic regime and fracture occurrence in the area of interest.

DHI's

The occurrence of DHI's in combination to the different field categories vary between shallow gas anomalies, gas chimneys, phase reversals and an occasional flat to dipping flat spot. The shallow gas anomalies and gas chimneys are mostly found in connection with the first three categories, where the degree of them increases when going from category 1 to 3. A connection between how much the salt structures have pierced through the overlaying layers, relative to the quantity of gas seepage on top of the structures can therefore be drawn. The connection basically explains itself, since as the salt piercement becomes more violent; more fractures are formed, which will increase the possibility of degrading the seal integrity, which again will lead to more gas seepage. To find a chalk field belonging to category 3 that has no gas chimney or shallow gas anomalies is therefore highly unlikely (Figure 6.7.1). For the other categories it is on the other hand not a given, especially for category 4 or 5, since they have less fracture formation and good seal integrity.

The occurrence of phase reversals and bright spot at the top of the reservoir level is found in combination with the presence of gas, so it has no correlation to what kind of category the field belongs to. The same count for the flat spots, but it is in general easier to spot them in the category 4 and 5 fields. This is because the salt structures in the remaining three categories often disturb the data in such a degree that one needs the well calibration to make sure were the GWC and OWC are (Figures 6.3.1, 6.4.1 & 6.5.1).

6. Conclusion

In this thesis, the different elements and processes that make up the petroleum system for the chalk play in the Danish and Dutch Central Graben have been reviewed and a small presentation of the remaining chalk prospectivity in these areas is provided. By using my own classification scheme, five different categories of chalk fields are identified, based on their structural or stratigraphic trapping characterization. The first four categories describe chalk fields that are formed within structural closures that are induced through either salt tectonics as in the first three categories or as inversion-generated anticlines as in the fourth category. The fifth category is a more special case and represents the non-structural stratigraphic trapping of HCs, as a result of late structural tilting. All the five categories are found in the Danish Central Graben, but only the third category is represented in the Dutch Central Graben.

Two source rocks that have charged the chalk fields are identified, the Bo Member from the Upper Jurassic Farsund Formation in the Danish Central Graben and the Lower Jurassic Posidonia Shale Formation in the Dutch Central Graben. This is indicated by the easily recognized GR increase for the Bo member in the composite well logs and the distinct reflection that marks the Posidonia Shales on the seismic. The maturation of these rocks is affected by the amount of subsidence and rapid sedimentation together with tectonic uplift and erosion during the time after its deposition. This has led to variable chalk thicknesses across the grabens and is the cause for different times of HC generation and expulsion throughout the grabens.

The HC migration from the source rocks is found to be mostly vertical in the first three categories where the salt structures together with the major faults have provided the natural HC pathways. Such migration is also indicated in the early stages of generation and expulsion in the fourth and fifth categories, when high pore pressures and a well-preserved porosity to permeability system made vertical HC migration possible without the aid of any major fault. Slow lateral migration because of the low permeability nature of chalk has later on dominated within the fifth category, due to late structural tilting.

The Danian and Maastrichtian chalks dominate the reservoir rocks on the Danish and Dutch Central Graben. It has a complex geometry that shows a good quality with large porosities that have been preserved as an effect of the burial depth, HC saturation, original depositional facies and overpressure. The permeability is varying and depends partly on the presence of fractures that are either induced through tectonic events or found as a natural appearance. The formation of these fractures in the reservoir rock of the first three categories shows a proportional effect with the degree of salt piercement, going from category 1 to 3. The same counts for the overlaying seal, where the integrity of the seal shows an inversely proportional affect with the degree of fracture formation and hence the degree of salt piercement. Thinning of the Palaeocene section above diapirs either because of the deposition on an already present structural high or due to the late movement of salt induces a significant risk for potentially breach points in the seal and the escape of HCs to overlaying layers. In the fourth category the fracturing is related to the degree of tectonic uplift and the natural fracturing mechanism of the chalk itself. In the fifth category the re-deposited chalks that constitute the main reservoir provide the fracture formation.

The structural closures and stratigraphic traps are all found in combination with an overlying seal that is made up of compact Palaeocene Shales. The seal completes the trapping mechanism by sealing it of and maintaining the over-pressurized chalk, which in turn has preserved the high porosity conditions in the chalk.

All the chalk fields with the exception of one (Harald East) that are located on top or at the flanks of salt structures are found in combination with weak to strong shallow gas anomalies. The opposite counts for the fields found in tectonic uplifted areas, with the exception of one (South Arne). Other than that, the presence of phase reversals have been noticed were gas is present in the fields and an occasional flat spot or tilted flat spot is sometimes seen, mostly in the category 4 and 5 fields.

Top seal failure and leakage through faults on top of salt diapirs, due to late salt tectonic movements during and after depositions are the most common reasons for failure in dry wells. Other reasons are related to lack of proper reservoir conditions and lateral seal failures.

For future studies a better understanding of the connection between the syn- and post chalk depositional structural events, relative to 1) the status of the source beds, 2) presence of the competent reservoir rock, 3) trapping mechanism, 4) age of the structure of the overall prospect and 5) fluid dynamics or pressure gradient in the formations involved, should be obtained. Another point is to increase our knowledge of the chalk subdivisions and their stratigraphic reservoir properties.

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Lulu-1, Gorm-2, Gorm-Deep, Nils-1, Ryan-1, Roar-2 & 2a, H-1X, Bo-1X, HDN-1X, S.E.Igor-1, Tove-1, Vagn-2, Iris-1, Inge-1/P-1X, Isak-1, Per-1

Appendix A

Appendix A gives an overview over all the composite logs, which were used during the seismic interpretation of the three main horizons and the petroleum system analysis in this thesis.

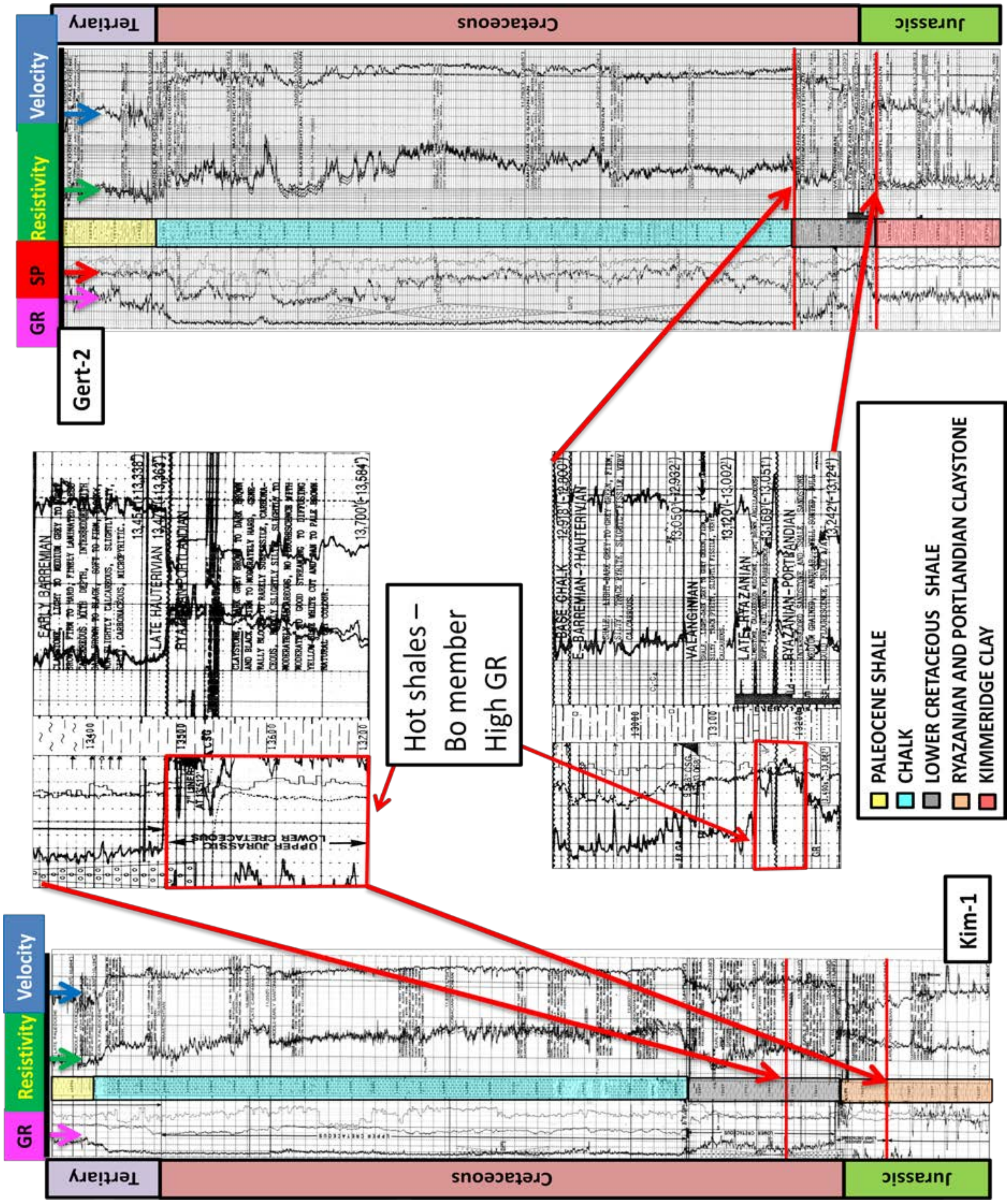
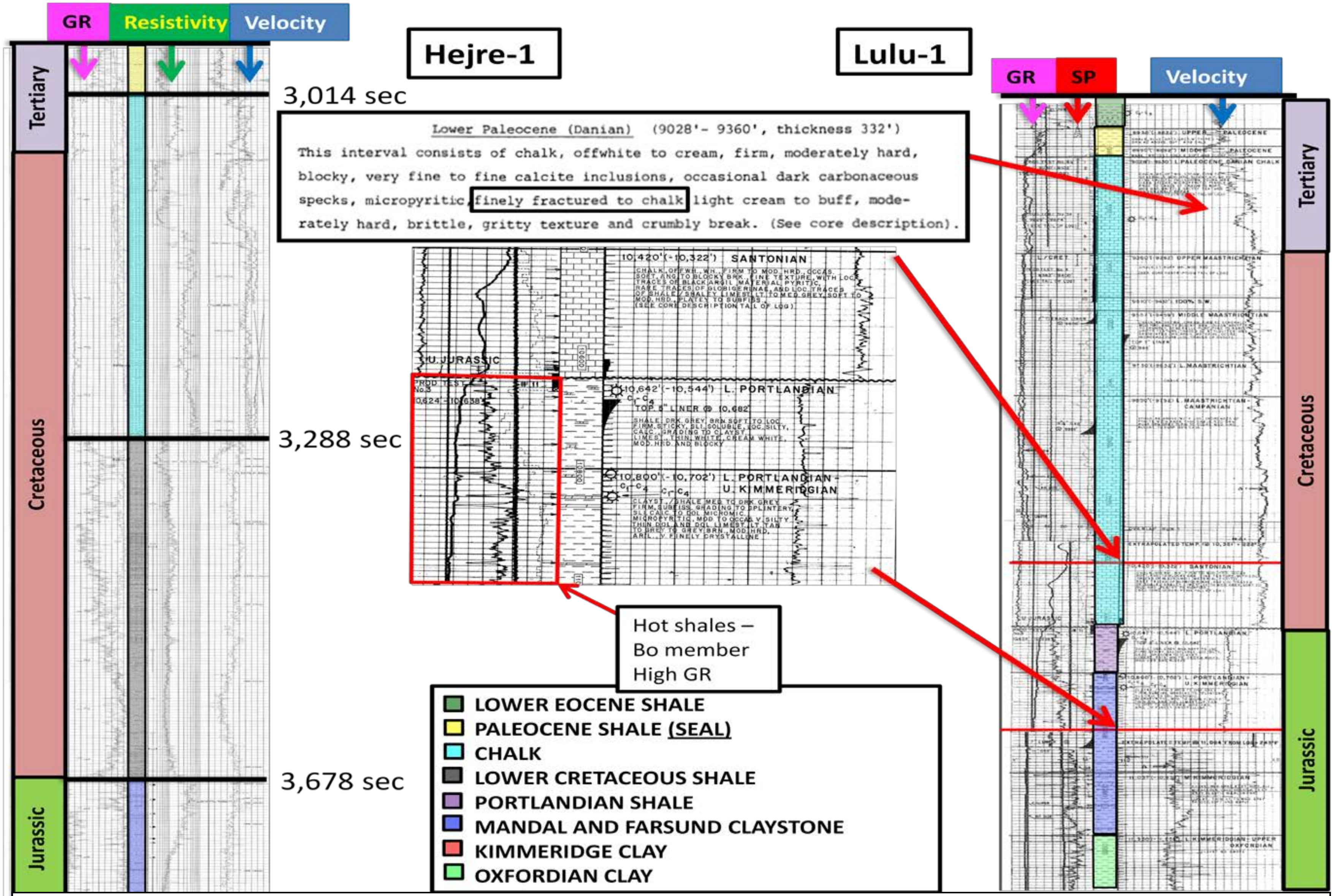


Figure A: Composite well logs of wells Kim-1 and Gert-2. They mark the presence of the Bo Member source rock within the Upper Jurassic to Lower Cretaceous layers.



Lower Paleocene (Danian) (9028'- 9360', thickness 332')

This interval consists of chalk, offwhite to cream, firm, moderately hard, blocky, very fine to fine calcite inclusions, occasional dark carbonaceous specks, micropyritic finely fractured to chalk light cream to buff, moderately hard, brittle, gritty texture and crumbly break. (See core description).

🟩	LOWER EOCENE SHALE
🟨	PALEOCENE SHALE (SEAL)
🟦	CHALK
⬛	LOWER CRETACEOUS SHALE
🟪	PORTLANDIAN SHALE
🟦	MANDAL AND FARSUND CLAYSTONE
🟥	KIMMERIDGE CLAY
🟩	OXFORDIAN CLAY

Figure B: Composite well logs of wells Hejre-1 and Lulu-1. A direct depth to time correlation for the three main reflectors, BCU, Base & Top Chalk, is shown in Hejre-1 and the Bo Member is seal rock is marked in Lulu -1.

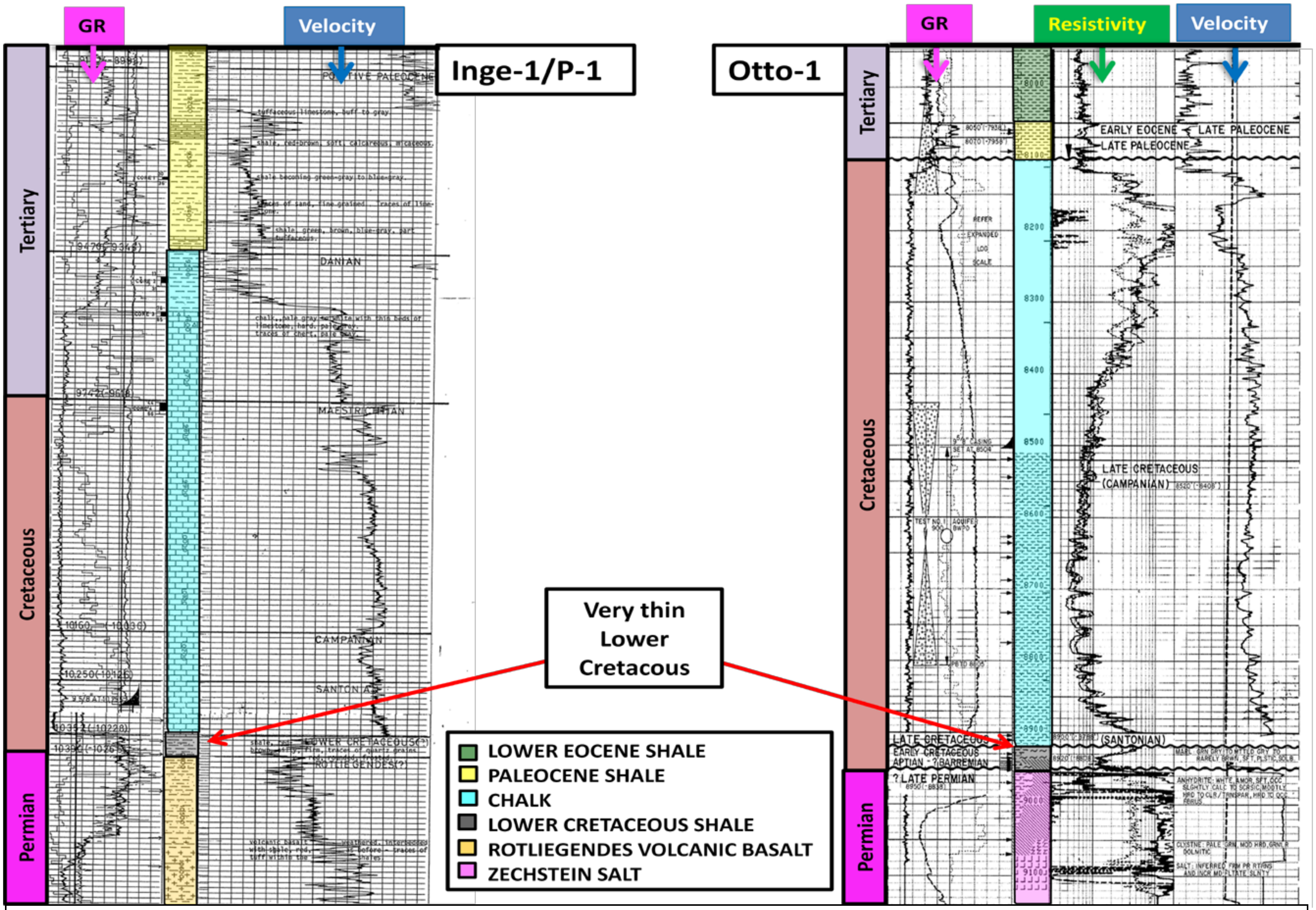


Figure C: Composite well logs of wells Inge-1/P-1 and Otto-1. The Lower Cretaceous Shales are very thin here in both wells and can therefore not be seen on the seismic.

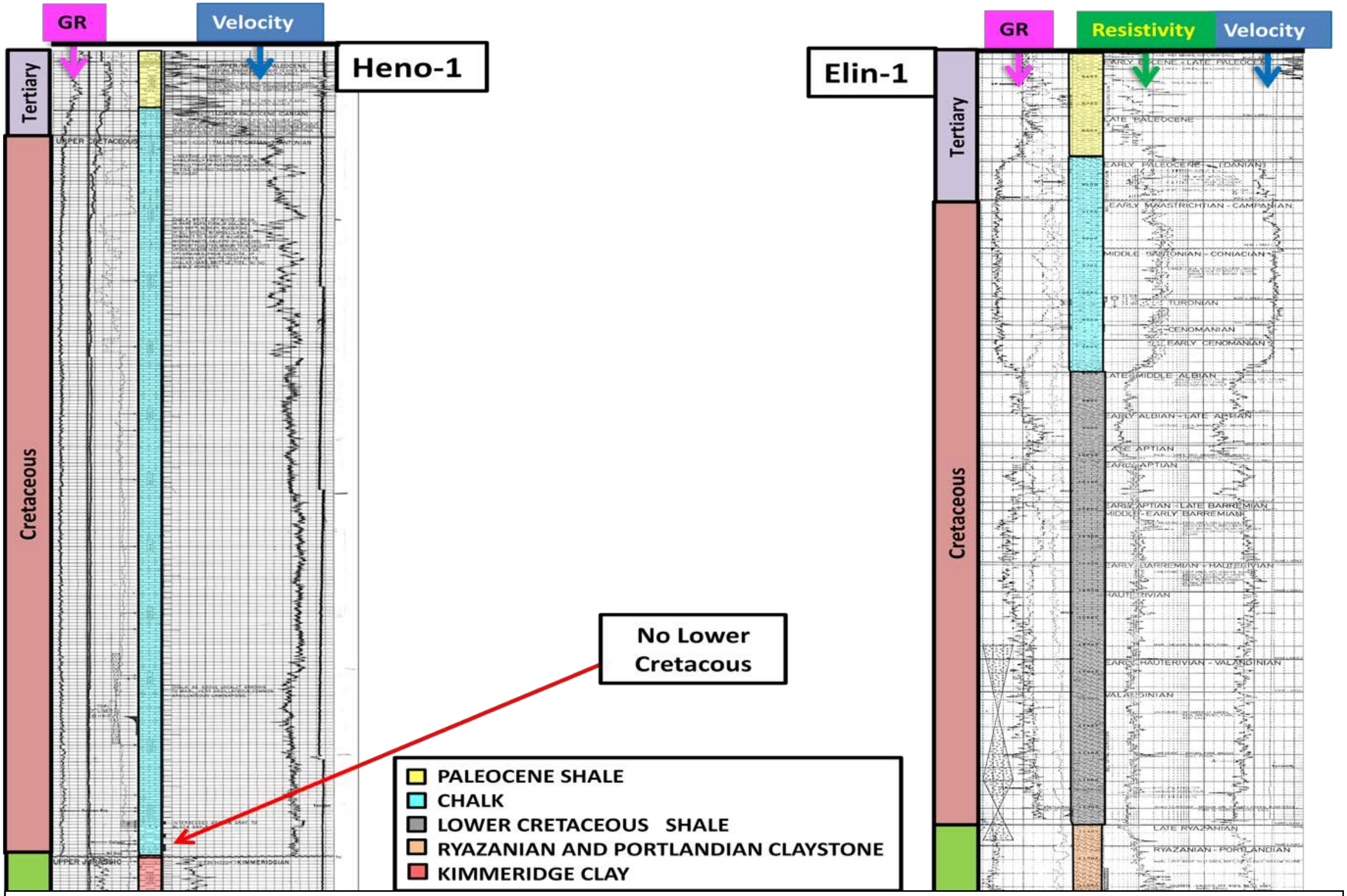


Figure D: Composite well logs of wells Heno-1 and Elin-1. No Lower Cretaceous Shales are observed in the Heno-1, but a very thick section of these shales are marked in Elin-1.

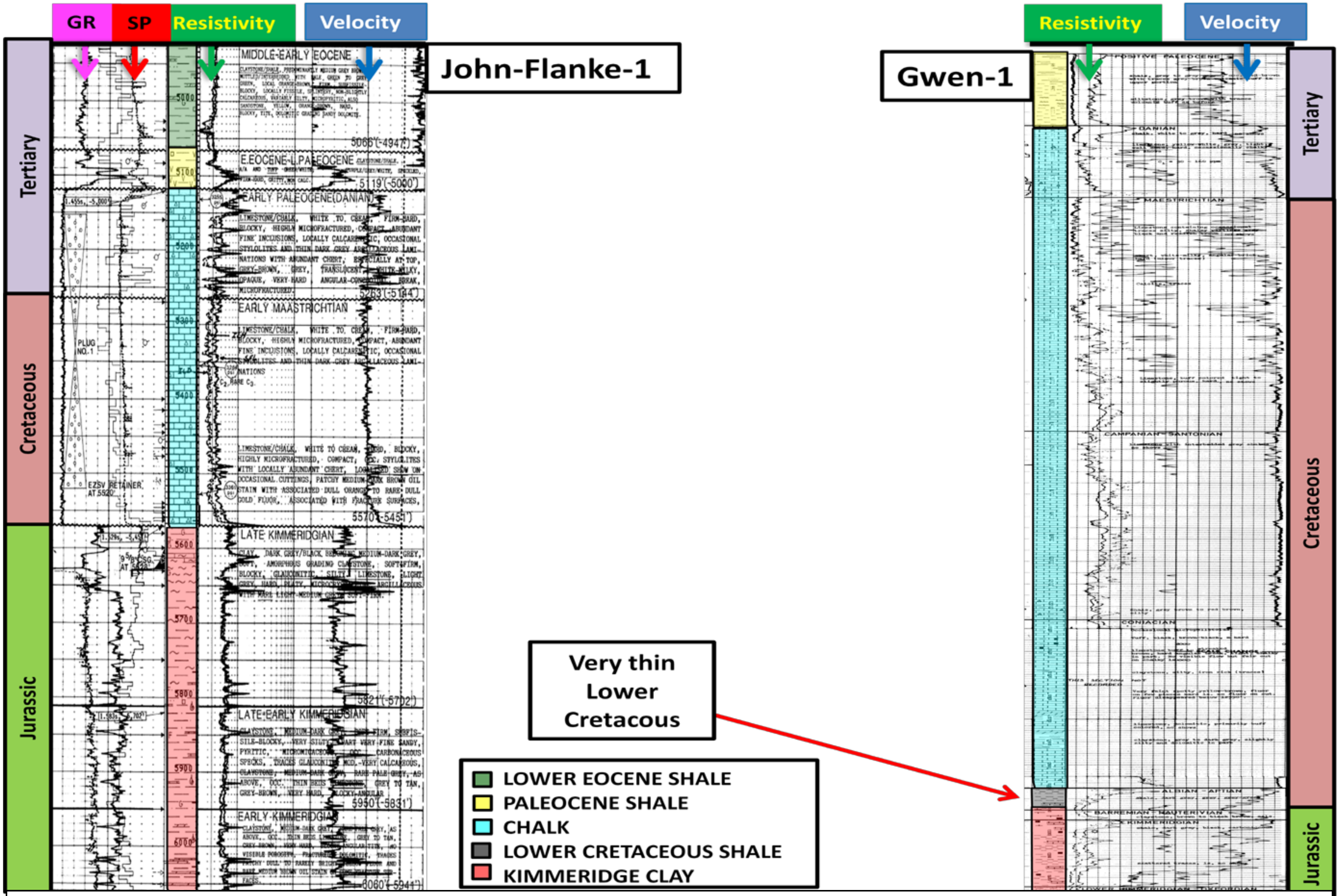
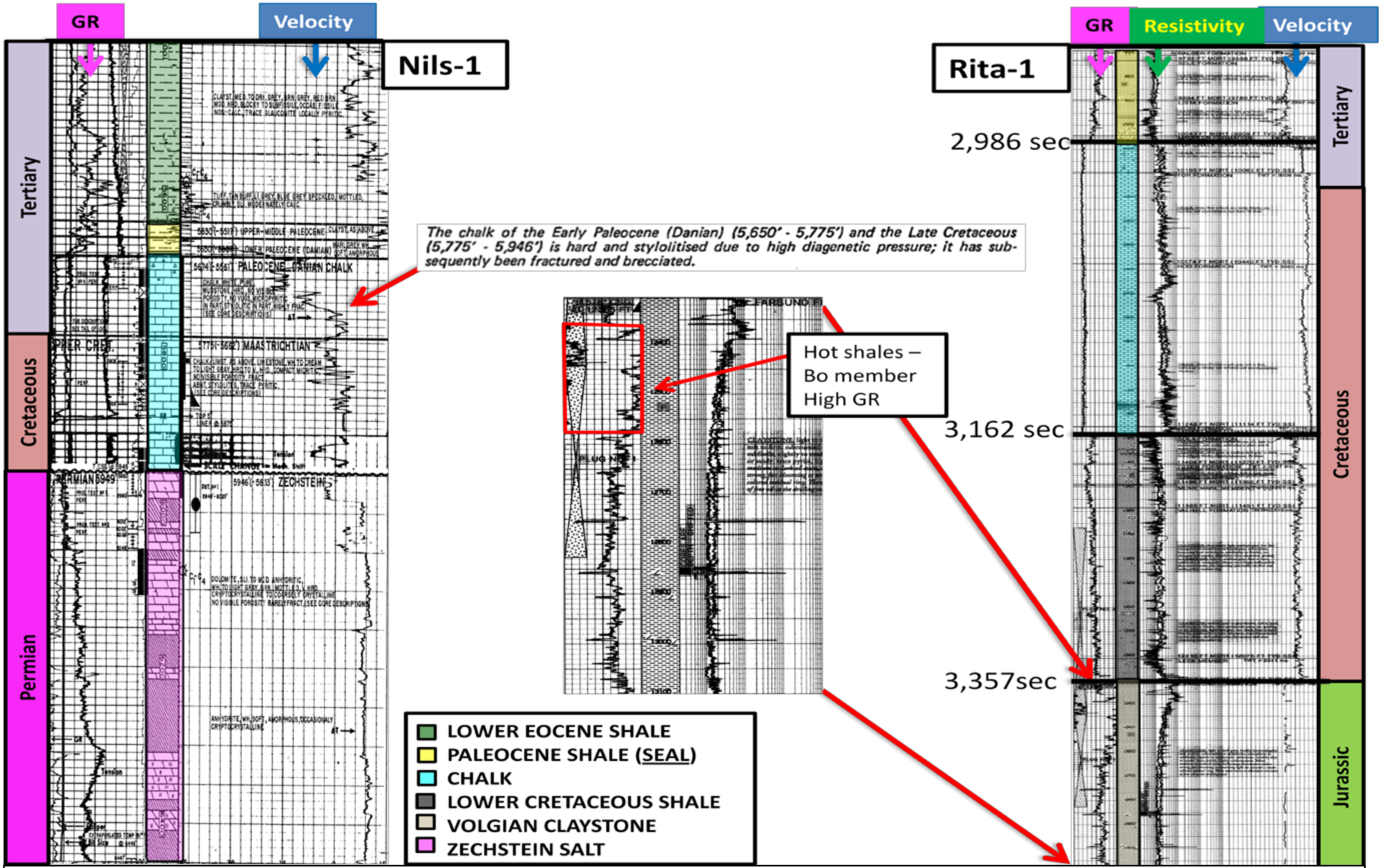


Figure E: Composite well logs of wells John-Flanke-1 and Gwen-1. No Lower Cretaceous Shales are observed in the John-Flanke-1 and a very thin section of these shales are marked in Gwen-1.



The chalk of the Early Paleocene (Danian) (5,650' - 5,775') and the Late Cretaceous (5,775' - 5,946') is hard and stylolitised due to high diagenetic pressure; it has subsequently been fractured and brecciated.

Figure F: Composite well logs of wells Nils-1 and Rita-1. No Lower Cretaceous Shales are observed in the Nils-1, so the chalk rests directly on top of the Zechstein salt. Rita-1 marks the presence of the Bo Member source rock and the time to depth relation.

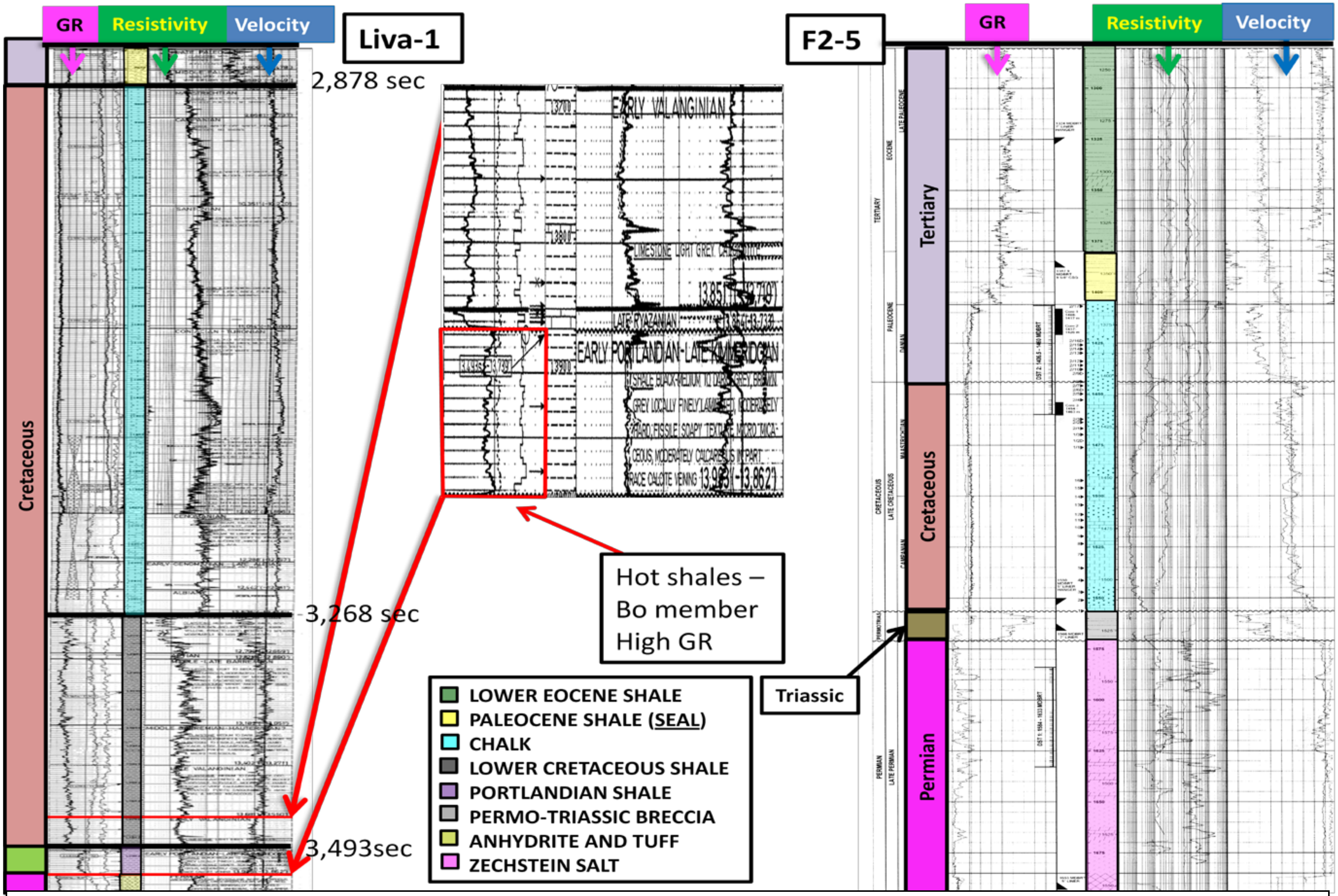


Figure G: Composite well logs of wells Liva-1 and F2-5. Liva-1 marks the presence of the Bo Member source rock and the time to depth relation. No Lower Cretaceous Shales are observed in F2-5, so the chalk rests directly on top Permo Triassic Breccia.

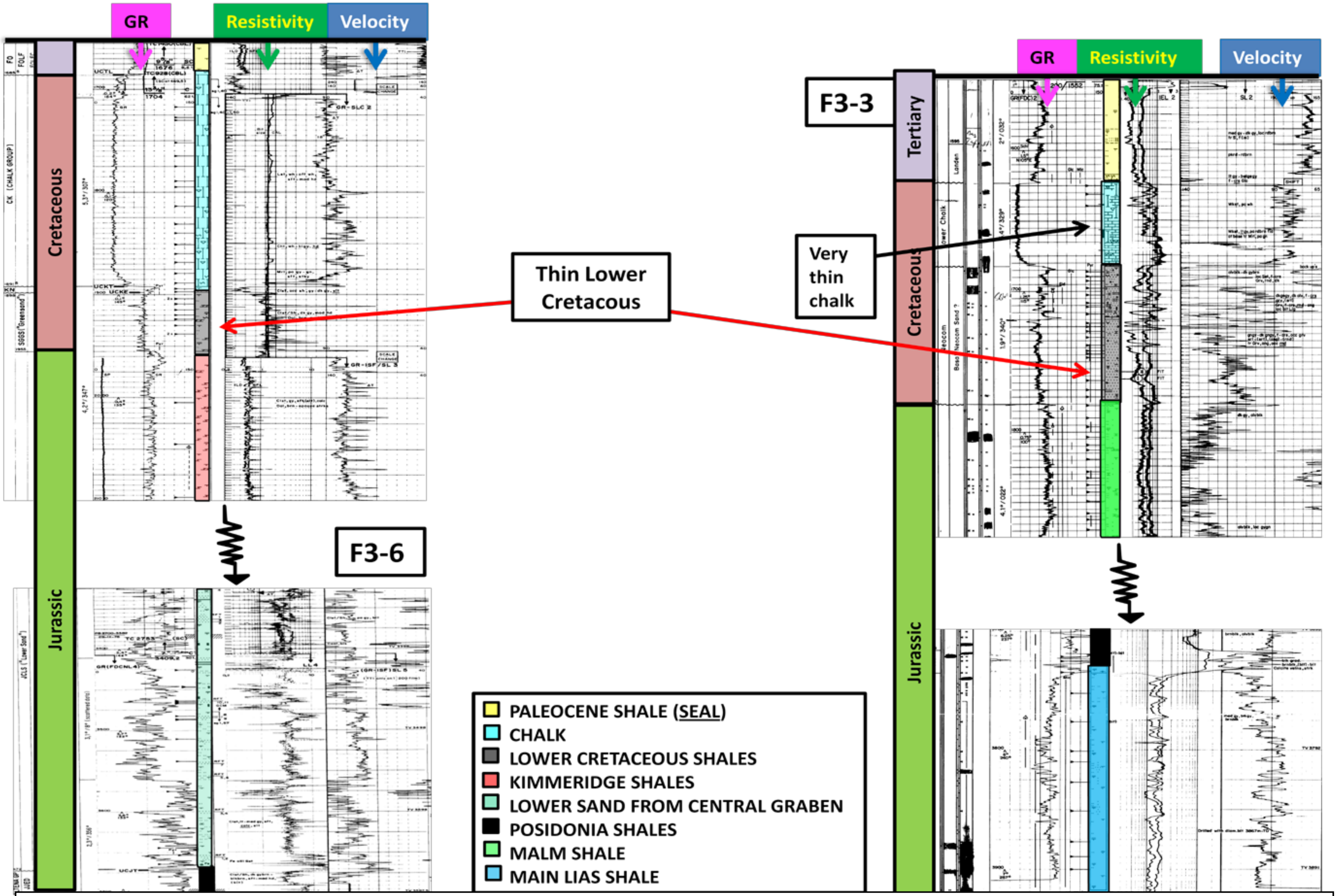


Figure H: Composite well logs of wells F3-6 and F3-3. They both mark the presence of the Posidonia Shales source rock within the Lower Jurassic layers.

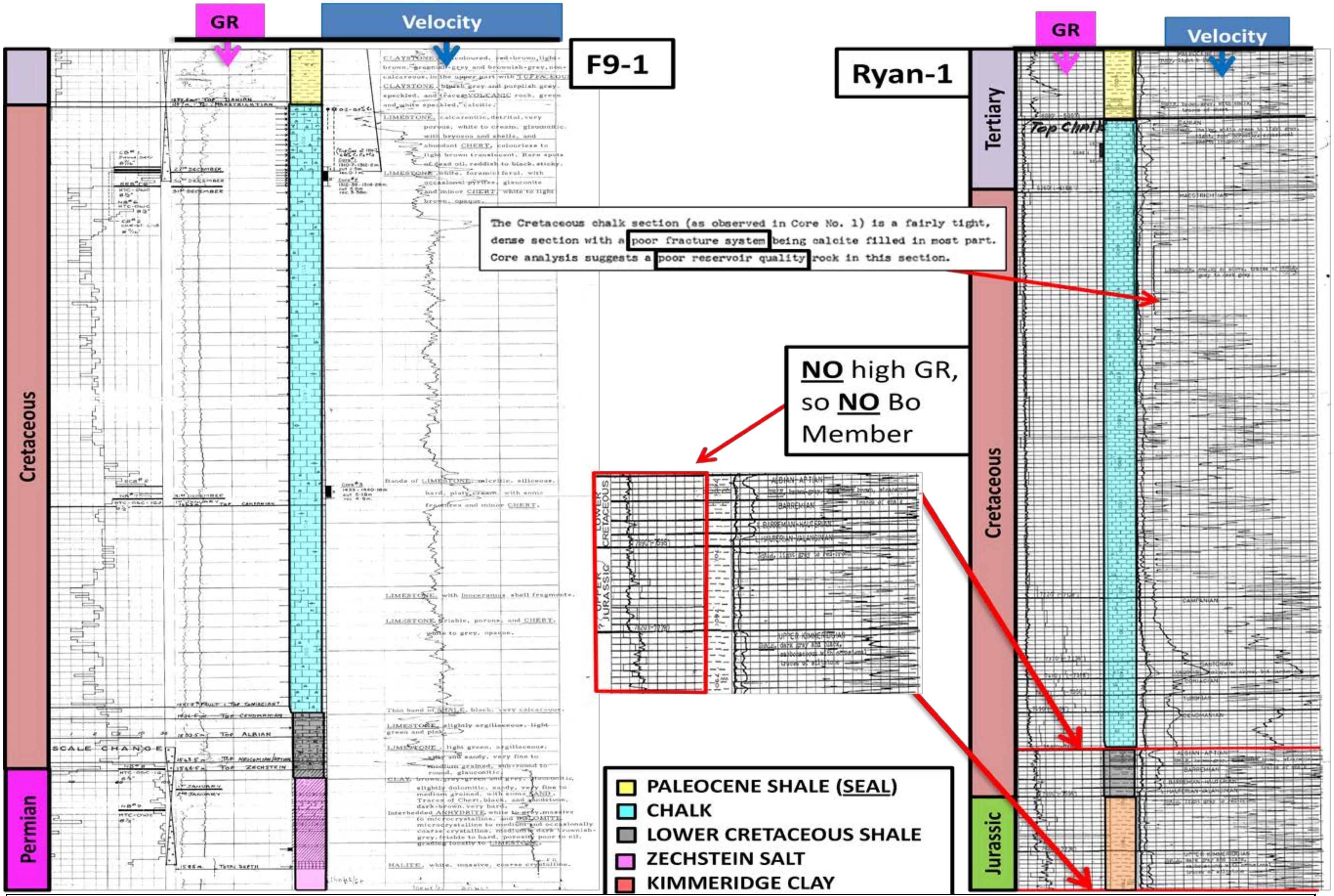
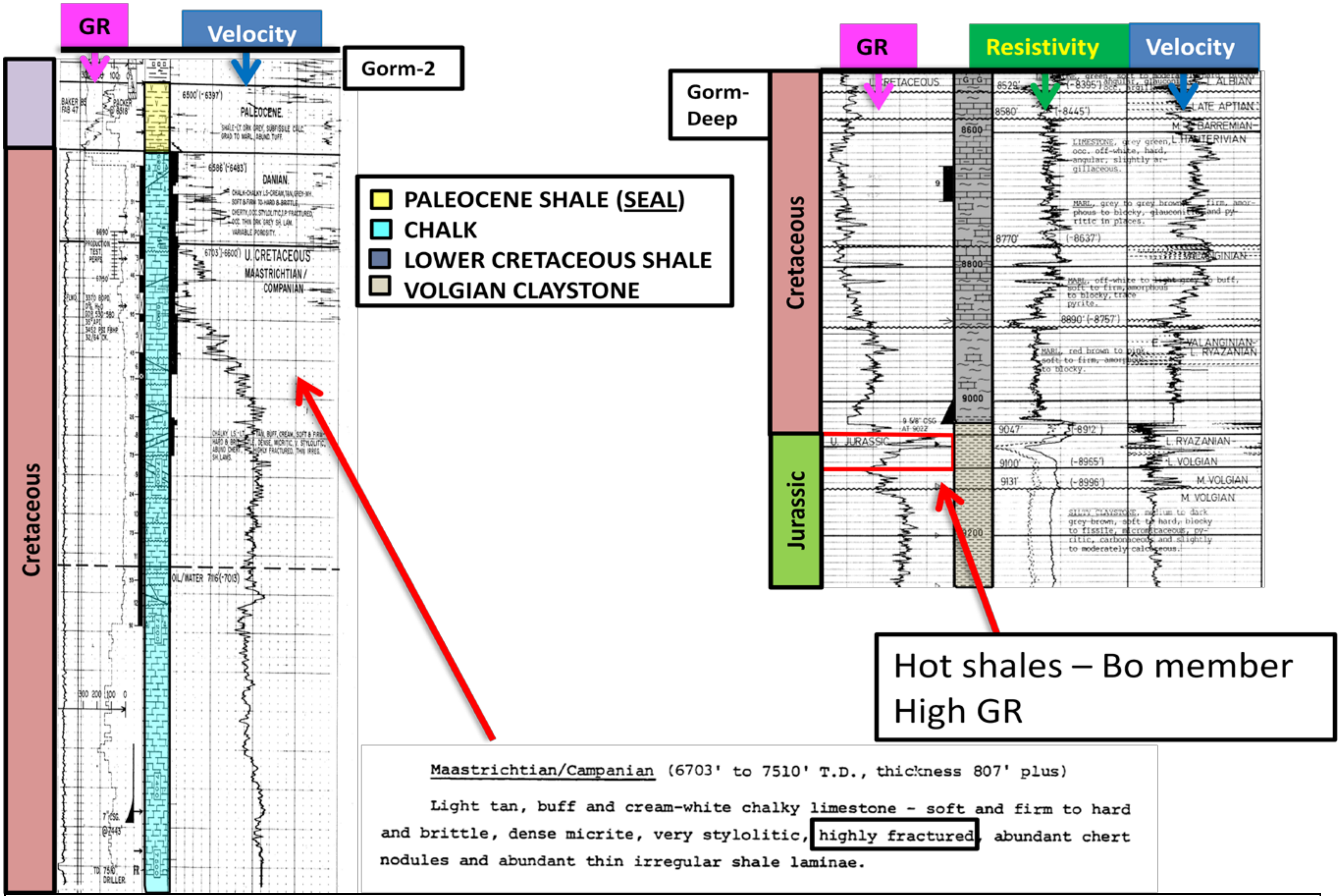


Figure I: Composite well logs of wells F9-1 and Ryan-1. F9-1 shows thin Lower Cretaceous Shales that rest directly on top of Zechstein salt. Ryan-1 marks the absence of the Bo Member and the thin Lower Cretaceous Shales.



Maastrichtian/Campanian (6703' to 7510' T.D., thickness 807' plus)

Light tan, buff and cream-white chalky limestone - soft and firm to hard and brittle, dense micrite, very stylolitic, highly fractured, abundant chert nodules and abundant thin irregular shale laminae.

Figure J: Composite well logs of wells Gorm-2 and Gorm-Deep. The Gorm-Deep well marks the presence of the Bo Member source rock within the Upper Jurassic layers.

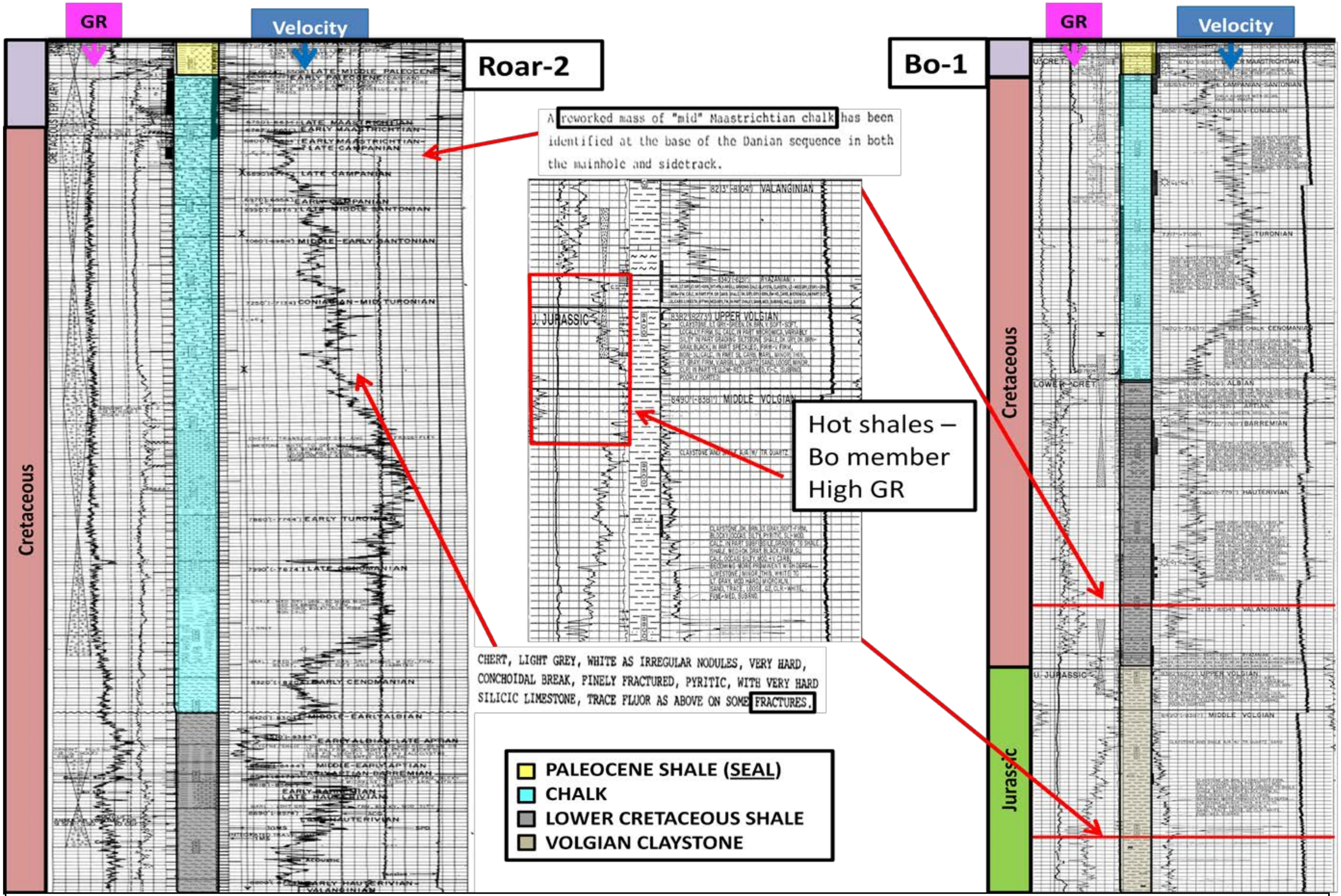
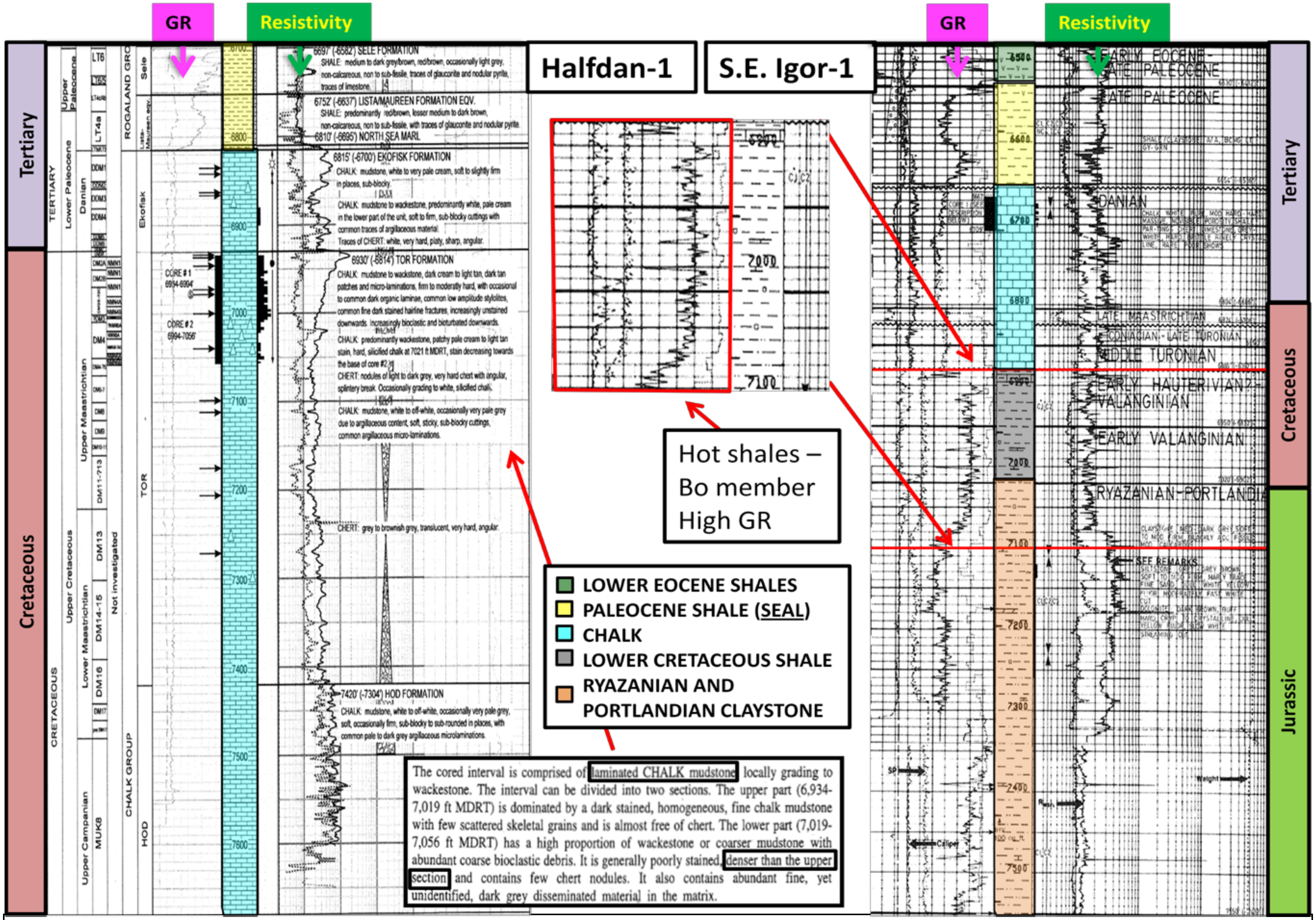


Figure K: Composite well logs of wells Roar-2 and Bo-1. Roar-2 marks a section of a reworked mass of "Mid" Maastrichtian chalk. Bo-1 marks the presence of the Bo Member source rock and the Paleocene seal rock.



6697' (-6582') SELE FORMATION
SHALE: medium to dark grey/brown, red/brown, occasionally light grey, non-calcareous, non to sub-fissile, traces of glauconite and nodular pyrite, traces of limestone.

6752' (-6637') LISTA/MAUREEN FORMATION EQV.
SHALE: predominantly red/brown, lesser medium to dark brown, non-calcareous, non to sub-fissile, with traces of glauconite and nodular pyrite.

6810' (-6695') NORTH SEA MARL

6815' (-6700') EKOFISK FORMATION
CHALK: mudstone, white to very pale cream, soft to slightly firm in places, sub-blocky.
CHALK: mudstone to wackestone, predominantly white, pale cream in the lower part of the unit, soft to firm, sub-blocky cuttings with common traces of argillaceous material.
Traces of CHERT: white, very hard, platy, sharp, angular.

6930' (-6814') TOR FORMATION
CHALK: mudstone to wackstone, dark cream to light tan, dark tan patches and micro-laminations, firm to moderatly hard, with occasional to common dark organic laminae, common low amplitude stylolites, common fine dark stained hairline fractures, increasingly unstained downwards. Increasingly bioclastic and bioturbated downwards.
CHALK: predominantly wackestone, patchy pale cream to light tan stain, hard, silicified chalk at 7021 ft MDRT, stain decreasing towards the base of core #2.
CHERT: nodules of light to dark grey, very hard chert with angular, splintery break. Occasionally grading to white, silicified chalk.
CHALK: mudstone, white to off-white, occasionally very pale grey due to argillaceous content, soft, sticky, sub-blocky cuttings, common argillaceous micro-laminations.
CHERT: grey to brownish grey, translucent, very hard, angular.

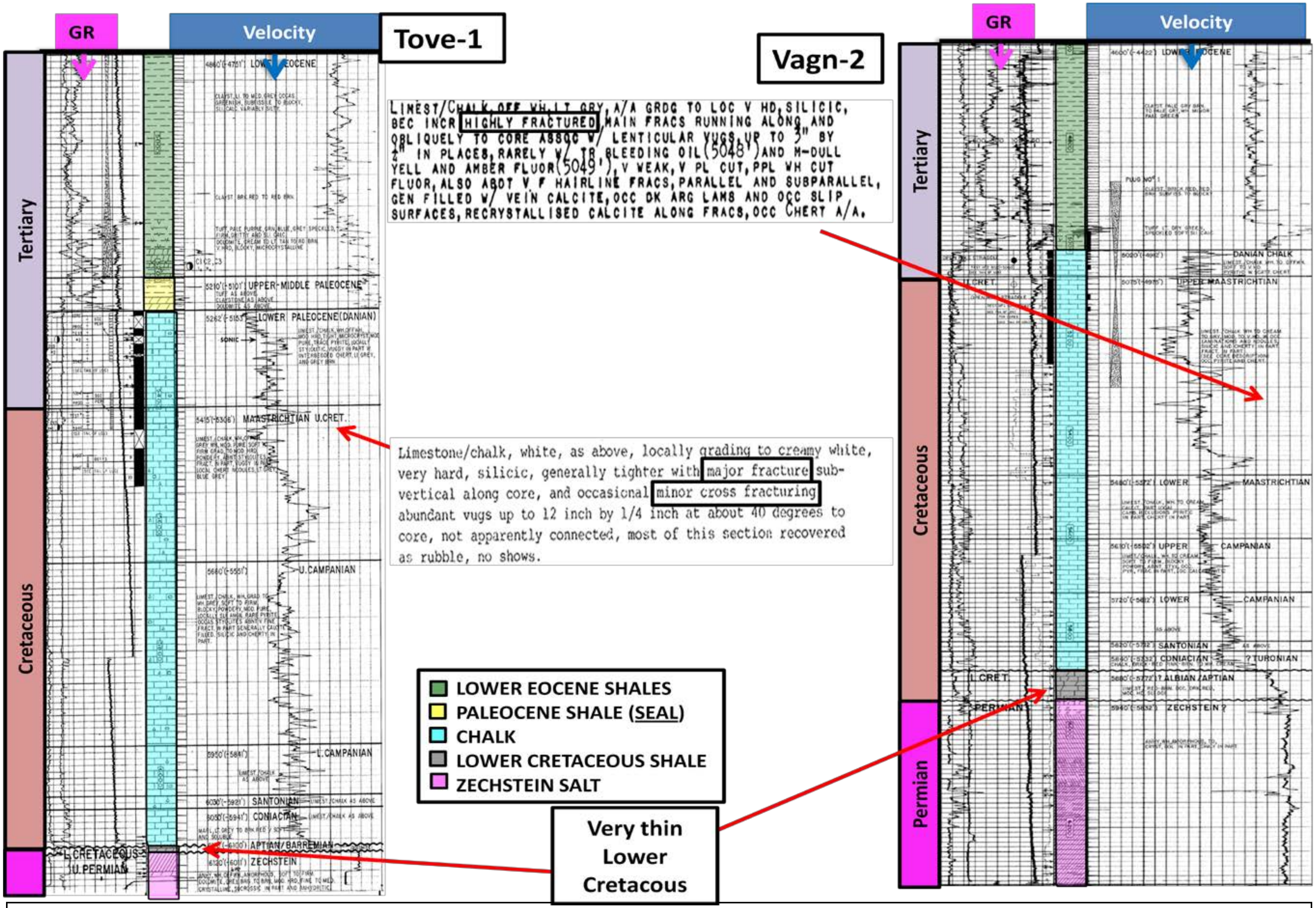
7420' (-7304') HOD FORMATION
CHALK: mudstone, white to off-white, occasionally very pale grey, soft, occasionally firm, sub-blocky to sub-rounded in places, with common pale to dark grey argillaceous microlaminations.

Hot shales –
Bo member
High GR

- 🟩 LOWER EOCENE SHALES
- 🟨 PALEOCENE SHALE (SEAL)
- 🟦 CHALK
- ⬜ LOWER CRETACEOUS SHALE
- 🟧 RYAZANIAN AND PORTLANDIAN CLAYSTONE

The cored interval is comprised of laminated CHALK mudstone locally grading to wackestone. The interval can be divided into two sections. The upper part (6,934-7,019 ft MDRT) is dominated by a dark stained, homogeneous, fine chalk mudstone with few scattered skeletal grains and is almost free of chert. The lower part (7,019-7,056 ft MDRT) has a high proportion of wackestone or coarser mudstone with abundant coarse bioclastic debris. It is generally poorly stained, denser than the upper section and contains few chert nodules. It also contains abundant fine, yet unidentified, dark grey disseminated material in the matrix.

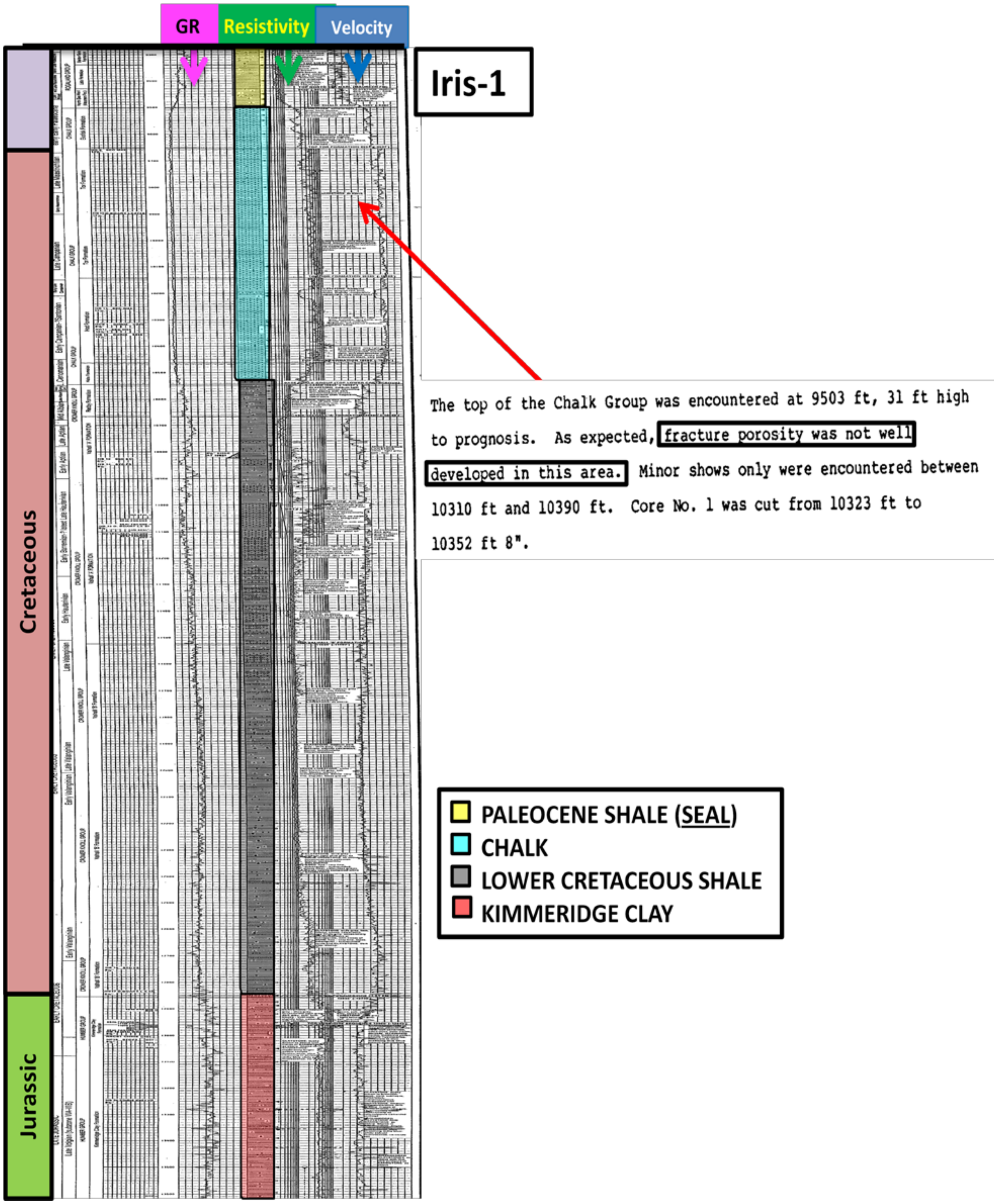
Figure L: Composite well logs of wells Halfdan-1 and S.E.Igor-1. Halfdan-1 marks the presence of the Paleocene seal and the low permeability and unfractured chalk. S.E.Igor-1 marks the presence of the Bo Member source rock



LIMEST/CHALK, OFF WH, LT GRY, A/A GRDG TO LOC V HD, SILICIC, BEC INCR **HIGHLY FRACTURED**, MAIN FRACS RUNNING ALONG AND OBLIQUELY TO CORE ASSOC W/ LENTICULAR VUGS, UP TO 3" BY 1/4" IN PLACES, RARELY W/ TR BLEEDING OIL (5048') AND M-DULL YELL AND AMBER FLUOR (5049'), V WEAK, V PL CUT, PPL WH CUT FLUOR, ALSO ABOT V F HAIRLINE FRACS, PARALLEL AND SUBPARALLEL, GEN FILLED W/ VEIN CALCITE, OCC DK ARG LAMS AND OCC SLIP SURFACES, RECRYSTALLISED CALCITE ALONG FRACS, OCC CHERT A/A.

Limestone/chalk, white, as above, locally grading to creamy white, very hard, silicic, generally tighter with **major fracture** sub-vertical along core, and occasional **minor cross fracturing** abundant vugs up to 12 inch by 1/4 inch at about 40 degrees to core, not apparently connected, most of this section recovered as rubble, no shows.

Figure M: Composite well logs of wells Tove1 and Vagn-2. Both wells marks chalk that is very highly fractured and a very thin Lower Cretaceous section.



The top of the Chalk Group was encountered at 9503 ft, 31 ft high to prognosis. As expected, fracture porosity was not well developed in this area. Minor shows only were encountered between 10310 ft and 10390 ft. Core No. 1 was cut from 10323 ft to 10352 ft 8".

Figure N: Composite well log of well Iris-1. The chalk is indicated by poorly developed fracture porosity in the well.

Appendix B

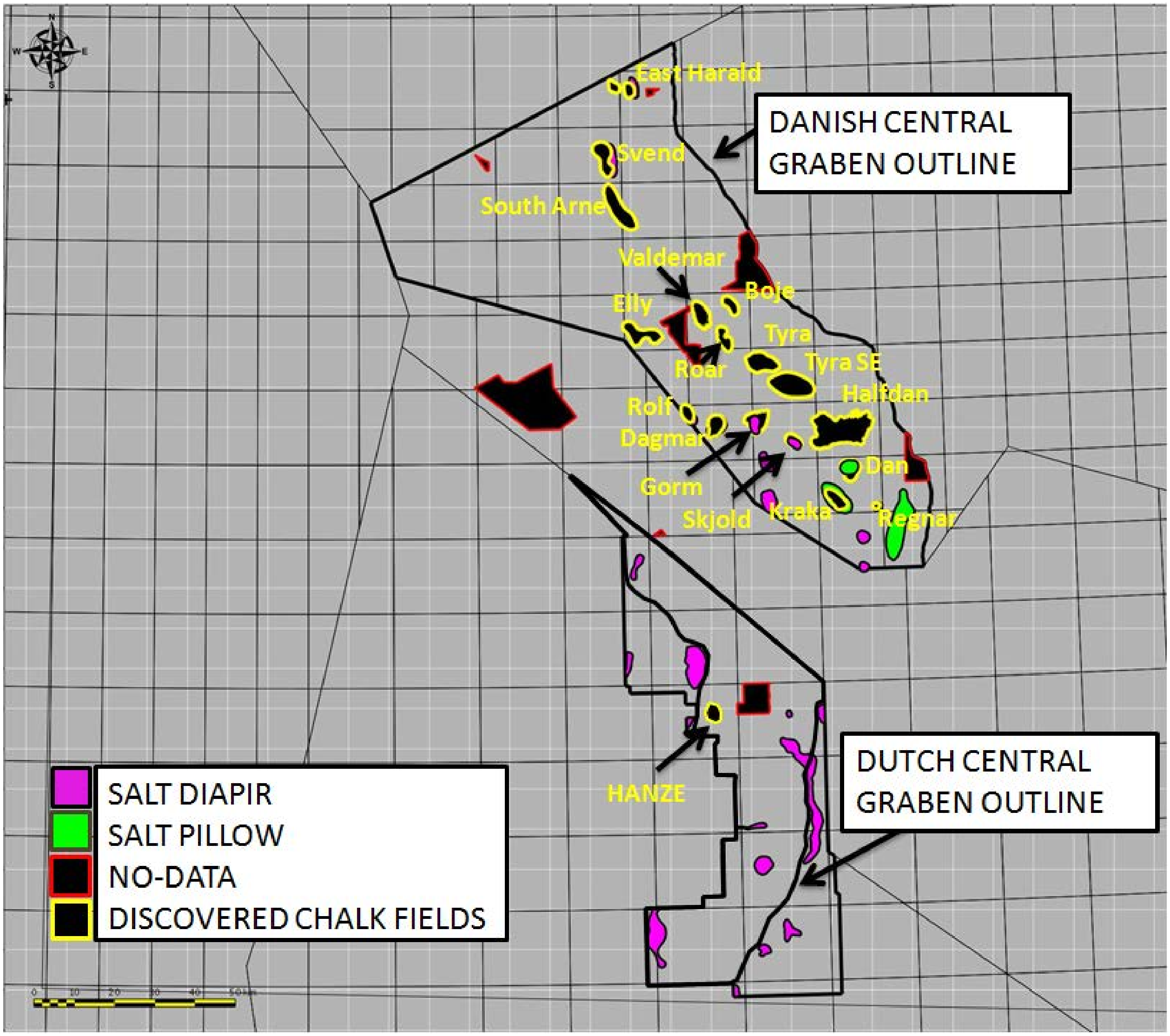


Figure A: Overview of the discovered chalk field in the Danish and Dutch Central Graben

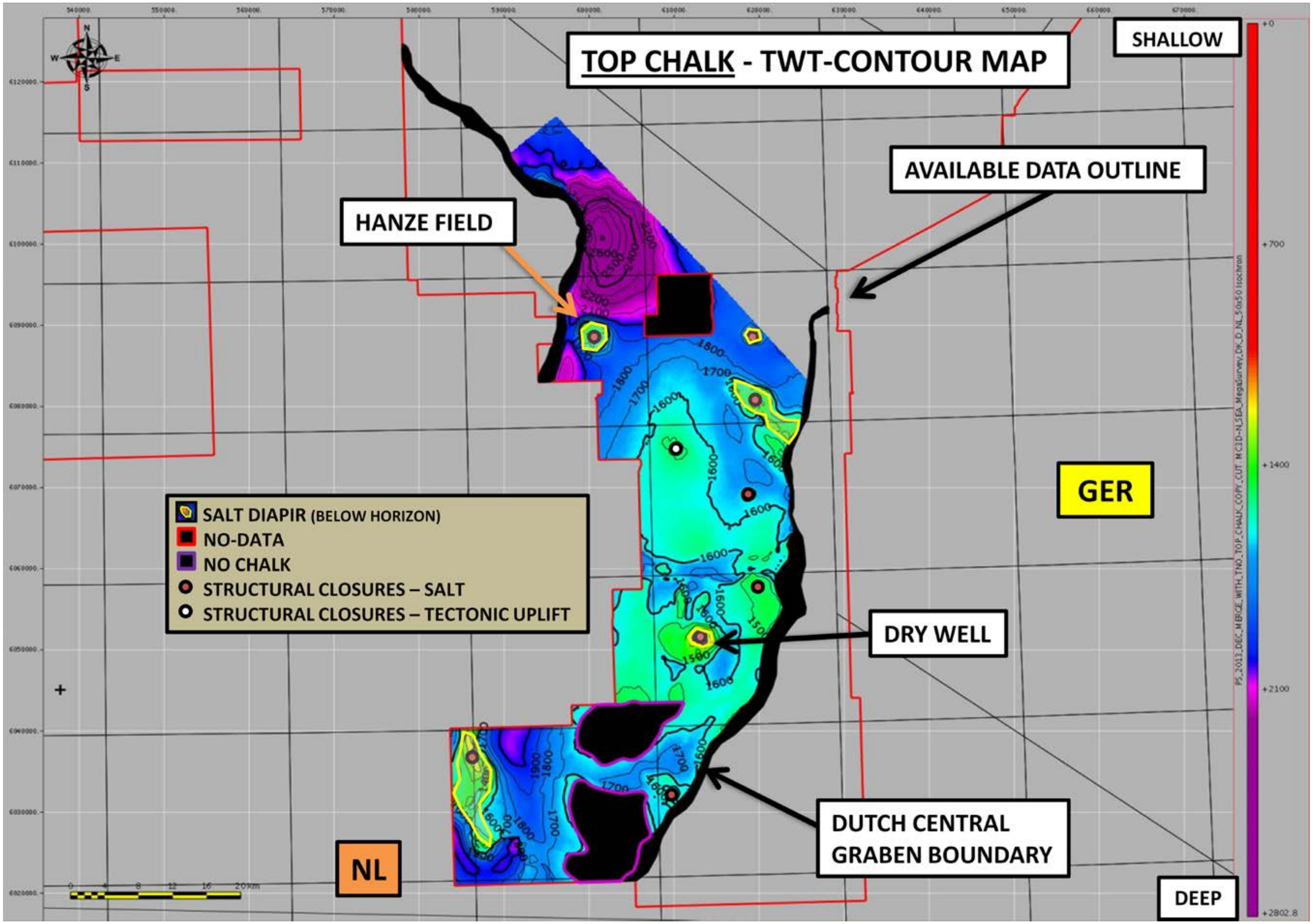


Figure B: Top Chalk – TWT – contour map showing the elevation of the layer and the presence of the salt structures and structural closures within the Dutch Central Graben.

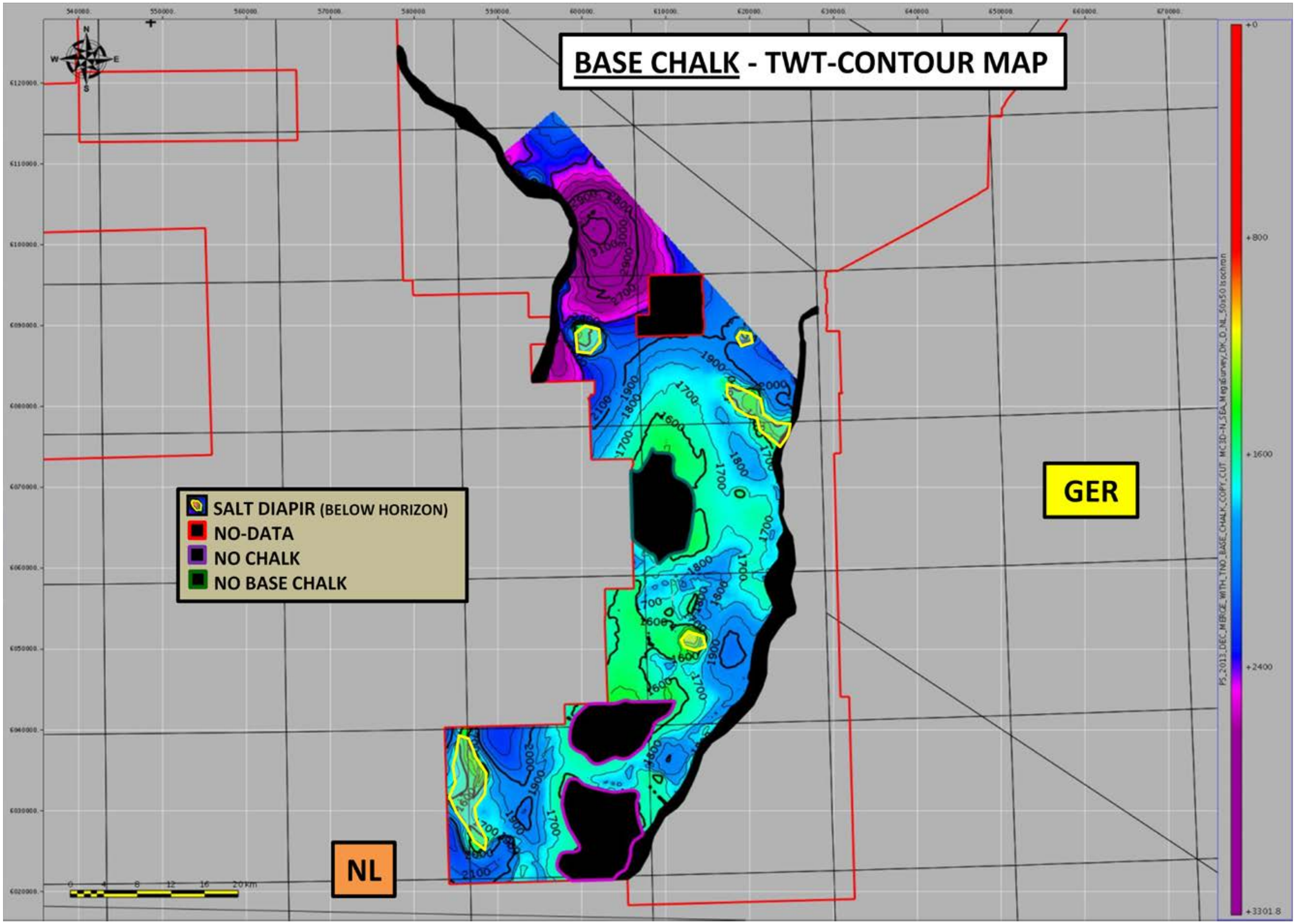


Figure C: Base Chalk – TWT – contour map showing the elevation of the layer and the presence of the salt structures within the Dutch Central Graben.

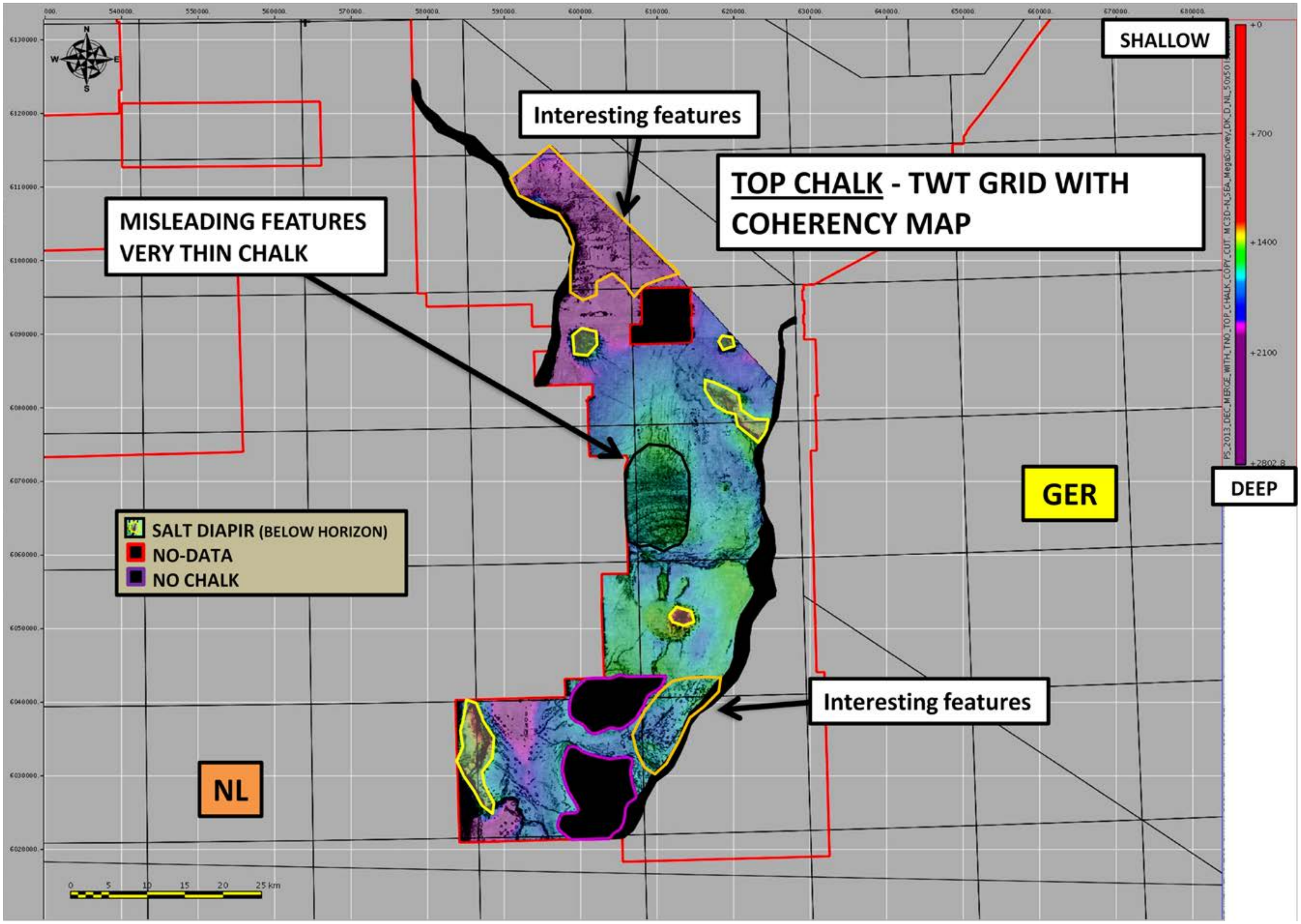


Figure D: Top Chalk – TWT grid with coherency map showing the presence of structural and stratigraphic elements within the Dutch Central Graben.

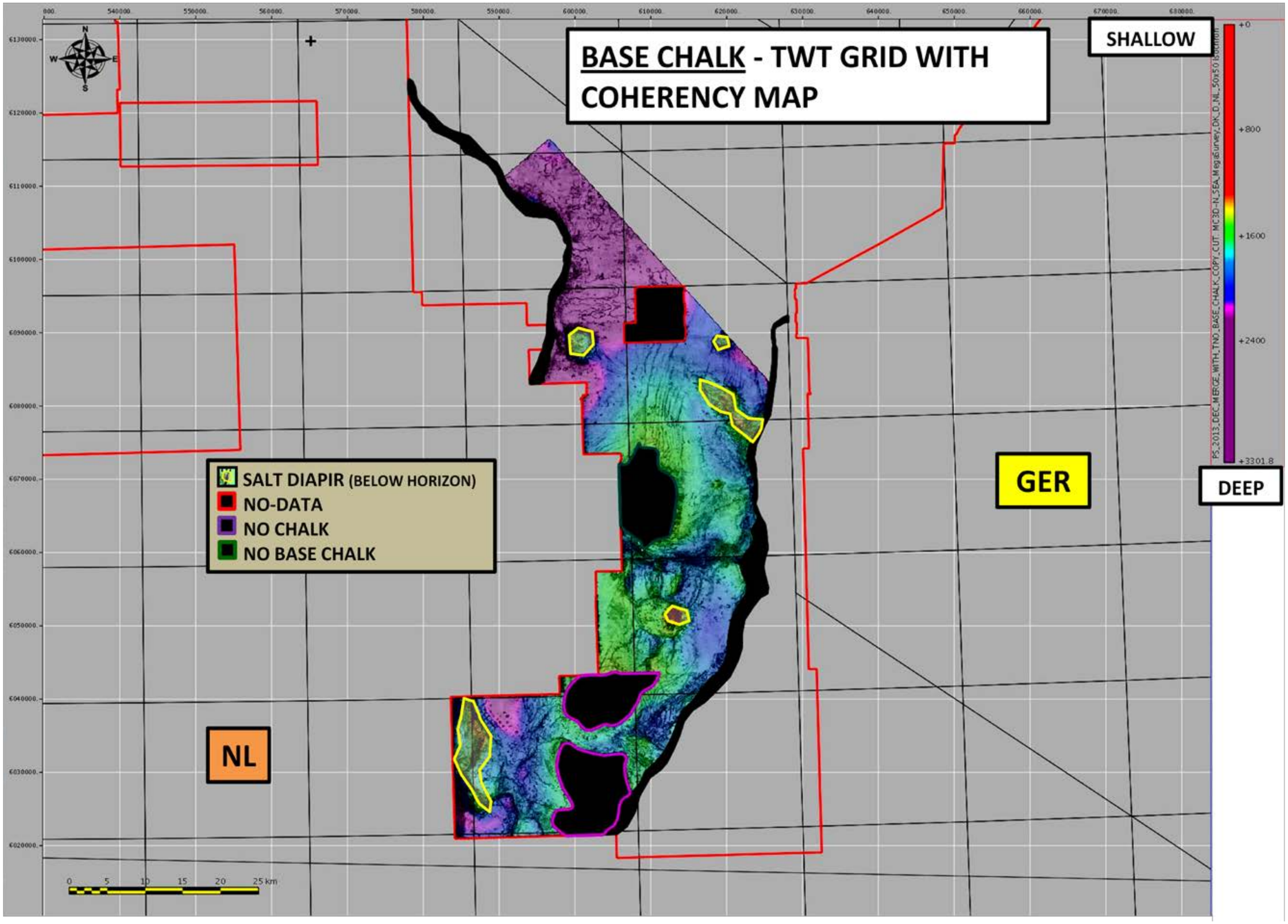


Figure E: Base Chalk – TWT grid with coherency map showing the presence of structural and stratigraphic elements within the Dutch Central Graben.

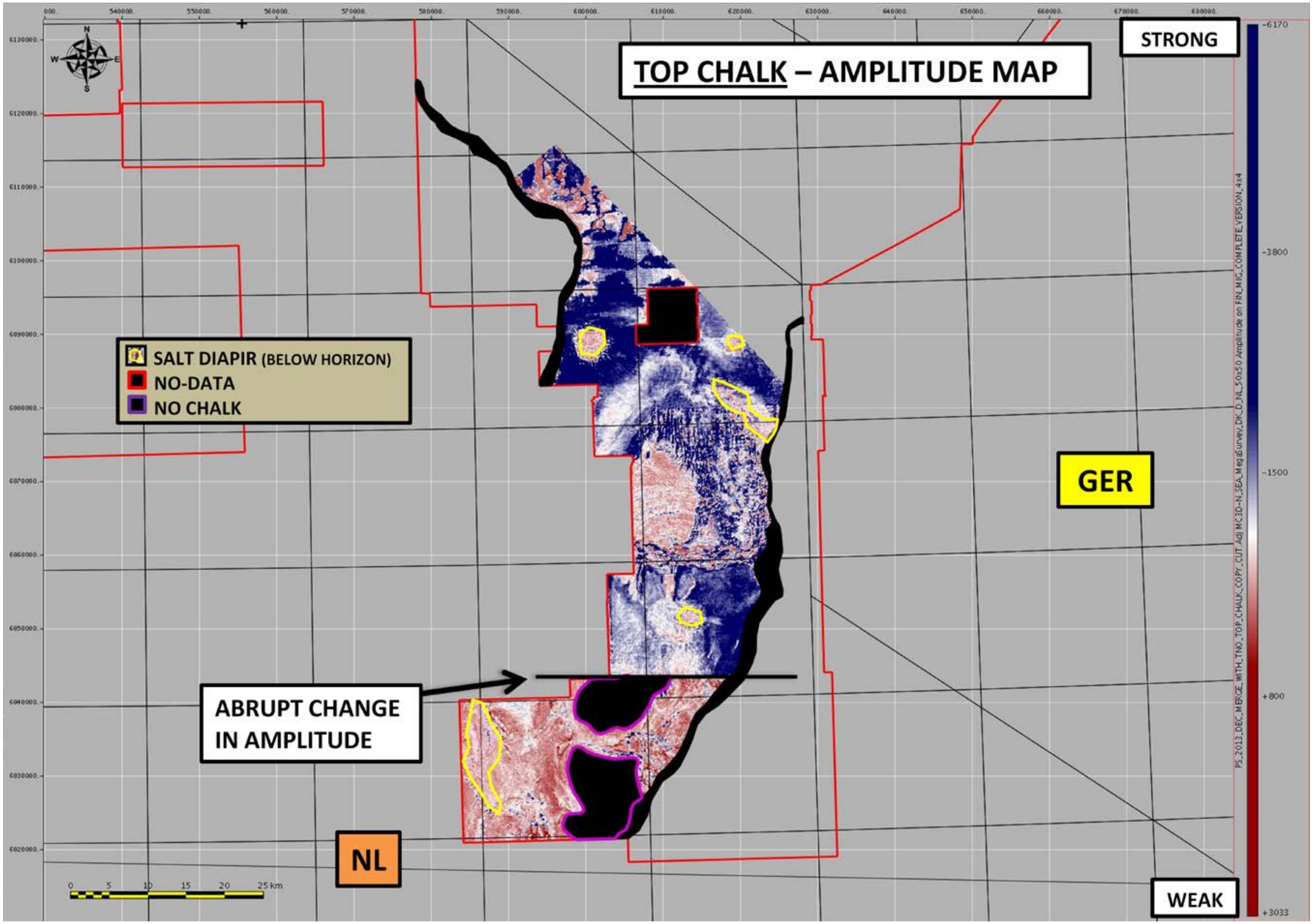


Figure F: Top Chalk – amplitude map showing how the strength of the amplitude changes throughout the Dutch Central Graben.

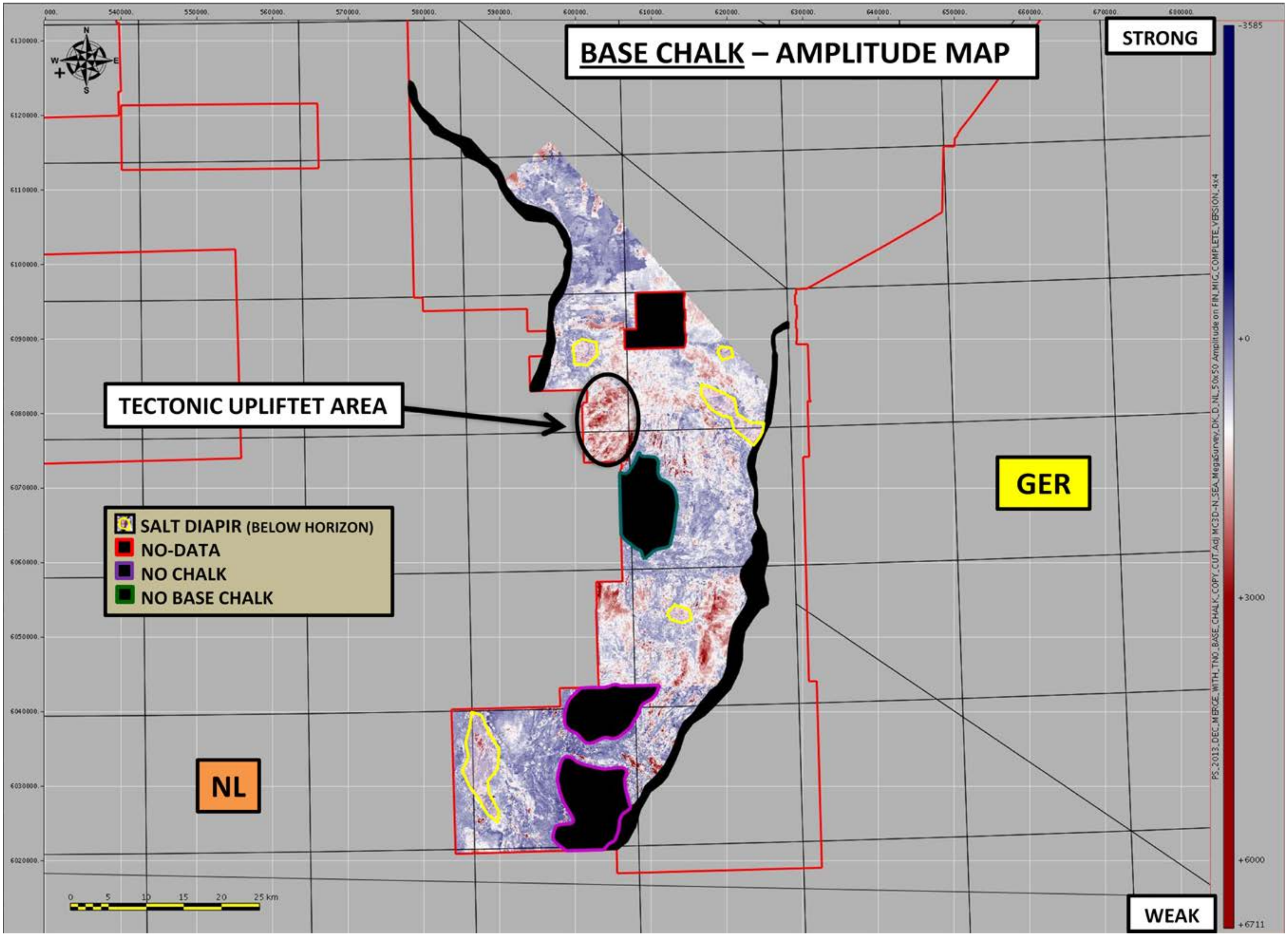


Figure G: Base Chalk – amplitude map showing how the strength of the amplitude changes throughout the Dutch Central Graben.

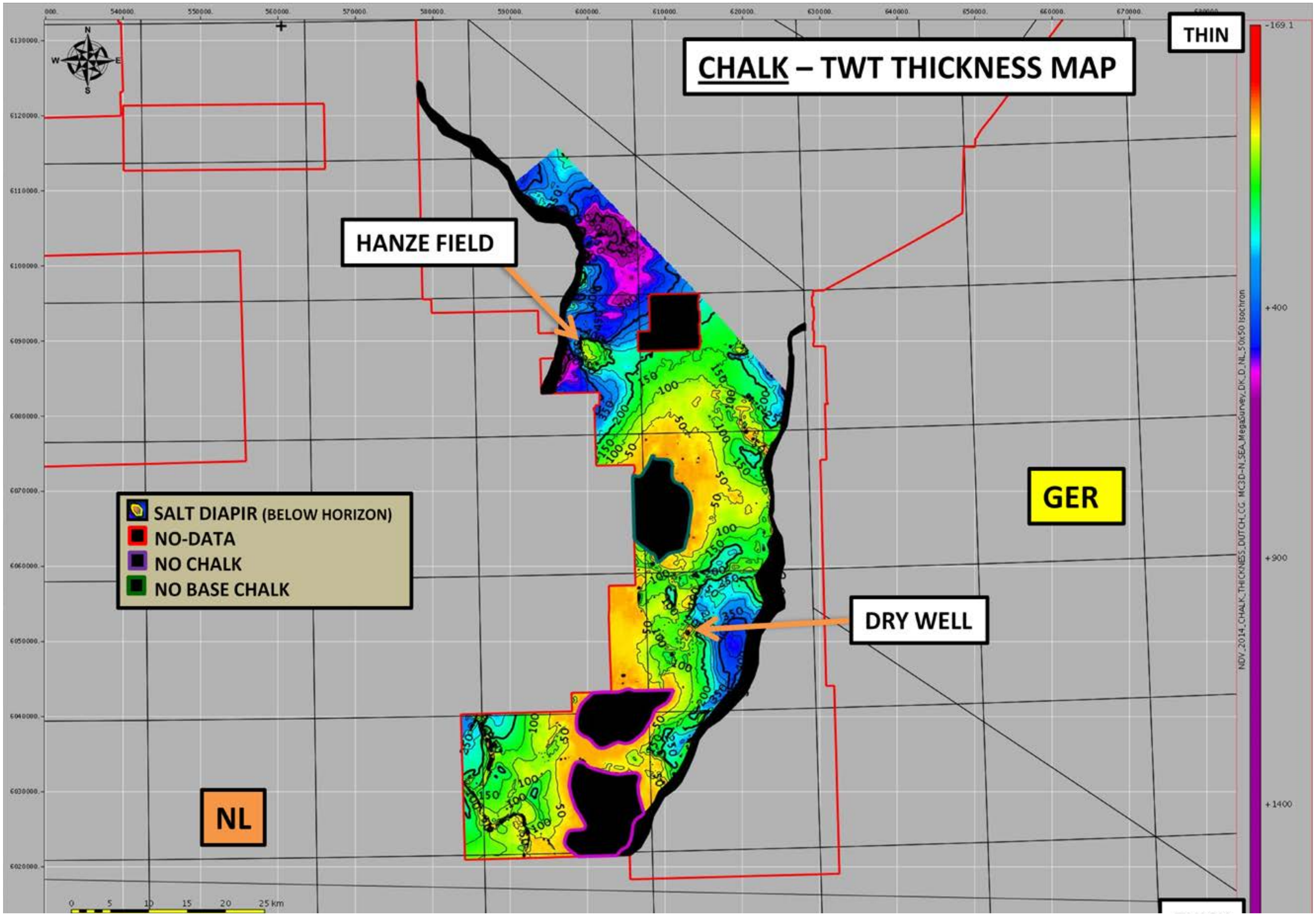


Figure H: TWT – Thickness map for the chalk layer across the Dutch Central Graben.

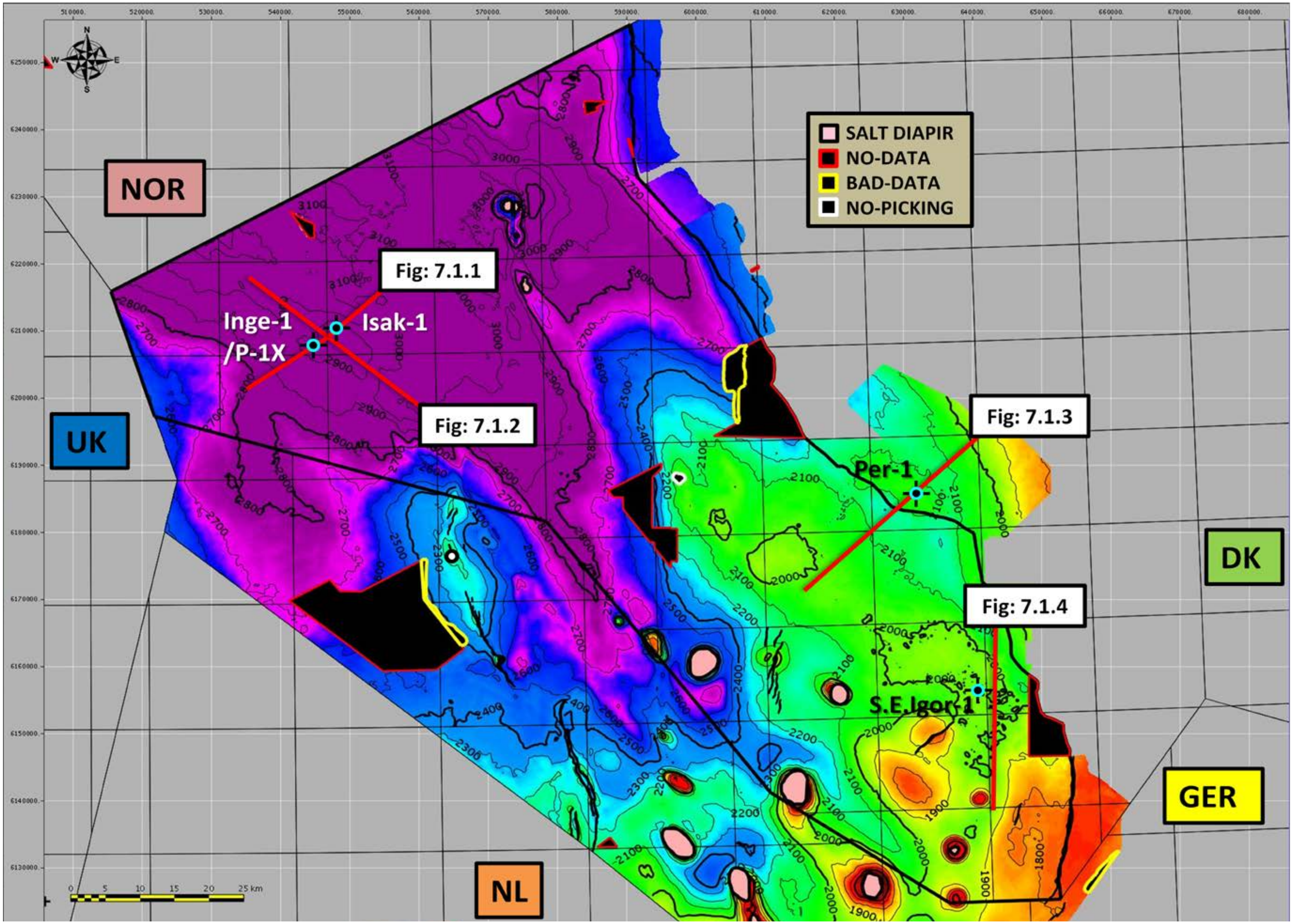


Figure I: Gives an overview of the locations of the seismic sections within the figures 7.1.1-7.1.4.