Assessment of CO_2 sequestration in saline formations in the Netherlands northern offshore: Upper Cretaceous Chalk

The Seven Sisters cliffs in East Sussex, England.
Photograph: eye35.pix/Alamy

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Abstract

The international energy agency has outlined that at least 15% of global emissions will be reduced through carbon capture and storage (Global CCS Institute 2022). Current studies and projects in the Netherlands are investigating the storage of CO_2 in depleted gas fields, and as such all studies focus on storage in Permian and Triassic clastic reservoirs. Although the carbonates, specifically Chalk play, has been prolific source of hydrocarbon in the Norwegian, Danish, and British sectors of the North Sea, it has only been discovered in four fields in the Netherlands. This study is the first to address the potential for deep offshore storage in the Chalk group in the K and L blocks of the Dutch offshore sector. The aim to produce a general assessment for the Chalk group's distribution, development, and quality of the main parameters that impact CO_2 injectivity and retention. The study focuses on L-K blocks in the northern offshore and utilizes a 3D survey with several well penetration that encountered, logged, and marked biostratigraphic intervals within the Chalk. The study demonstrated a workflow to evaluate and assess the Chalk utilizing seismic interpretation and attributes extraction. As a product, a general guideline was produced for the exploration of subsurface potential in the Chalk. Furthermore, the two most promising prospects within the survey were evaluated representing the two types of depositional Chalk (autochthonous and allochthonous). Autochthonous prospect F is analogous to the proven Chalk fields discovered in the Netherlands while allochthonous Prospect G is analogous to reservoirs in the UK sector. Both prospects at this stage are risky due to the lack of well data and adequate research on the Chalk to constrain the observation made, with an added risk to allochthonous prospect attributed to it not being encountered in the Dutch offshore before. To de-risk these prospects, future work was highlighted including building a detailed intra-Chalk interpretation to isolate and map seismically the proven reservoir intervals within the Chalk (Danian and Maastrichtian). Also, a detailed tectono-stratigraphic study that evaluates the inversion events impacting reservoir development. As Chalk is primarily discovered via geophysical methods, reprocessing the seismic for Chalk exploration and conducting seismic inversion to translate and quantify the geophysical parameters obtained of the seismic anomalies to reservoir character models would be key.

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1. Introduction

Carbon capture and storage (CCS) has grown in popularity within the past decade as a solution to prevent the release of hard to abate CO_2 emissions into the atmosphere and a method for nations to honor their commitment of curbing climate warming as per the Paris climate agreement. In fact, the international energy agency has outlined that at least 15% of global emissions will be reduced through carbon capture and storage (Global CCS Institute, 2022). The Netherlands has an especially key role to play in geologic carbon storage not only for its own emissions but for the EU, without which, the 2030 climate agreement will be unachievable (Advies Ministerraad, 2022). Since roughly 2005, The Netherlands has conducted extensive regional studies (ROAD project and CATO) to assess the subsurface potential for storage. These studies have focused primarily on clastic depleted gas fields because of their proven reservoir properties and the potential to refit existing facilities (Neele et al., 2021). Unlike depleted gas fields, deep saline aquifers have the largest identified storage potential with enough estimated capacity to store emissions for a century (Celia, et al. 2015). The scope for storage in carbonate rocks has been reviewed with respect to the Chalk in the Danish sector of the North Sea (Bonto et al., 2021). Storage capacities assessed through three main projects (Joule II, GESTCO, and GeoCapacity) recognize the immense capacities that saline aquifer creates when compared to that proven in depleted oil and gas (figure 1).

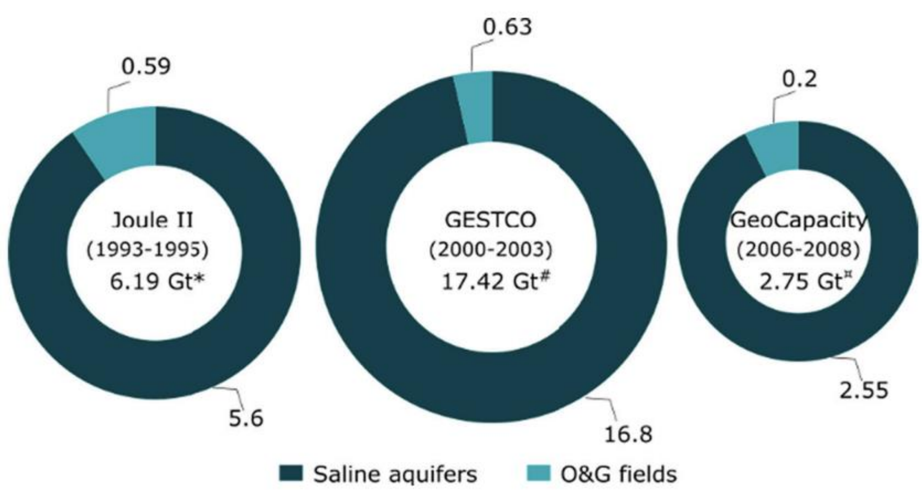


Figure 1: CO_2 Storage capacity estimates in Joules from Denmark. From Bonto et al. (2021).

This study is a part of the Deep Offshore Carbon Storage (DOCS) project hosted in the Vrije Universiteit Amsterdam and in coordination with the State Energy company, EBN (Energie Beheer Nederland). DOCS aims to screen for geologic carbon storage sites in saline aquifers in the Netherlands. The study examines requirements for storage in the carbonate Chalk group in general and identifies sites that would be candidate for storage. This study builds on the recommendations of previous work by DOCS member Rijsdijk (2022), where she conducted a regional assessment of all potential saline aquifer reservoir and indicated that the Upper Cretaceous Chalk represents a potential play for saline carbon storage in the northern Dutch offshore. This study will focus on the northwest corner of the L block and the adjacent K block to map several trap geometries as well as utilize various visualization techniques to evaluate the Chalk potential (figure 2).

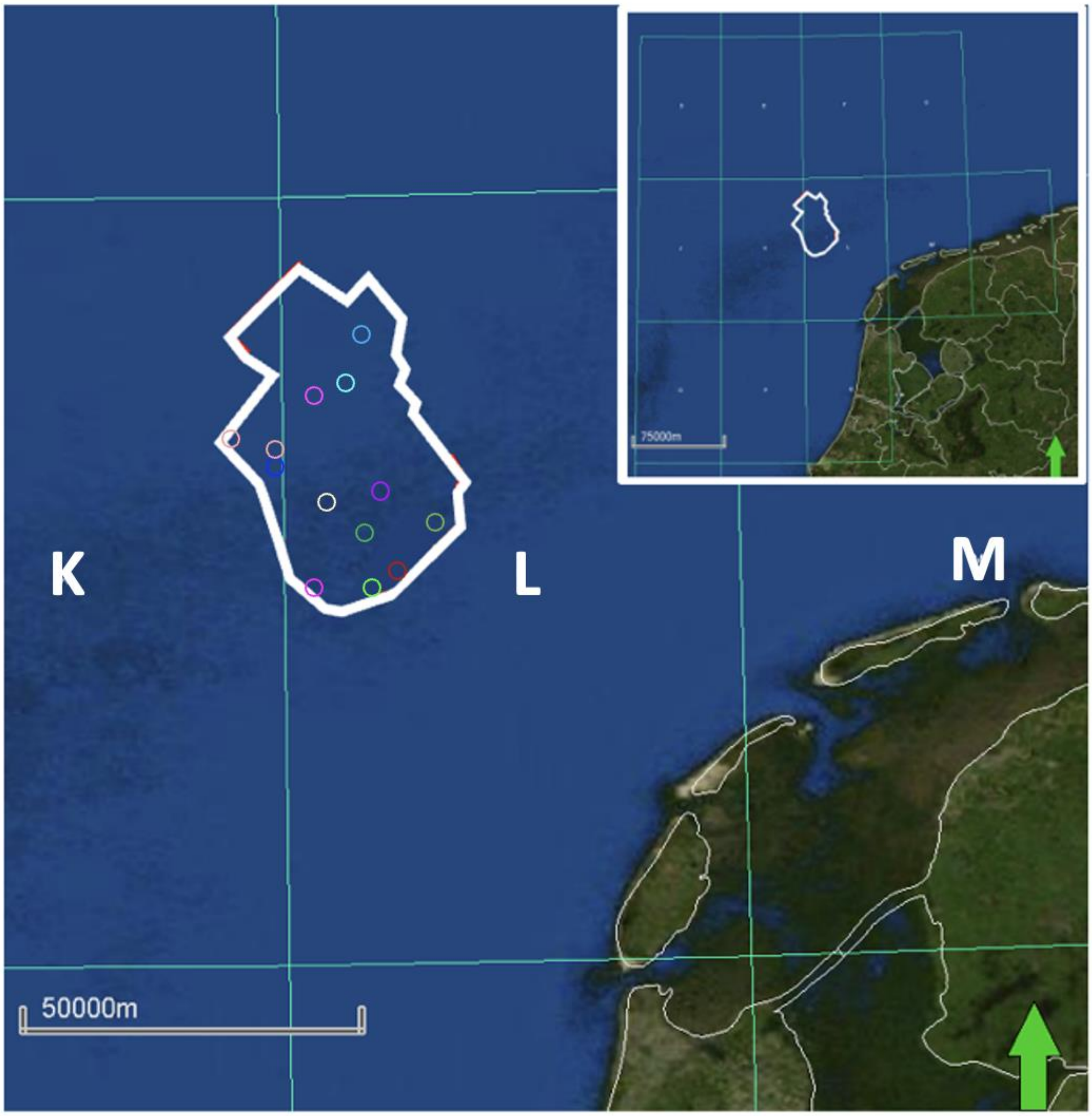


Figure 2: Location of study area highlighting the seismic survey and wells utilized in this study.

The Chalk play has been a prolific source of hydrocarbon in the North Sea, mainly in the Norwegian, Danish, and British sectors (figure 3). In the Dutch sector, a handful of discoveries were made in the Chalk with most of the petroleum being produced from the Permian and Triassic clastic reservoirs (de Jager et al., 2007). This led to the scarcity of available well data and consequently less published work on the Chalk in Dutch sector compared to the Danish, Norwegian, and British side. In fact, a report published by EBN in 2019 highlights the Chalk as a "proven yet underexplored" play (EBN, 2019). The report further highlights that the play is technically challenging but is rewarding and sited the most recent Dutch Chalk field discovery Rembrandt field, Denmark's Halfdan field, and UK's Fife field (EBN, 2019).

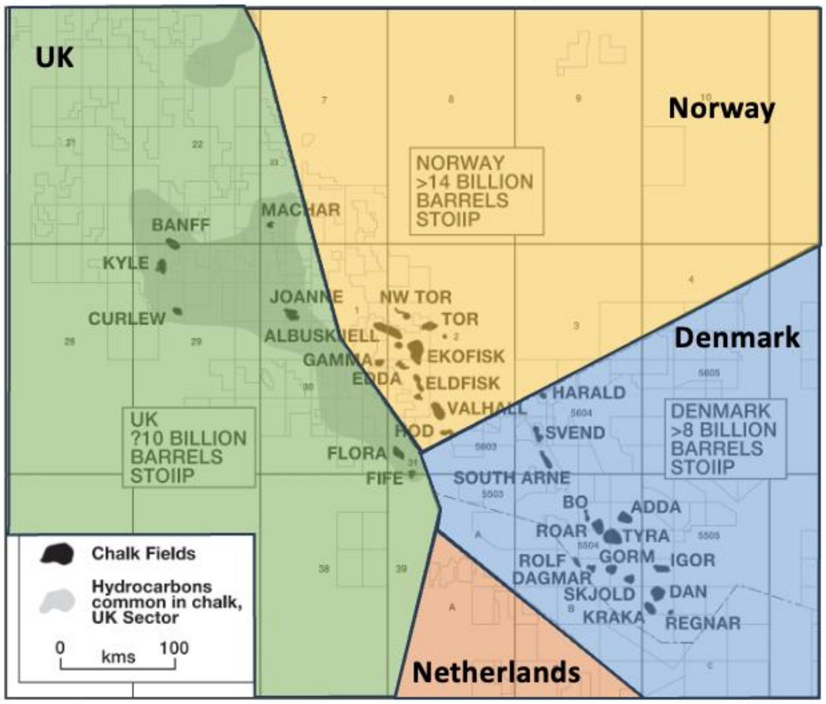


Figure 3: Map of Chalk Fields in the North Sea. From Megson et al, 2001.

This study will aim to produce a general assessment of the Chalk group's distribution, development, and main reservoir parameters that impact CO2 injectivity and retention. Furthermore, it will identify and map potential "sweet spots" where options for injection may exist with an evaluation of trapping mechanism, reservoir size, and risking. As this study is the first to address the potential for deep offshore storage in the Dutch sector's Chalk group, its conclusions will help develop a general understanding of the challenges and opportunities of targeting the Chalk group. As an early-stage assessment study, reservoir engineering, economic, and environmental aspects will not be covered. Instead, the study will indicate other areas for future studies to investigate and contribute to the creation of a portfolio of opportunities and a comprehensive evaluation of the Chalk across the prospective zones in the Dutch offshore. Finally, it will also highlight focus areas for future studies to de-risk and develop the high-graded prospects. The key aim of this work is to aid in expanding of the geographic and geologic options for CCS in the Dutch offshore. Beyond the Netherlands, it will also have transferrable workflow and lessons to localities that have Chalk within the optimal depth for CCS, such as neighboring Denmark.

2. Geologic and Stratigraphic Setting

2.1. Location

The study area is in L and K blocks of the Dutch sector of the North Sea (figure 2). The main survey is in the central offshore platform, defined as a small structural element bound to the north by the southernmost tip of the Dutch central graben and to the south the by the Broad Fourteen Basin to the south and is confined by bounding fault lineaments with an NNW-SSE orientation from the east and west (figure 4-a). In the study area, the Chalk has thick deposits that thins out to the east and thickens significantly towards the west (figure 4-b) (Duin, et al. 2006). Furthermore, the study area has a wealth of legacy petroleum data that penetrate and log the Chalk, partially, as the top is a regional casing point[1]. Finally, the area is proximal to the Aramis Project, a national CO_2 storage cluster planned to target depleted L and K block gas fields.

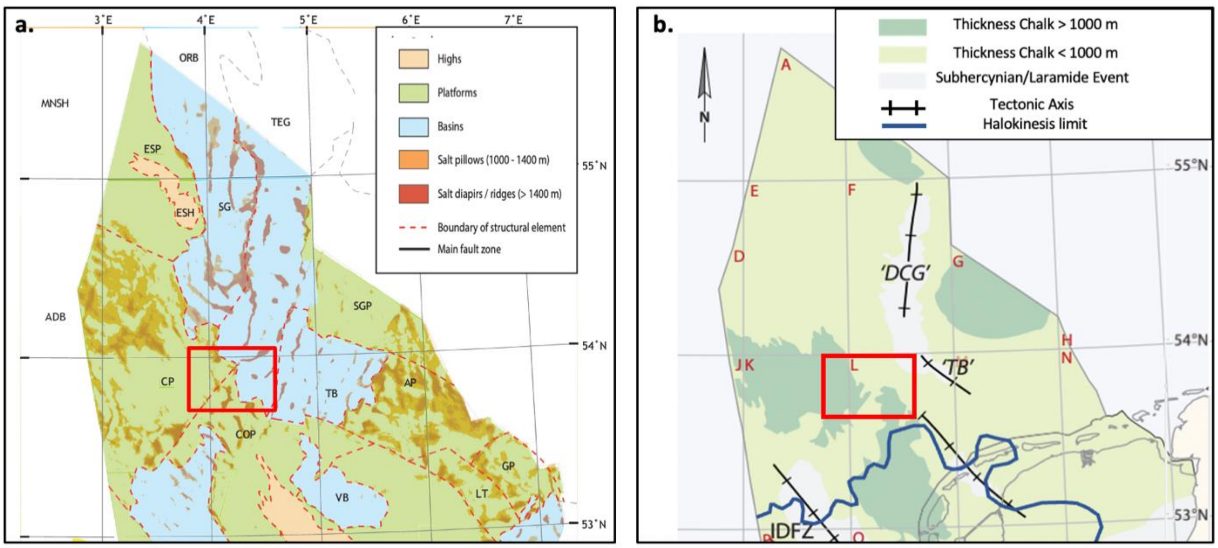


Figure 4: Dutch sector in the North Sea Maps. AOI- Red Box. (a) structural elements with the study area highlighted. (ten Veen, et al. 2012). SG = Step Graben, DCG = Dutch Central Graben, CP = Cleaverbank Platform, COP = Central Offshore Platform, TB = Terschelling Basin, AP = Ameland Platform. (b) Chalk Thickness Map in the Netherlands (Duin, et al. 2006).

2.2. Tectonic and Structural Evolution

2.2.1. The Carboniferous

Marked by the deposition time of the Limburg group, the super continent Pangea was assembling and the central offshore platform and much of the Dutch offshore was in an intercontinental foreland of the Variscan orogeny (figure 5) (de Jager, 2007). It is composed of thick clastic formations and contains coals seams within the middle and upper part, while the older part locally developed silicified limestone layers are present (TNO-GDN, 2023). The

[1] Casing point: the point the well hole size is reduced. Usually marks the stop of drilling and encasing the drilled section's walls with cement. When this process is conducted, well logging is usually interrupted over the area the casing point.

Carboniferous coals were a main source of energy when mined and a prolific source rock for gas (Kombrink, et al. 2010). For most plays, it mainly charges the overlying Rotligened sandstones but also has been known to charge the Cretaceous Chalk in the Harlingen field with the aid of faults.

2.2.2. The Permian

The deposition time of the widespread Rotliegend reservoir and its main seal Zechstein evaporite group. The Permian is separated from the underlying Carboniferous by an unconformity that formed due to the formation of a wrench faulting system that caused extensive magmatism, thermal uplift, and subsequent erosion (de Jager, 2007) (Ziegler, 1990). The late Rotliegend is characterized by thermal subsidence which led to the deposition of the reservoir clastic members that form many of the gas fields in northwest Europe (Gast, et al. 2010). As a part of the Southern Permian Basin, the area was subject to periodic marine ingression in the time of deposition of the late Rotliegend that grew to marine transgression during the Zechstein deposition time (Gast, et al. 2010). The Zechstein is composed primarily of a sequence of evaporites (primarily anhydrite and rock salt), carbonates, and thin mudstone layers (TNO-GDN, 2023).

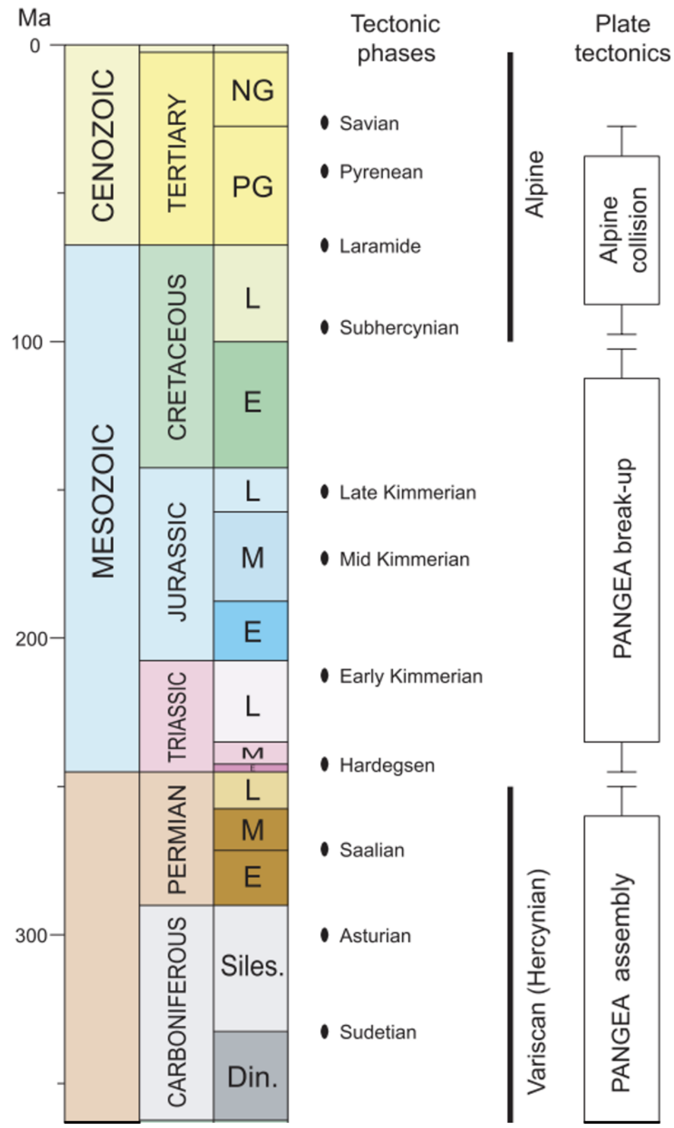


Figure 5: Tectonic phases affecting the Dutch offshore from de Jager 2007

2.2.3. The Triassic

Strongly influenced by the breakup of Pangea, an extensional system setting governed the deposition of the Triassic Germanic group (de Jager, 2007). The lower Germanic group is composed of successions of sandstones and claystones deposited in lacustrine to fluvial environments gradually changing to the upper Germanic group that was deposited in shallow marine and floodplain environments (TNO-GDN, 2023). Much like the Rotliegend, the Triassic is a prolific gas reservoir that extends throughout NW Europe (Bachmann, et al. 2010).

2.2.4. Jurassic - Lower Cretaceous

In the Middle Jurassic, a basin wide uplift event occurred and led to the erosion of the Jurassic section except within rifting basins (Ziegler, 1990) (de Jager, 2007). This led to the Lower Cretaceous Rijnland group sitting unconformably on the Triassic and separated by the Late

Cimmerian unconformity (Vejbaek, et al. 2010). The Rijnland is composed of shallow to deep marine clay Formations and occasionally the occurrence of sandstones layers (TNO-GDN, 2023).

2.2.5. Upper Cretaceous

This was characterized in its start to be a period of subsidence and rising sea level that led to the deposition of a significant carbonate section (de Jager, 2007). In the late Cretaceous, the regional stress fields changed because of the initiation of the alpine orogeny-Subhercynian phase leading to the prevalence of compressional forces (de Jager, 2007). This led to the formation of NW-SE strike slip faults, episodic inversion, and halokinesis during the deposition of the late Cretaceous (Vejbaek, et al. 2010). The Chalk consists of mainly pelagic sediments to marly limestones with zones of calcareous mudstones and glauconitic sands that occur locally (TNO-GDN, 2023).

2.2.6. The Tertiary

The early Paleocene is a period with continuous deposition of Chalk followed by the onset of the strongest inversion as a part of the Laramide phase (de Jager, 2007). This led to the end of Chalk deposition and the commencement of the clastic system of the North Sea group (de Jager, 2007). Multiple inversion pulses continued throughout the Eocene and Oligocene which heavily impacted the thickness of the North Sea group throughout the basin (de Jager, 2007) (Vejbaek, et al. 2010).

2.3. Stratigraphy

2.3.1. Subdivisions

The Chalk group consists of sediments deposited in the late Cretaceous, between the Cenomanian to Danian stages (TNO-GDN, 2023). In the Dutch offshore, it is divided into three formations: Cenomanian Texel Formation, Turonian to Maastrichtian Ommelanden Formation, and the Danian Ekofisk Formation (figure 6) (van der Molen, 2004). A study conducted by van Wingerden (2016) looked at Chalk cores across the Dutch offshore and concluded that the most prospective zones of the Chalk group is the middle to late Maastrichtian which corresponds to the upper Ommelanden Formation and Danian Ekofisk Formation when they are not interbedded with clay layers (van Wingerden, 2016). This is tied to the fact that those two stages were connected to significant halokinesis that led to fracturing and enhancement of reservoir permeabilities in the late Cretaceous inversion due to the Laramide orogeny pulse (de Jager, 2007).

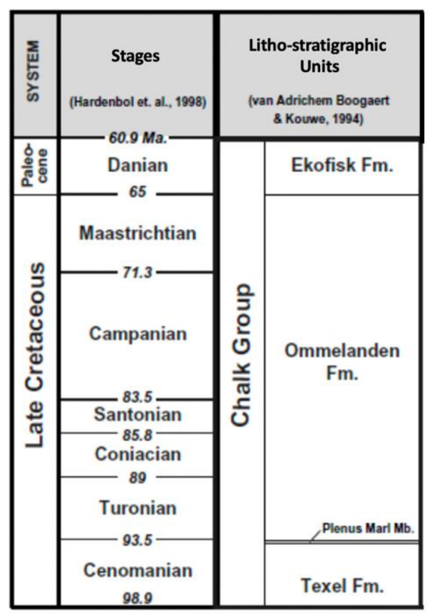


Figure 6: Lithostratigraphic Column of the Chalk group in the Dutch offshore. From van der Molen, 2004.

2.3.2. Chalk Formation and Deposition

Clean chalk forms through the deposition of pelagic carbonates through settling of nanoplankton remains (mainly coccolithophores) from suspension. The deposition could be interrupted with beds of sands and clay due to erosional detrital influx in proximal locations (van Wingerden, 2016). In figure 7, we see the depositional processes that led to the deposition of the two main types of Chalk recognized in the North Sea. The first, autochthonous Chalk deposited by the process of pelagic rain (van der Molen, 2004). The second type is allochthonous Chalk that is due to re-mobilization of Chalk by gravitational process, ocean currents, and tectonic events, fault block uplift, basin inversion, or halokinesis induced re-deposition downslope (van der Voet, 2015). The variability of Chalk redistribution across the basin leads to thickness variations that are strongly influenced by tectonic stress variation and sediment supply (van der Molen, 2004).

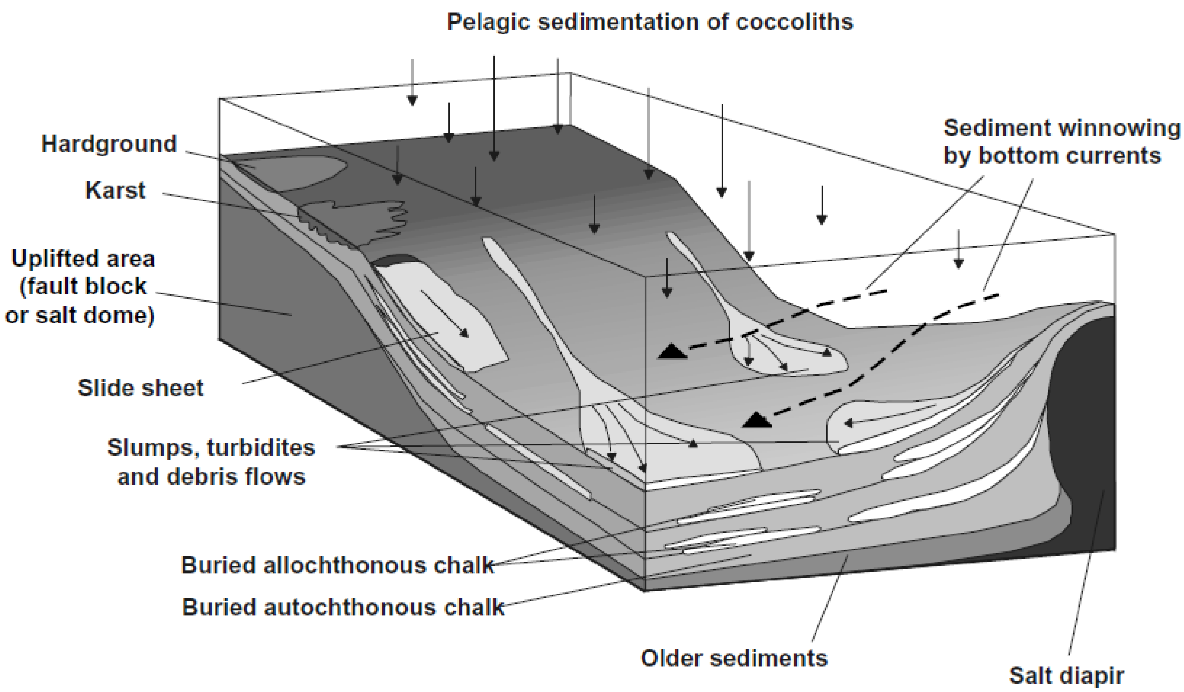


Figure 7: Conceptual model of Chalk depositional processes from van der Molen, 2004.

2.3.3. Chalk Reservoir Analogues

Chalk is one of the first petroleum reservoirs in the North Sea, with the discovery of many fields such as Norway's Ekofisk and Valhall, Denmark's Dan and Skjold fields, and the UK's Machar and Banff (van Lockem, 2023). In the Dutch sector the Hanze oil field (F2) and Harlingen gas field were discovered in the 1990s. In 2015 two new Chalk fields were discovered in block F17, Rembrandt and Vermeer (figure 8). The reservoir was autochthonous Chalk fractured above a salt dome and sealed by Paleocene claystone Formations and trapped in four-way dip structures (van Lockem, 2023)(Kombrink et al., 2012). Allochthonous Chalk has not been encountered in the Dutch sector but has been identified to be a reservoir in the British sectors of the North Sea (Mallon et al,. 2002).

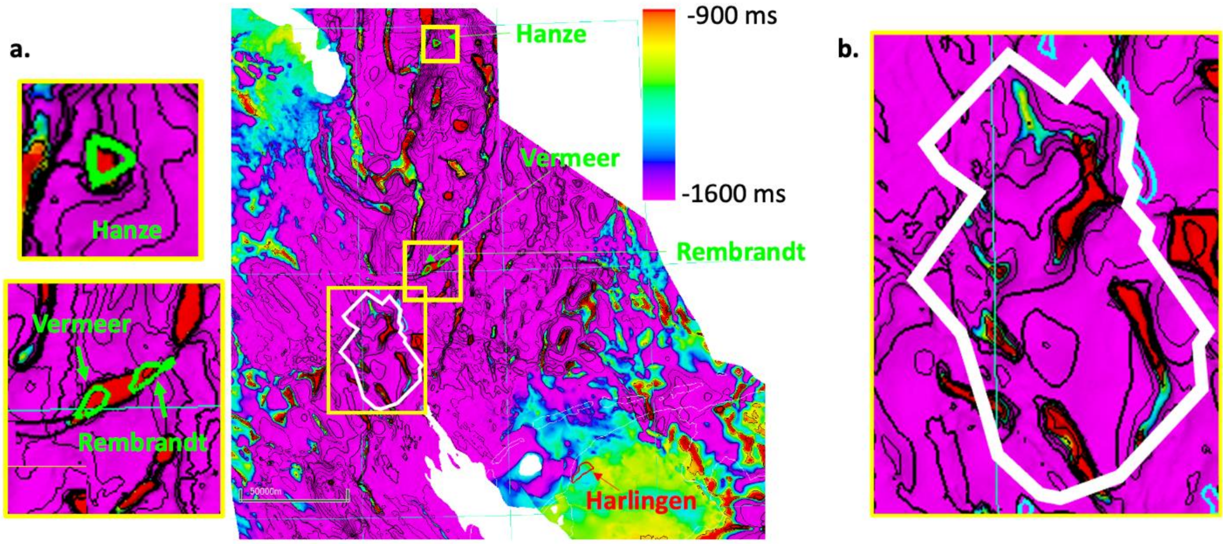


Figure 8: Zechstein Top Regional TWT Map. (a) All the Dutch Chalk fields are present above salt domes. (b) The seismic volume investigated in the study displayed on the Zechstein map.

The discovered Dutch fields show overpressure to which seal integrity is being cited as possible causes (de Jager, 2007). The Chalk petroleum play hasn't been extremely prolific due to the presence of many claystone layers in the Jurassic and Lower Cretaceous that hinders charging the reservoir from the Posidonia shale (van Lockem, 2023). In addition, halokinesis pulses triggered by late Cretaceous basin inversion is believed to have impacted and potentially enhanced autochthonous Chalk permeabilities as well as create allochthonous Chalk (van Wingerden, 2016). The middle to late Maastrichtian and Danian Chalk are the period of most significant inversion pulses phases, Sub-hercynian and Laramide, and led to the development of the most prospective zones when they are not interbedded with clay layers (van Wingerden, 2016).

3. Data & Methodology

3.1. Workflow

The study followed a conventional petroleum exploration workflow that begins with data collection, mainly 3D seismic survey and well data (figure 9). In the data processing stage, the data was checked for quality, well top correlation and seismic to well tie was performed. Subsequently, seismic interpretation and horizon picking was performed, and the generated horizons were converted into depth. Finally, thickness distribution maps were extracted, advance seismic attributes and structural reconstruction were done.

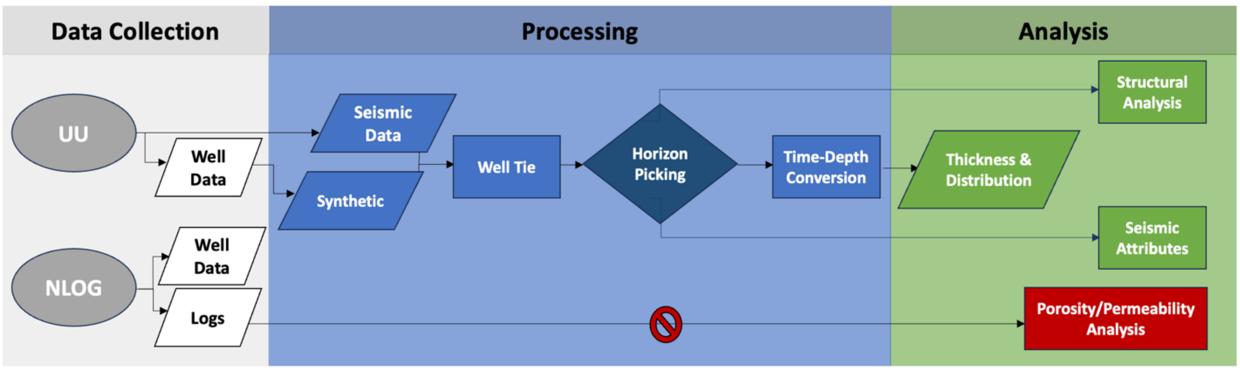


Figure 9: Overview of methods workflow undertaken in this study.

3.2. Seismic Reflection Data

A 3D surveys acquired by Elf-Petroland was utilized in this study: Z3PETET1992A. The survey mainly covers blocks L07 and L04 and has an area of 1096.43 km^2. Seismic data is present from 0 to 5 seconds but only 0 to 3 seconds were of relevance to the investigation of Chalk. The data is displayed in a European polarity in which a transition from a low density and velocity layer (e.g., shale) to a relatively higher density and velocity layer (e.g., Chalk) represents a decrease in acoustic impedance and positive amplitude or a hard event and vice versa (figure 10).

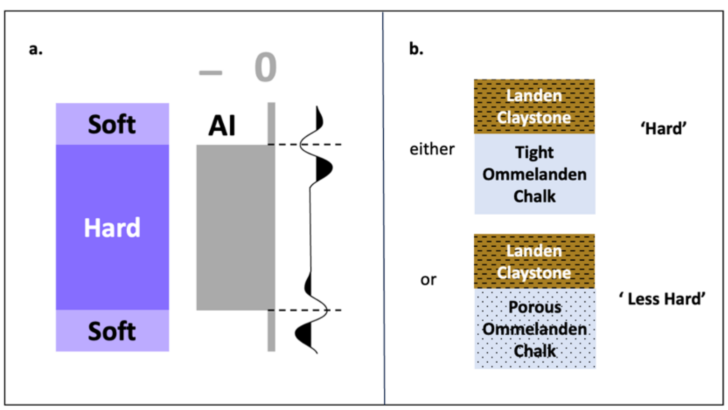


Figure 10: (a) European polarity zero phase diagram showcasing an increase in acoustic impedance ("hard kick") producing a negative amplitude. (b) A model to predict the seismic response of two different Ommelanden reservoir properties.

To proceed with data visualization and interpretation, the surveys were loaded onto SLB Petrel® software from a master project present on the data publication platform of the faculty of geosciences in Utrecht University (Matenco and Beekman 2023).

3.2.1. Acquisition artifacts

Near surface or acquisition artifacts have been observed in some sections of the seismic data. It is key to examine their effect on underlying horizons. For the Chalk, it has been determined that it has no significant impact on horizon interpretation and amplitude extraction as the far offsets heal the image acquisition at the target depth.

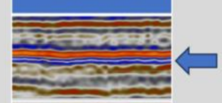
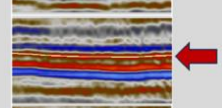
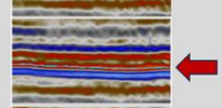
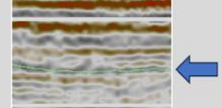
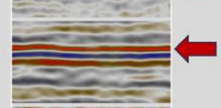
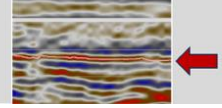
3.3. Well Data

Utilizing the Dutch oil and gas database (NLOG), an inventory of wells in the study area was prepared outlining which penetrated the Chalk group (which Formations and what overlies it), depth, thickness, and well log availability over the Chalk interval (Appendix, table 1). The wells drilled in the area did not target the Chalk, and instead were targeting the Permian to Triassic clastic. As such, the gamma ray was the only available log across all wells in the Chalk interval while sonic and density logs were limited. The wireline logs across the Chalk are insufficient to discern any subdivisions or facies based on wireline measurements (van Wingerden, 2016). If the section is influenced with siliclastic associations, then the gamma ray would indicate those zones clearly (van Wingerden, 2016). This is because sections of interbedded sands and shales would have higher gamma ray responses in comparison to typical pelagic Chalk.

3.4. Seismic Interpretation

The interpretation of seismic data is utilized to identify reflections, connect them to lithostratigraphic units, creating TWT surface maps that are later converted to depth maps. Afterwards, the mapping allows for the construction of a stratigraphic framework, structural history reconstruction, and attribute extraction. To make sense of the Chalk Formation and properties, many horizons were interpreted from formation tops to intra-formation horizons such as biostratigraphy intervals. Table 1 highlights the general character of these horizons. Not all the interpretations were carried out initially and instead were done over two stages.

Table 1: Seismic character of mapped horizons across the study area.

	Horizon Interface	Configuration	Continuity	Amplitude & Frequency	Confidence	Example (z=150ms)
1	**Top Middle NSG**	Parallel	Continuous	High amplitude, high frequency	High	
2	**Top Ekofisk**	Parallel	Continuous	low amplitude, high frequency	Moderate	
3	**Top Ommelanden**	Parallel	discontinuous	High amplitude, high frequency	High	
4	**Top Maastrichtian**	Sub-parallel	semicontinuous	low amplitude, low frequency	Low	
5	**Top Texel**	Parallel	Continuous	high amplitude, low frequency	High	
6	**Top Zechstein**	Mound shaped	discontinuous	high amplitude, low frequency	High	

3.5. Seismic Attributes

3.5.1. Extraction window

Two interpretations have been used to determine the window for the attribute extraction, the Landen interpretation that lies in the reflector directly above the Ommelanden and below Ommelanden which maps the reflector right below the Ommelanden (figure 11).

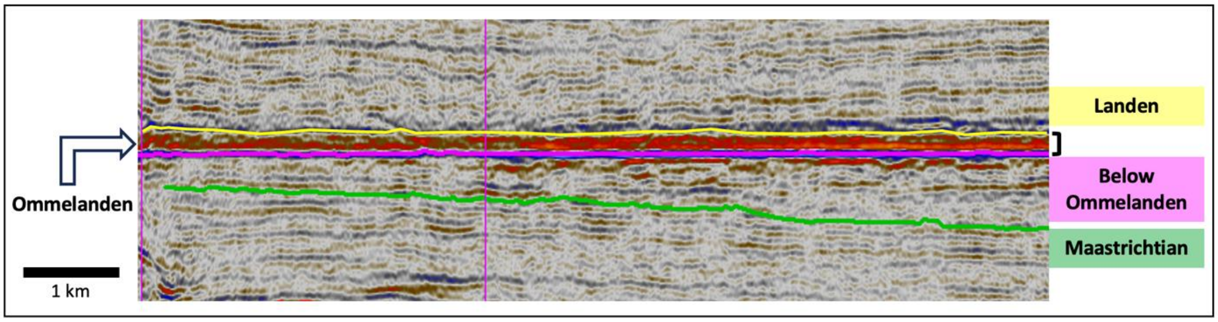


Figure 11: The extraction window of surface attributes.

3.5.2. RMS amplitude

Computes root mean squares (RMS) over a specific window to measure reflectivity and highlights anomalous higher amplitude reflections. Van der Voet (2015) found a correlation between RMS amplitudes and the presence of a thicker Danian succession (van der Voet, 2015). In this study, the RMS amplitude was utilized to average amplitude values in the extraction window (covering the Ommelanden reflector only) and map out where are the relatively low amplitudes are, both positive and negative. This is because a tight Ommelanden is expected to have a high amplitude negative hard response while a porous zone would have a lesser response (figure 10-b). The RMS amplitude was extracted as both a surface attribute, which produces a surface map, and a volume attribute, which produces a cube. The extraction window was from the Landen surface, the reflector directly above the Ommelanden and the reflector below the Ommelanden directly.

3.4.3. Variance (Edge Detection)

Stratigraphic attribute that isolates edges in the horizontal continuity of the amplitude of seismic data and delineate geologic features discontinuities (Almasgari, et al. 2020). In this study, variance has been utilized to delineate fractures and faults that are not clear due to lack of stratigraphic offset. It has been noticed that it's an attribute influenced by seismic quality and the presence of salt.

3.6. Selection criteria

There are several selection criteria that are overarching for all carbon storage sites (Chadwick, et al. 2008) (Tomic, et al. 2018) while others will be specific for Chalk sites. This study is a preliminary investigation of Chalk as a carbon storage target and as such mainly looked at general geologic and physical thermobaric criteria. At later stages of Chalk portfolio development and after its development as a storage target, further detailed criteria might arise to include economic storage estimations, seal integrity, and injection modeling studies are not considered at this stage.

Table 2: Key Criteria for Site Selection after Chadwick et al. (2010), Tomic et al. (2018)

		Positive Indication
Site	Location	Offshore
	Seismic Coverage	3D Coverage
	Petroleum Perspectivity	Low
	Salt Dome	Present
Reservoir	Depth	800-2500 m
	Porosity	>20%
	Permeability	>300 mD
	Thickness	>50 m
	Salinity (mg/l)	>100,000
	Capillary Entry Pressure	Mild overpressure
Seal	Capillary Entry Pressure	greater than predicted injection induced pressure increase
	Thickness	>20 m
	Lateral continuity	Uniform
		No to Small intra-seal faults

3.6.1. Site Specific Criteria

Only offshore projects are considered since onshore storage is not favored in the Netherlands. These offshore sites, however, must remain in proximity to CO_2 emission sources onshore. Three carbon storage clusters were identified, the first is offshore Rotterdam, and two others in the north offshore Den Helder and Ijmuiden. High quality seismic coverage of the potential injection site is paramount to map out the trap from all side and ensure its efficacy as well as allow for the extraction of advanced seismic attributes to delineate the reservoir and de-risk the seal. Sites of high petroleum prospectivity are avoided to reduce the complication that would arise from injecting CO_2 into multi-fluid phase reservoirs. The criteria for salt dome presence are specific to Chalk reservoirs as halokinesis has been proven to be an effective method to enhance Chalk permeabilities in several analogues in the Dutch sector and across the North Sea.

3.6.2. Reservoir Specific Criteria

For maximum storing efficiency, supercritical CO_2 is the ideal form of injection as it means that CO_2 will have gas-like viscosity and liquid-like density (Chadwick, et al. 2008). The critical point beyond which CO2 is in the supercritical phase is at temperatures higher than 31.1 and pressures higher than 73.8 bar (figure 12).

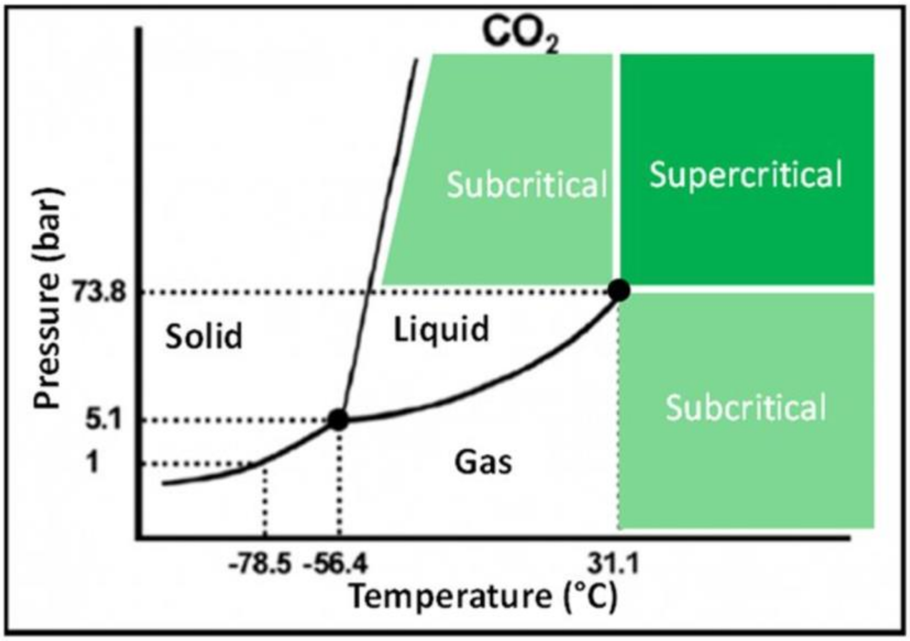


Figure 12: Phase Diagram of CO2. from Laboureur et al., 2015.

To meet minimum supercritical CO_2 conditions, the reservoir depth must be at least 800 meters and not deeper than 2500 meters. Furthermore, the reservoir permeability value provided in table 2 are usually considered with reservoir thickness as it determines kh value[2]. The values could change based on the project's minimum economical injection rates which would depend on factors such as the availability of better reservoir alternatives and proximity to CO_2 emitters. Finally, the site selected nees to be only mildly overpressure. Underpressure would hint to a lack of seal integrity while high overpressures will make it operationally challenging to inject and control the site. Moreover, a pressured system that traps fluids, mainly petroleum, has been concluded to preserve the porosity (van Wingerden, 2016).

3.6.3. Seal Specific Criteria

The seal must have a failure pressure that is much higher than that induced by maximum injection. In this study, this is done through investigating seals that are thicker than 20m as well as indirectly deducing seal efficacy from regional pressure gradients of Chalk in the region. Furthermore, the seal must be homogenous and laterally extensive to ensure its efficacy.

3.7. Geologic Carbon Trapping

Saline aquifer trapping usually requires unconventional trapping, injecting CO_2 in synclinal depressions that are surrounded by seals from the top and laterally (Siebels, et al. 2022). (Siebels, et al. 2022). When considering a homogenous reservoir, the suggested injection site is in the lowest part of the container to allow the CO_2 plume to migrate upward towards the seal (figure 13). Bonto et al. (2023) highlights that there are an abundance of sites suitable for

[2] kh value is an engineering term that is the product of multiplying the permeability (k) with the reservoir thickness (h) to predict the flow capacity of the rock.

carbon storage in the Chalk, however, the trap mechanism and geometry will be unique to every site when taking into account the diverse physical and chemical conditions the various prospects have (Bonto, et al. 2021).

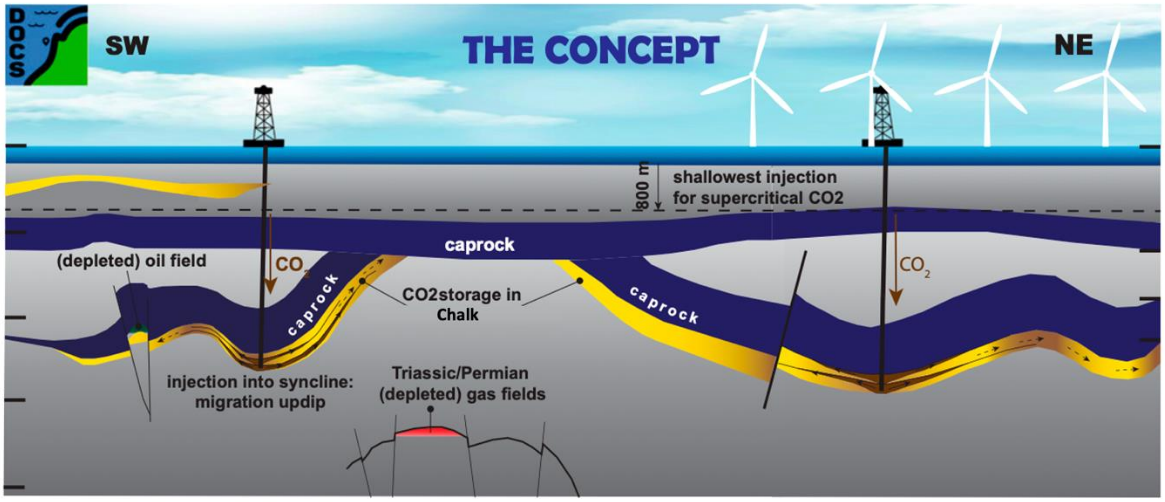


Figure 13: Schematic highlighting the concept and types of CO_2 Geologic Storage. Modified after Siebels et al., 2022.

4. Results

4.1. Well Top Correlation

Before tying the wells to the seismic, it was essential to go through the well picks and ensure they are consistent with NLOG as well as log signatures. To perform the consistency and quality of top picks, the gamma ray and sonic were displayed for a selection of wells (Figure 14). Gamma ray logs would reflect an argillaceous Chalk interval with high readings versus a clean Chalk with low values. Sonic also would indicate lithological and density changes arising from lithological variation. The Chalk in the area generally did not produce a strong response in the logs, with an overall low gamma and low sonic. On the other hand, the interval above and below the Chalk group exhibited relatively high log response which confirmed the quality and consistency of well top picks.

4.2. Seismic to well tie

Many wells drilled within the seismic survey were targeting Formations lower than the Chalk, primarily the Permian Rotliegend. Since the well interest was below the Chalk, most wells did not run density and sonic logs across it, and as such a synthetic seismogram could not be produced to tie the Chalk tops to the seismic. Selected wells had logged the Chalk but only missed the top interval (table 3: 1-4). These wells were primarily utilized to tie the well to the seismic and extend an interpretation of lower Chalk (Texel Formation) across the volume. A tie was also produced for the Rotliegend wells (table 3: 5-10), to extend and tie other well tops, with higher certainty in the Rotliegend section and lower uncertainty in the Chalk zone. It can be noticed that the interval thickness that the seismogram can be created was relatively wider in the wells that covered the Chalk, this allows for a better tie of seismic versus a short seismogram.

The best tie is well K06-C-01 that lies in the top left edge of the survey. The corresponding synthetic seismogram covers a relatively larger interval of 1078ms, only missing a short interval from the top of the Chalk (figure 15/16). This well was key in identifying and tracing the Ekofisk Formation across the survey. The seismic quality as well as horizon clarity near this well allowed for the traceability of horizon across the adjacent area confidently. Furthermore, the presence of this well in an area not affected by salt tectonism ensured the tie was well constrained in every direction the seismic was sliced (inline, xline and any other direction). This, however, was not the case with the tie for well L04-04 as it was near a salt dome and slight variation in the bulk shift was observed depending on seismic slice direction (figure 17/18).

Table 3: Summary of wells within the area of the seismic volume of interest. Green rows highlight priority well ties that logged the Chalk. Blue rows highlight support well ties that guide the interpretation across the area.

	Borehole	Interval (TWT-ms)	Interval thickness (TWT-ms)	Bulk Shift	In-Scope	Coverage
1	K06-C-01	1451-2529	1078	-25	Yes	Missing Top CK
2	L04-04	1820-2667	847	-10	Yes	Missing Top CK
3	L04-10-S1	1145-1826	681	-220	Yes	Missing Top CK
4	L04-10	1144-1805	661	-220	Yes	Missing Top CK
5	K06-02	2259-3490	1231	35	No	Rotliegend
6	K09-02	2246-2412	166	-10	No	Rotliegend
7	L04-05	2225-2863	638	50	No	Rotliegend
8	L07-04	3675-4188	513	-10	No	Rotliegend
9	L07-08-S2	2544-2633	89	-10	No	Rotliegend
10	L10-29	2581-2703	122	-25	No	Rotliegend

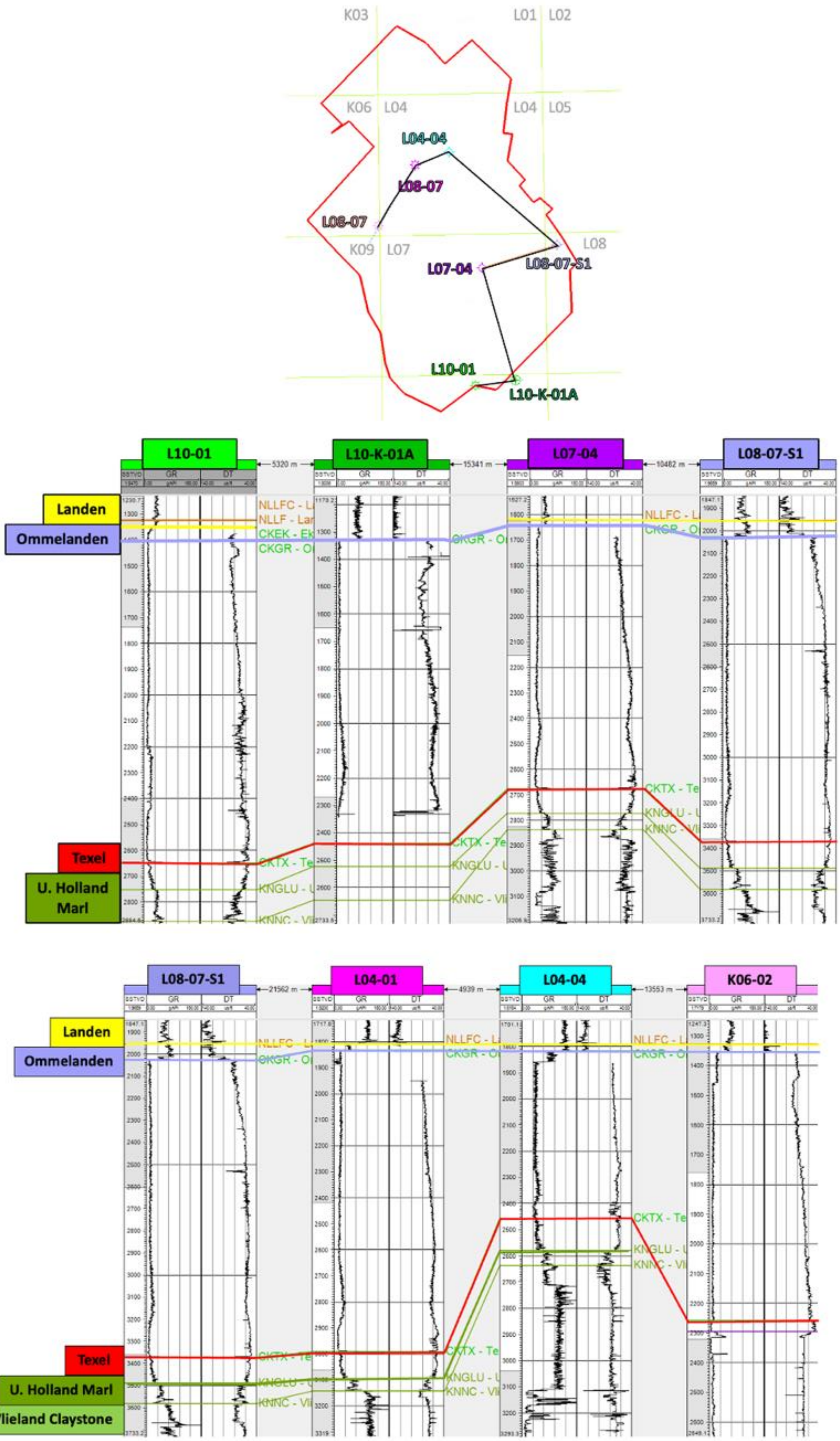


Figure 14: Well correlation panel going through key wells in the area of interest.

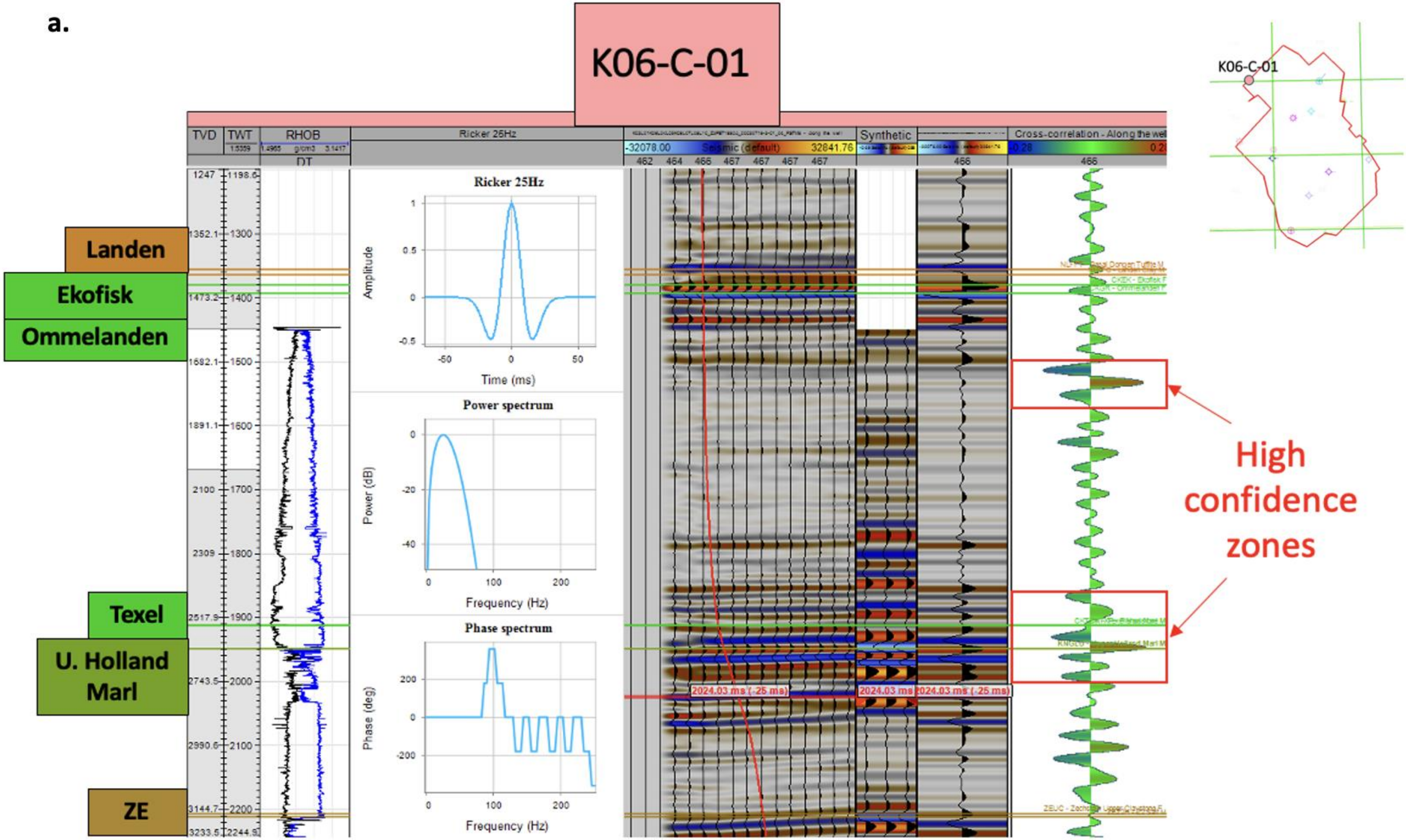


Figure 15: Best well tie covering Chalk interval in well K06-C-01. (b) well tops tied and displayed on a seismic line.

b.

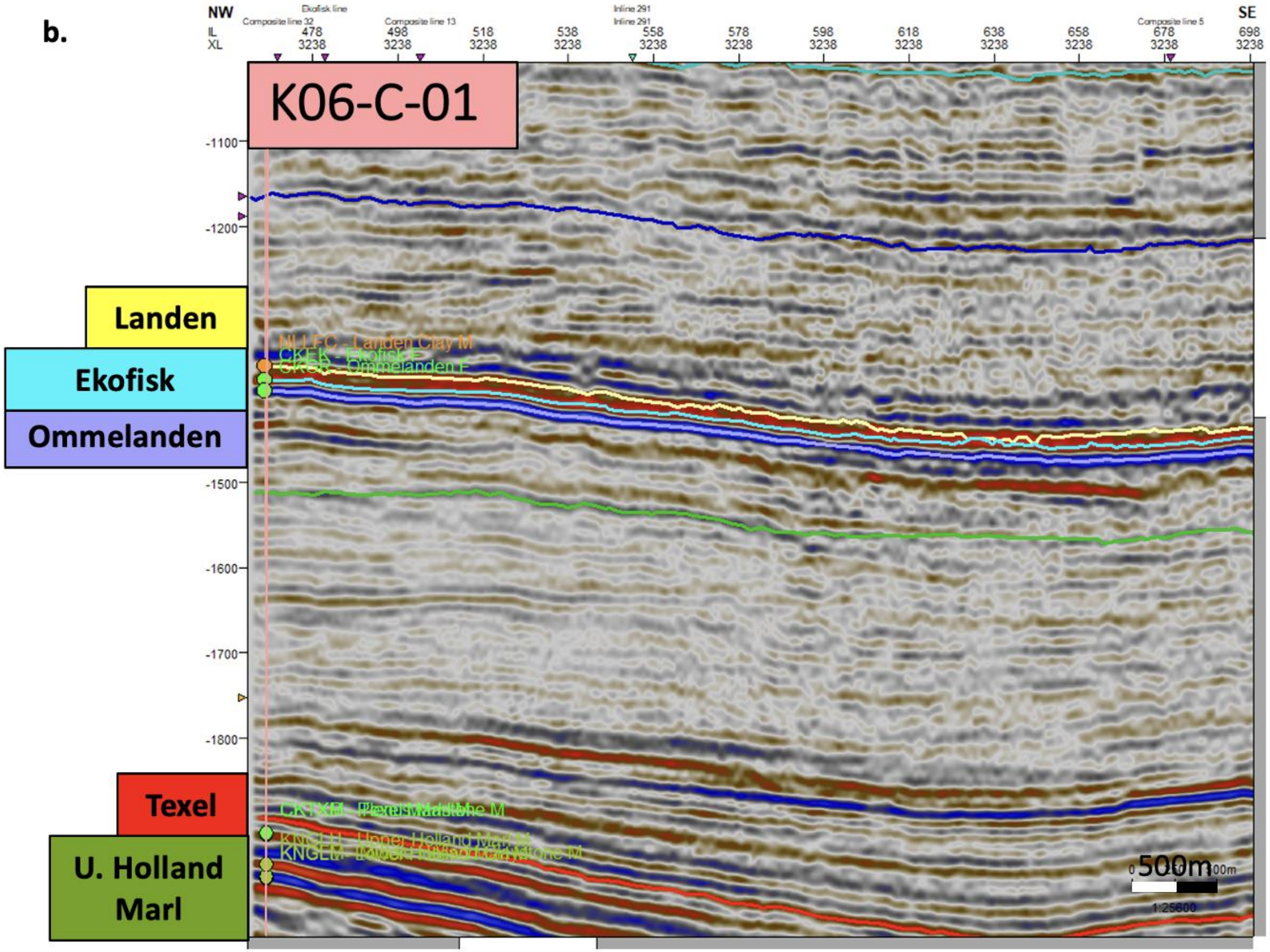


Figure 16: Best well tie covering Chalk interval in well K06-C-01. (a) synthetic seismogram highlighting the well tops the seismogram covers and tie confidence zones. (b) well tops tied and displayed on a seismic line.

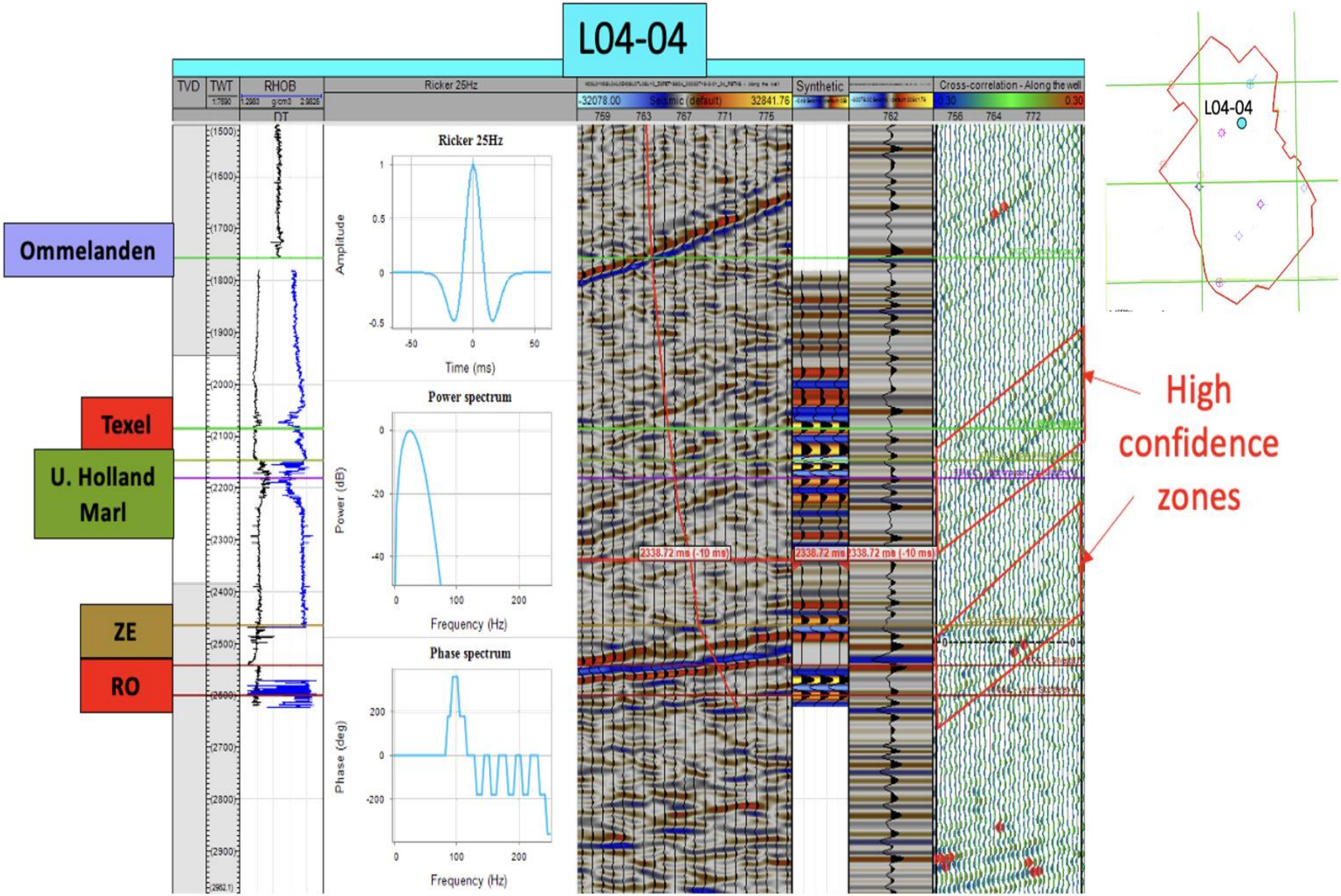


Figure 17: Well L04-04 tie showcasing the challenges tying adjacent to salt features. (a) synthetic seismogram highlighting the well tops the seismogram covers and tie confidence zones.

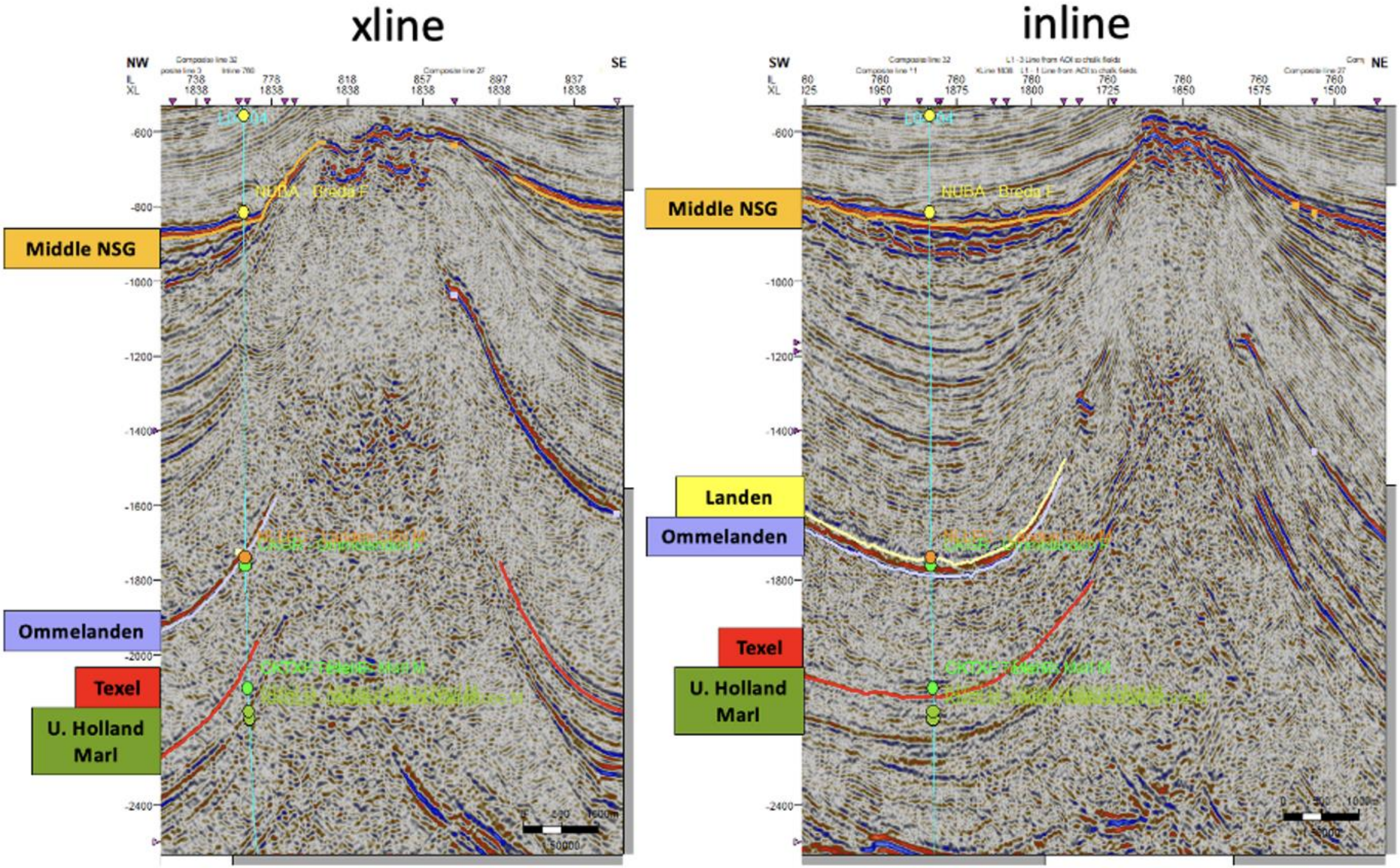


Figure 18: well tops tied and displayed on two seismic lines showcasing subtle variation due to interference from the salt diapir.

4.3. Seismic interpretations: Initial Scoping

Two horizons, Middle North Sea Group and Texel Formation were interpreted across the seismic survey for initial scoping and structural analysis of the area (figure 19). The obtained surfaces were interpreted to consist of diapirism induced highs and rim basins between those highs (figure 20). This interpretation resulted in the identification of 8 diapirism induced highs, each high was labeled with a letter in figure 21, table 4. To further characterize the area, a composite seismic line was created to view these leads and compare them to each other to rank them from low risk to high risk (figure 22). The risking criteria consisted mainly of two rules: ensuring the presence of a structurally uninterrupted Middle North Sea group horizon, and the presence of a seismically traceable top Chalk horizon (Ommelanden surface). Seismic lines representing this stage of the analysis are incorporated in the appendix, section 1. The structures were labeled with either red or white boxes. Red boxed areas indicate low potential due to salt dome interference and/or the master seal (Middle North Sea Group) being compromised. White boxed areas indicate the potential to investigate the Chalk due to presence of an intact master seal and/or a salt dome that does not obliterate the reservoir and instead only disrupts it (via fracturing). The Chalk fracturing that leads to enhanced reservoir properties was not directly observed and instead inferred from the character of the Ommelanden reflector, to be discussed further in the next section. The western most part of the survey (area of leads F &G) was determined to be the area with highest potential and lowest risk leads.

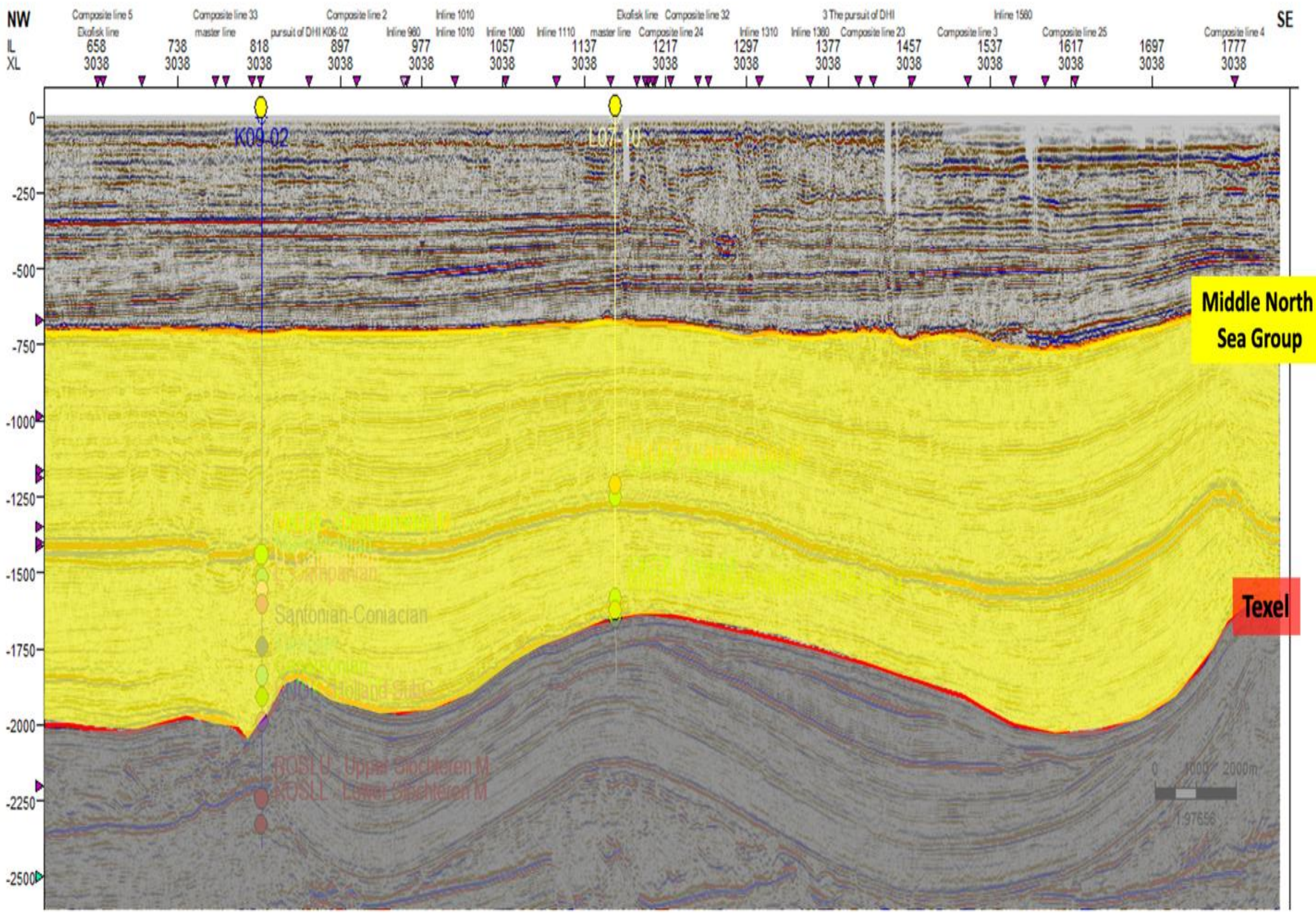


Figure 19: Seismic line highlighting preliminary interpreted horizons, Middle North Sea Group and Texel.

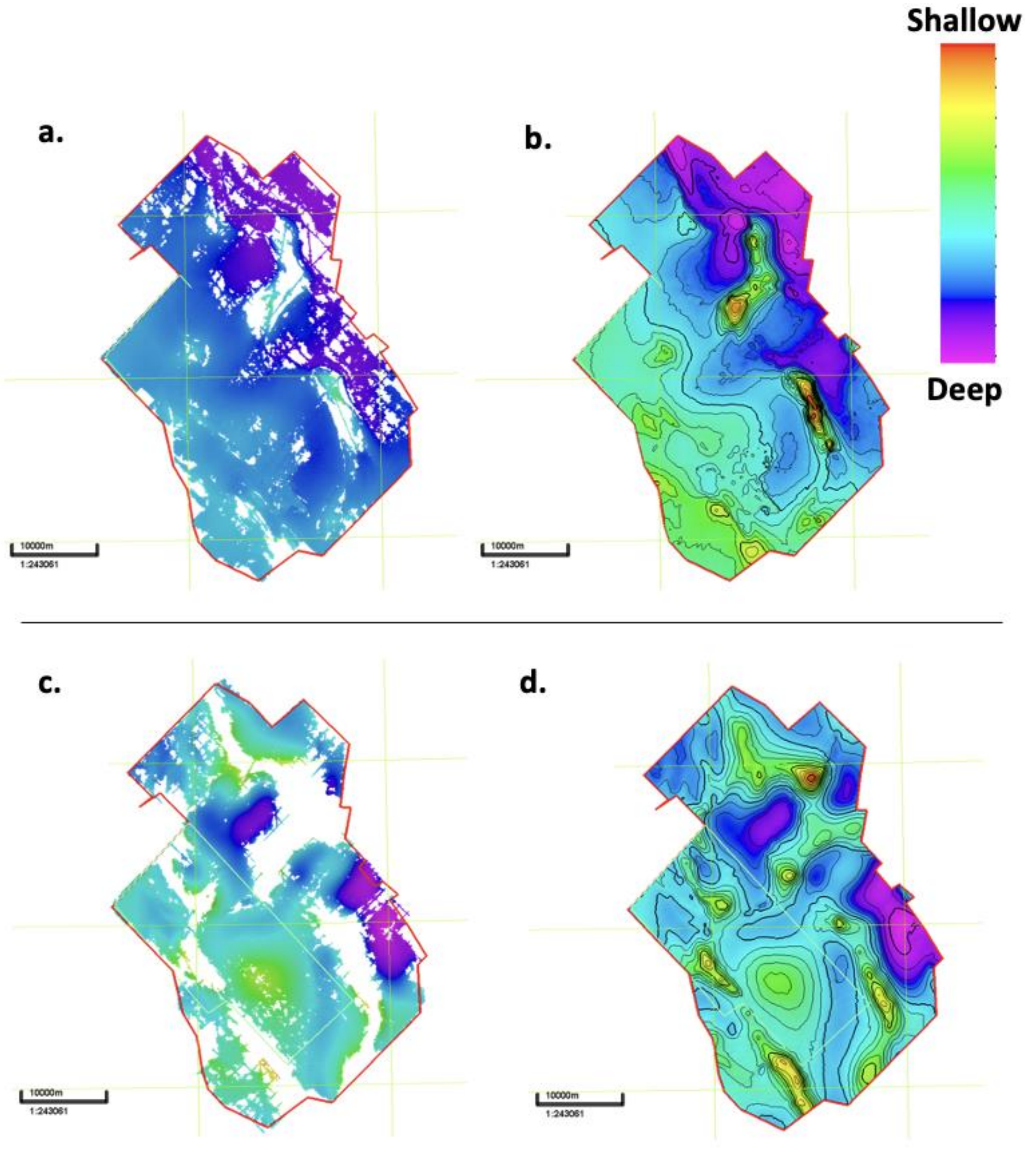


Figure 20: Initial scoping interpretation. (a) Middle North Sea Group interpretation extent. (b) Middle North Sea Group TWT surface. (c) Texel Formation interpretation extent. (d) Texel Formation TWT surface.

Table 4: Ranking of diapirism induced high (leads) within the Area of Interest.

Lead	Rank	Trap Risk	Risk
A	3	Medium	Top seal integrity– updip leak
B	9	High	Salt updip seal – reservoir presence
C	6	Medium	Top Seal integrity
D	7	High	Top Seal integrity
E	4	Medium	Top seal integrity
F	2	Low	Top seal integrity
G	1	Low	Updip leak
H	8	High	Top seal integrity

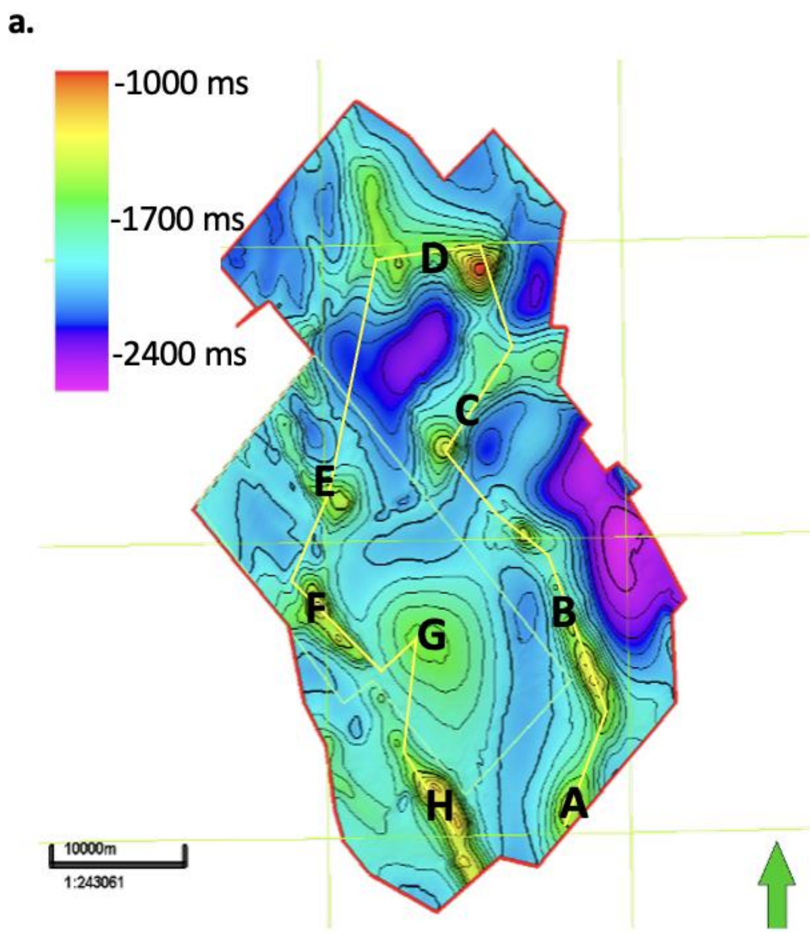


Figure 21: Survey wide TWT surface of Texel highlighting master seismic line passing through alphabetized leads.

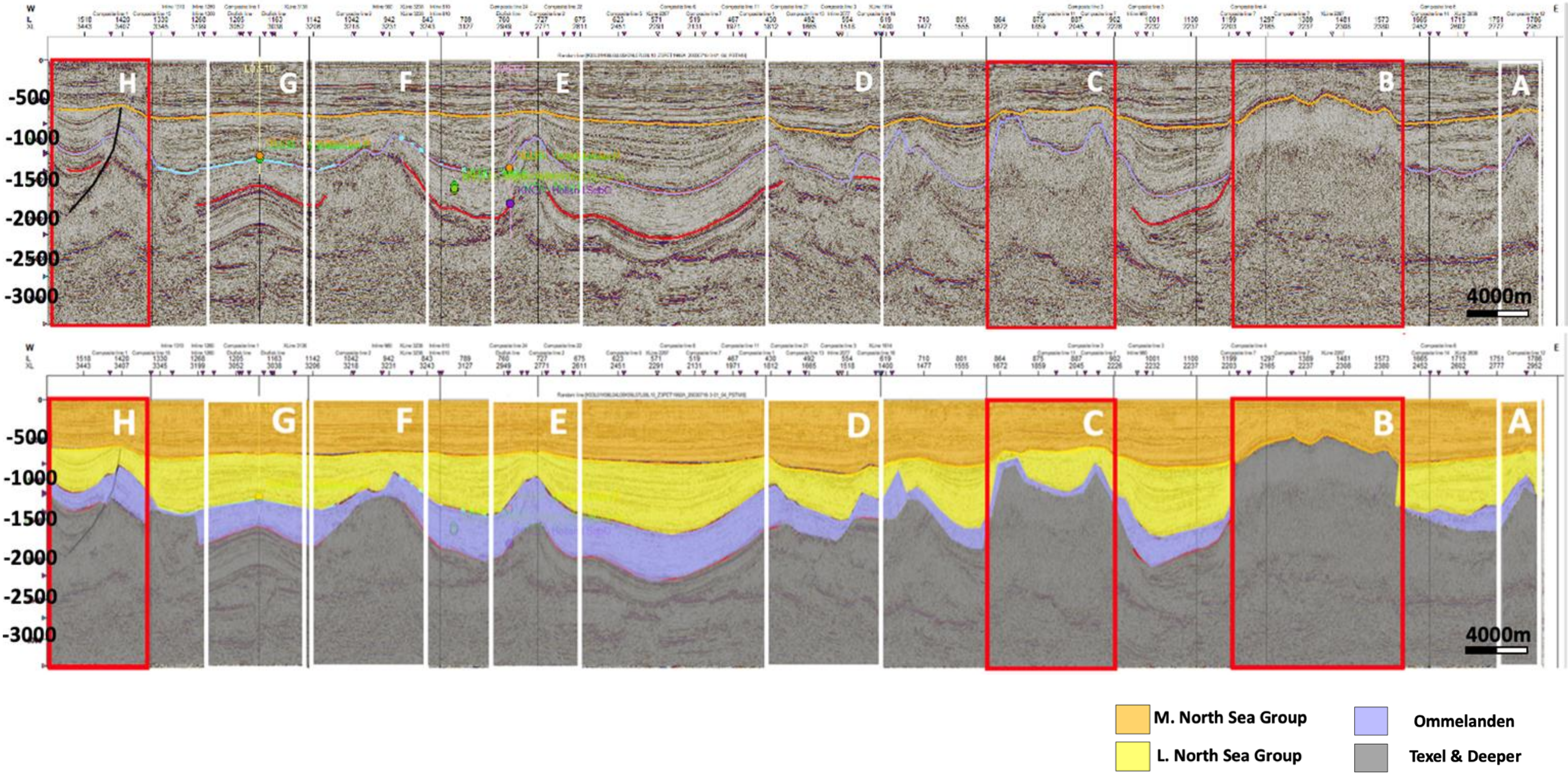


Figure 22: Composite seismic line highlighting general structural of survey, orange represents Middle North Sea Group, purple indicates location of Top Chalk: Ommelanden, and red highlights Texel. White boxes highlight high potential areas for Chalk investigation while red areas showed low potential.

4.4. Seismic interpretations: Focused Area Interpretation

A polygon was drawn around leads F and G to high-grade them to prospects and within it the interpretation was expanded to 5 horizons (table 1). The goal was to understand Chalk distribution, thicknesses, and structural development (figure 23). The top of the Zechstein was interpreted to understand salt geometry, as in the system as reservoir quality is strongly influenced by salt movement. Following that, the Ekofisk and Ommelanden, and the reflector immediately below the Ommelanden were interpreted with care to utilize it later for seismic attributes extraction. Finally, two prominent horizons were consistently interpreted within the North Sea group to investigate the presence of structural pulses after the deposition of the Chalk. Lead G is characterized by a prominent anticlinal fold structure, where the degree of folding becomes less pronounced, and its amplitude decrease as the section's shallows from the base ZE to the Middle North Sea group. On the other hand, lead F appears to have the most prominent diapir with structurally deformed shallower layers.

The two-way time surface map of the Ommelanden (Chalk group top) was converted to depth surfaces utilizing the (Velmod 4b_Vint) velocity model that references well generated velocities (figure 24). The depth of the Ommelanden is shallower above the salt structures (in range from 1300 to 900m) and gradually deepens towards the northeastern section of the area (deeper than 1500m). The thickness of the top portion of the Chalk group (from the Ommelanden to Maastrichtian), can be seen to be influenced by structuration. At the top of structures, the thickness is reduced (blue shade-less than 100m) with the lows in the northeastern section of the area at an average thickness of 350-400m (orange to red shades).

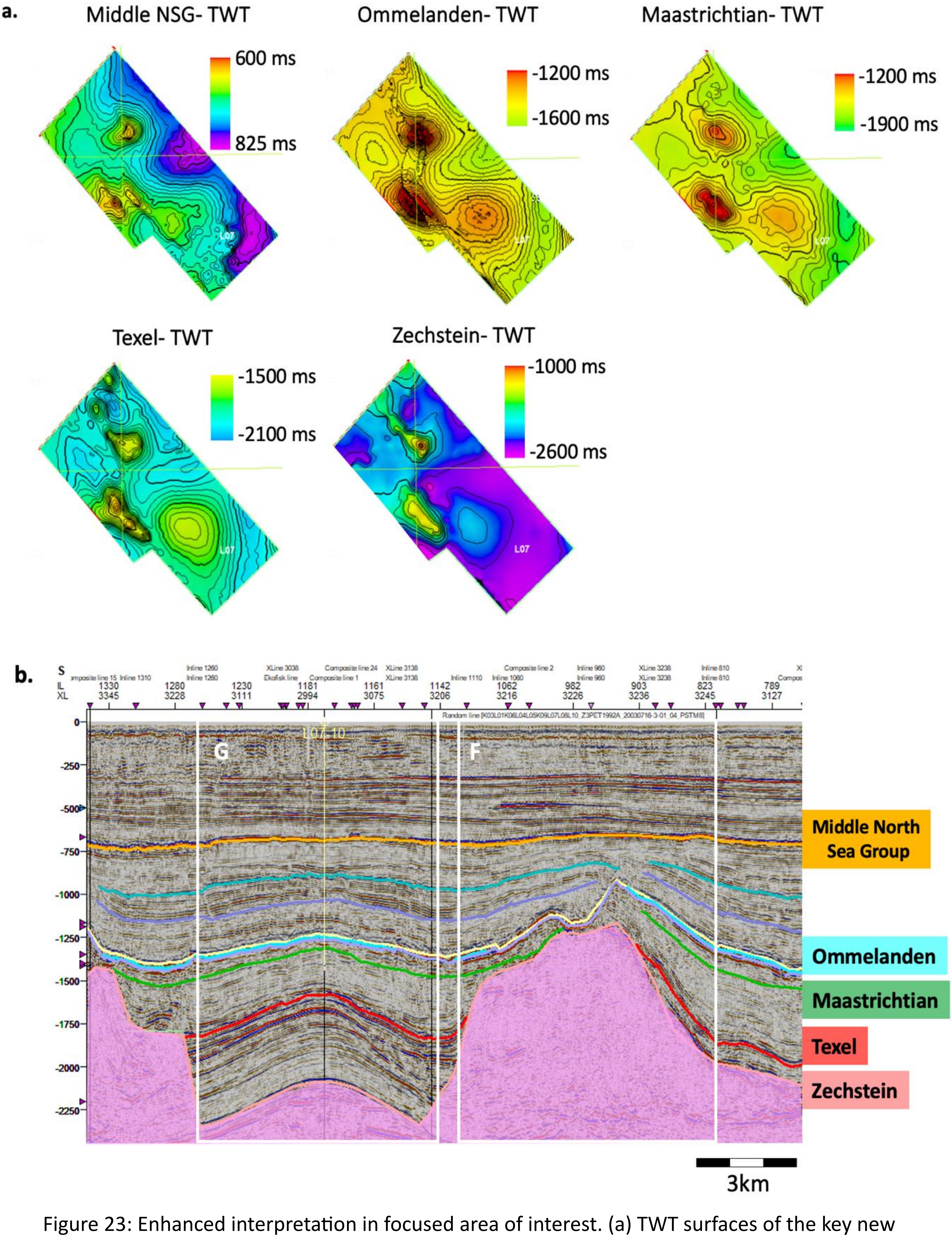


Figure 23: Enhanced interpretation in focused area of interest. (a) TWT surfaces of the key new interpreted horizons. yellow line in North Sea Group surface highlights (b) seismic line trajectory. (b) seismic line showing the enhanced interpretation surfaces across two zones of high potential (white boxes).

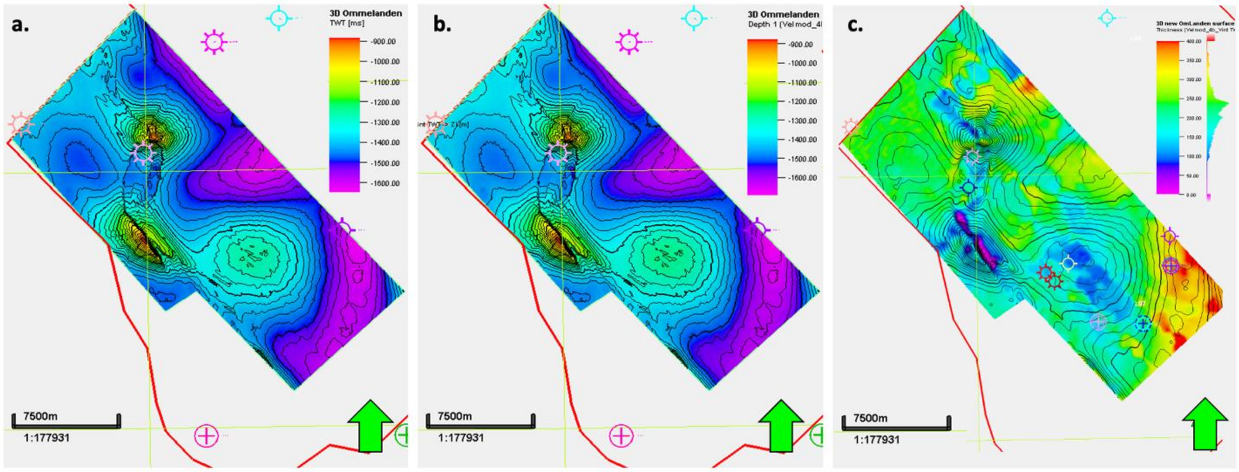


Figure 24: Ommelanden surface maps encompassing the area of prospect F and G. (a) TWT surface map. (b) Depth surface Map. (c) Thickness Map of upper most section of the Chalk (Ommelanden-Maastrichtian top).

4.5. Structural History Reconstruction

Utilizing the interpreted surfaces, a geological reconstruction was possible through the flattening of varying horizons (figure 25). During the deposition of the Zechstein and Rijnland group, the area was quiet and as such the layers were deposited horizontally. At the time of base Chalk deposition (Texel Formation), the region experienced thermal relaxation and as such the Zechstein and Rijnland layers started to form a curvature (fig.25-b). At the time of upper Chalk deposition, the sub-Hercynian tectonic phase began to influence the area and as such we see a reversal of the previous state of subsidence to uplift with active diapirism. This trend continues throughout the to the shallowest interpreted horizon (Eocene Middle North Sea group) but with lessening intensity as it moves shallower. From this reconstruction, it can be concluded that the region in the lower Cretaceous experienced thermal subsidence that carried out until the time of deposition of top Texel. This was reversed when the Ommelanden was deposited, and the stress changed to inversion. The inversion continued throughout the upper Cretaceous and onward to the deposition of the Top Eocene Middle North Sea Group. The most impactful inversion event happened within the deposition of the Ommelanden which corresponds with the sub-hercynian phase of the alpine orogeny.

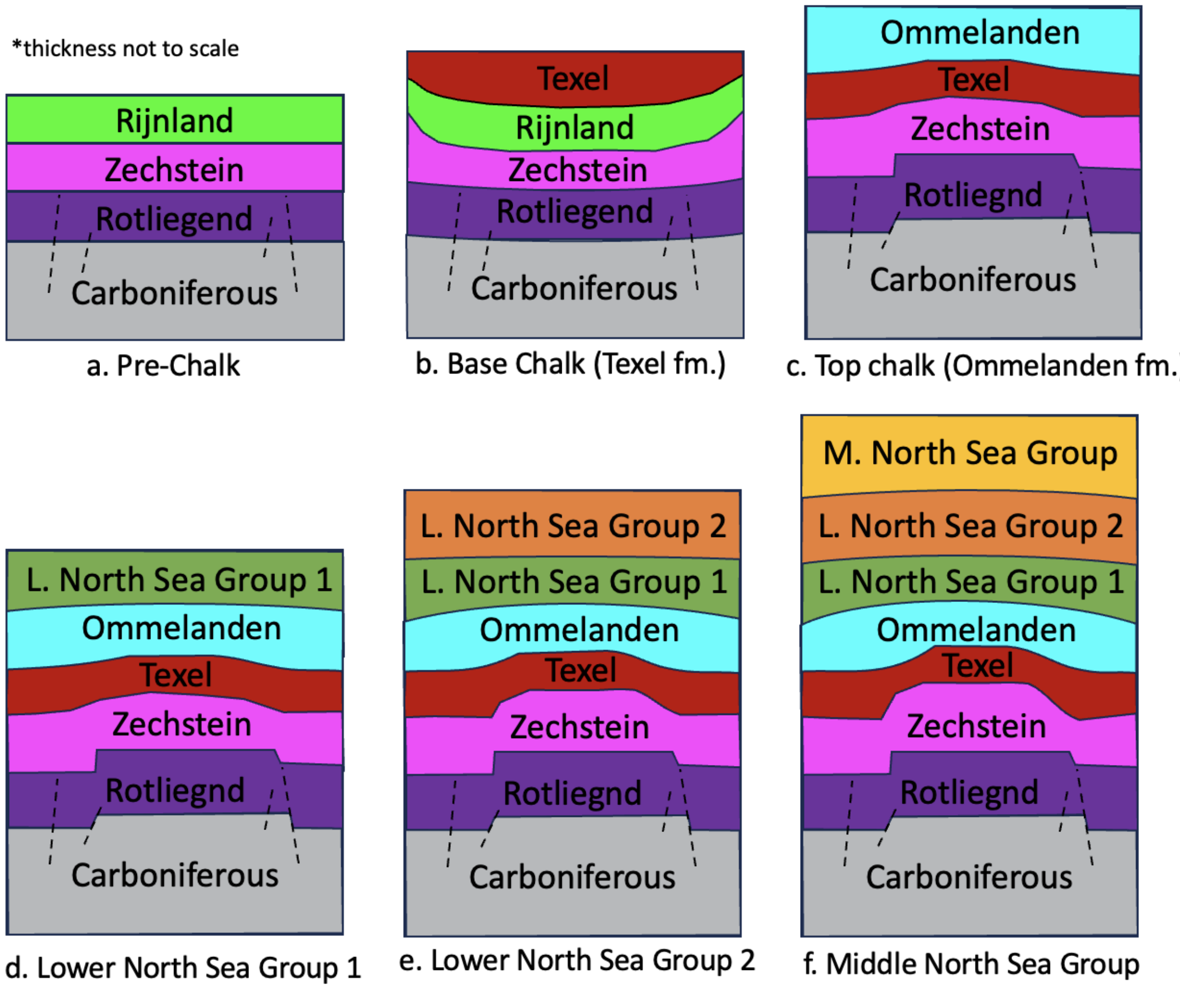


Figure 25: Conceptual cartoon (a)-(f) showing schematic structural development of the area from the upper Permian Zechstein to the Eocene Middle North Sea group.

4.6. Seismic Attributes

4.6.1. Surface attributes

To understand the distribution of lateral deformation across the focus area, a surface attribute such as root mean square (RMS) was extracted (figure 26). For a porous Ommelanden, a low relative amplitude zones would be favorable (figure 26-a) and as such the yellow encircled portion (blue shades) would have high potential. Furthermore, in figure 26-b, the zones that fall within the low RMS yellow circles were superimposed over the Ommelanden thickness map and are set to represent the zones of high potential Ommelanden in the focus area, further investigated in the next section.

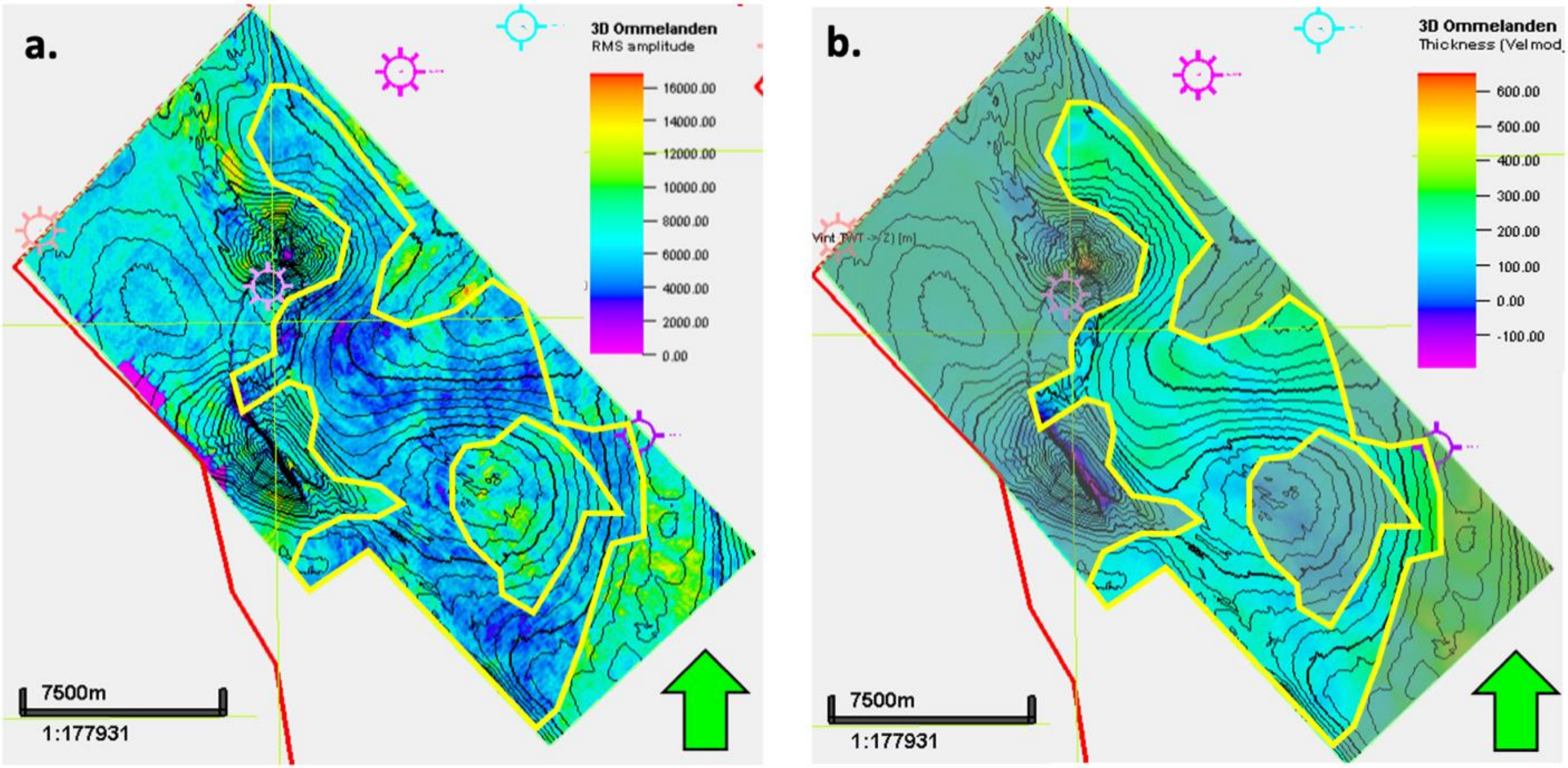


Figure 26: Ommelanden surface attribute maps. (a) RMS amplitude Map. (b) Ommelanden-Maastrichtian thickness map.

4.7. Prospects

4.7.1. Prospect F

4.7.1.1. Summary

- **Name:** Prospect F (Judith Leyster)[3]
- **Salt Structure Type:** Salt pillar
- **Targeted Chalk Type:** Autochthonous
- **Structural Analysis:** From section 4.4, it was established that the structure is induced by the salt pillar and that it does not breach the Middle North Sea reflector and as such has potential.
- **Amplitude Analysis:** The analysis done in section 4.6 highlights the presence of amplitude anomalies on the northwestern flank of the prospect F (figure 26). The following analysis will further delineate the prospect components.

4.7.1.2. Reservoir

- In order The RMS volume attributes were extracted to determine the regions of low amplitudes that would hint to the presence of a good Chalk reservoir (figure 28). In prospect F, the zone of low RMS amplitude is confined to a narrow (2km) strip at the top of the salt dome where a fault dome induced fault offset the Ommelanden and fractured it. In the thickness map, it was difficult to obtain a representative value due to the discontinuity faced by the two reflectors (Ommelanden and Maastrichtian) from which the map was extracted. Unfortunately, due the lack of wells going through the prospect, the real thickness remains uncertain. The variance attribute (figure 28-c) does show some discontinuities and what appears to be fractures across the zone with the lowest impedance, but the overall extraction is strongly imprinted with the effect of salt diapirism which clouds smaller discontinuities within the Ommelanden. Noteworthy, the Ommelanden shows a distinct zone of low variance (white) or high connectivity in comparison to other zones. This might be due to the depositional nature of Chalk in comparison to shallower claystone and their lithification properties. Clays usually dewater upon lithification while Chalk remains porous and with low permeability that does not allow fluids to escape.

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[3] Chalk fields discovered recently were named after Dutch 17th century painters, this study will name the prospects in accordance with Dutch 17th century female painters.

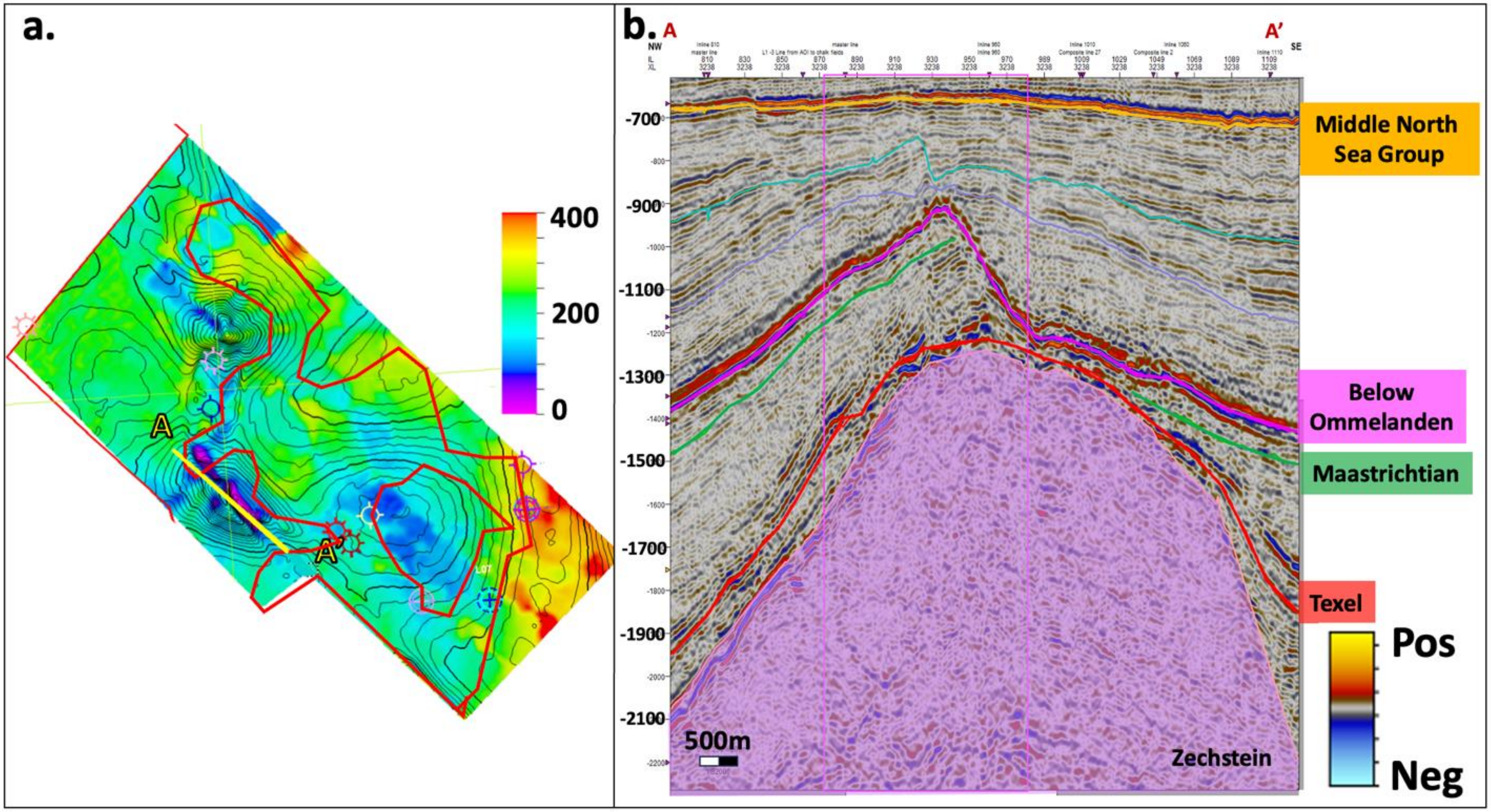

Figure 27: Prospect F transect lines. (a) Ommelanden thickness map with seismic line passing through Ommelanden high potential zone on the flank of prospect F. (b) south-north seismic line going through the southern flank of the structure, across the high potential zone.

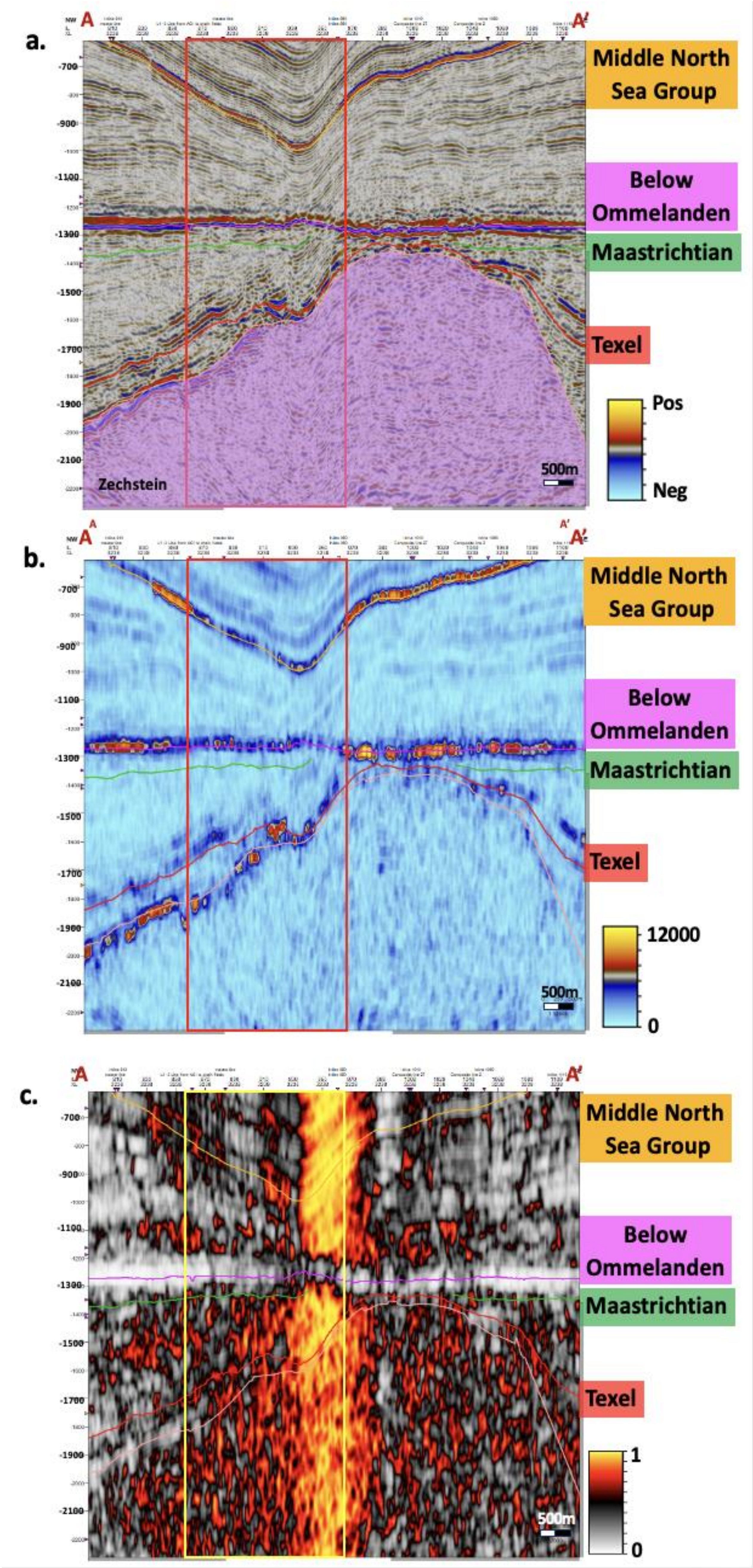

Figure 28: Prospect F flattened transect lines on Ommelanden. (a) same seismic line flattened on Ommelanden surface. (b) RMS volume attribute line. (c) Variance volume attribute line.

4.7.1.3. Seal

Because the salt dome faulting, the Ommelanden surface was moved shallower and as such the thickness of the Lower and Middle North Sea group has been significantly reduced. This increases the risk of leakage along with the possibility of the fault extending beyond the Middle North Sea Group, despite it appearing continuous in figure 28-a. The variance also shows significant discontinuities that might arise from the salt induced deformation overprinting on the whole section (figure 28).

4.7.1.4. Trap

This prospect would utilize a combination trap, whereby it is composed of an enhanced reservoir section amid a faulted zone surrounded by sealing facies inside a structural trap (figure 29). The risk with this prospect is that the faults breach the seal. Furthermore, due to the lack of wells in this structure and the structural complexity of this trap, it is hard to extend the regional assumption on seal effectiveness. A way to de-risk this opportunity is to attempt to filter the seismic and enhance its quality to be able to carefully map out the fault and see if they breach the seal.

4.7.1.5. Prospect F vis-à-vis Rembrandt Field

A regional seismic line has been extended from the prospect area to the closest analogue field, Rembrandt in figure 30. It can be observed that both locations share a visual similarity in having discontinuous Ommelanden reflection due to faulting. In the Rembrandt, we see how thin the Chalk interval is while it significantly thickens towards prospect F. In Rembrandt, we see that the Ommelanden reflector is dim, relative to the northeastern flank, and highly discontinuous at the zone drilled. In fact, the well appears to pass through a visible fracture that most probably enhanced the permeability. Prospect F seems to replicate these discontinuities with a thicker succession which if successful would lead to a significant thickness, in comparison to Rembrandt, of a well-developed reservoir.

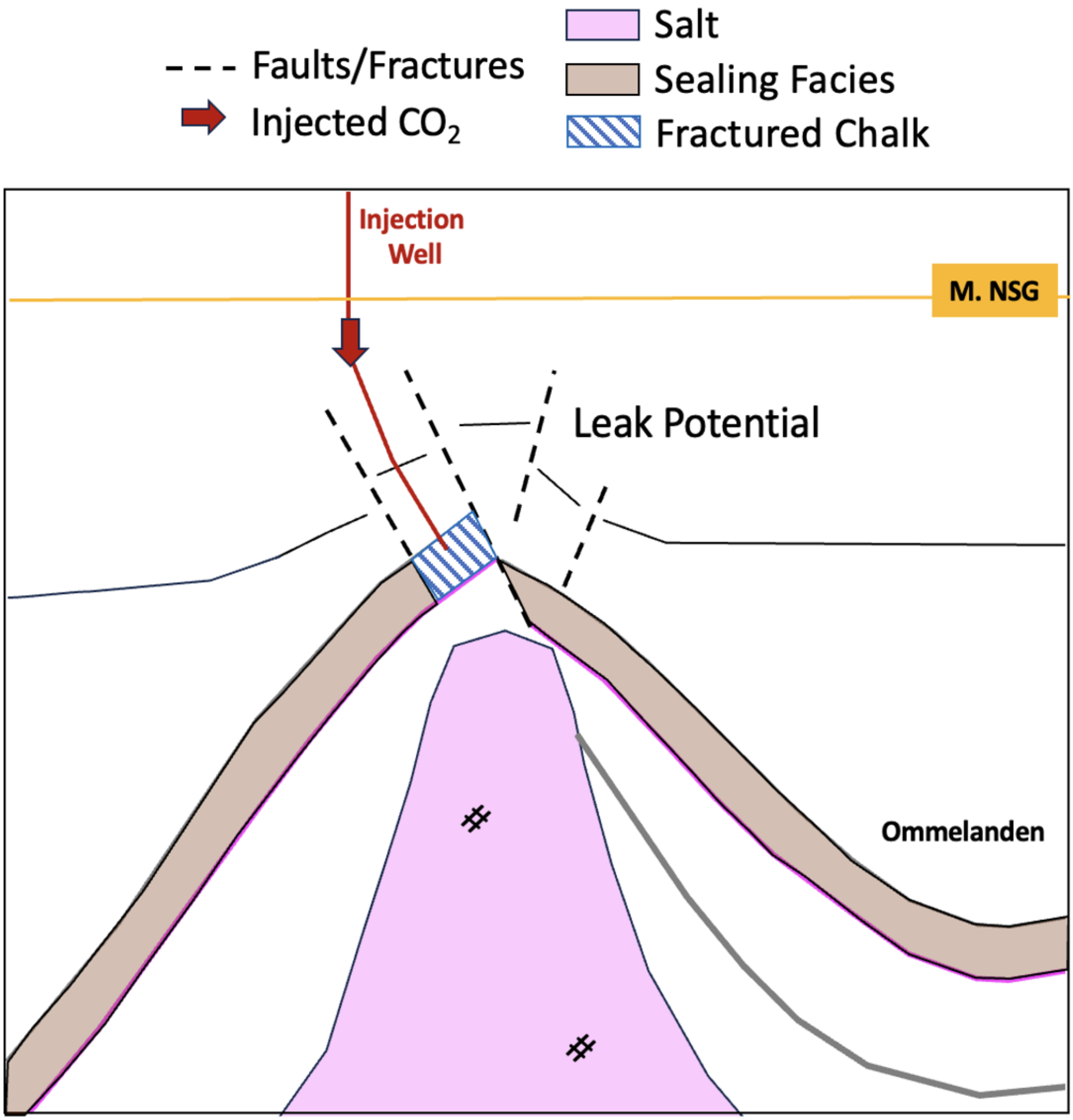

Figure 29: Schematic of prospect F trap.

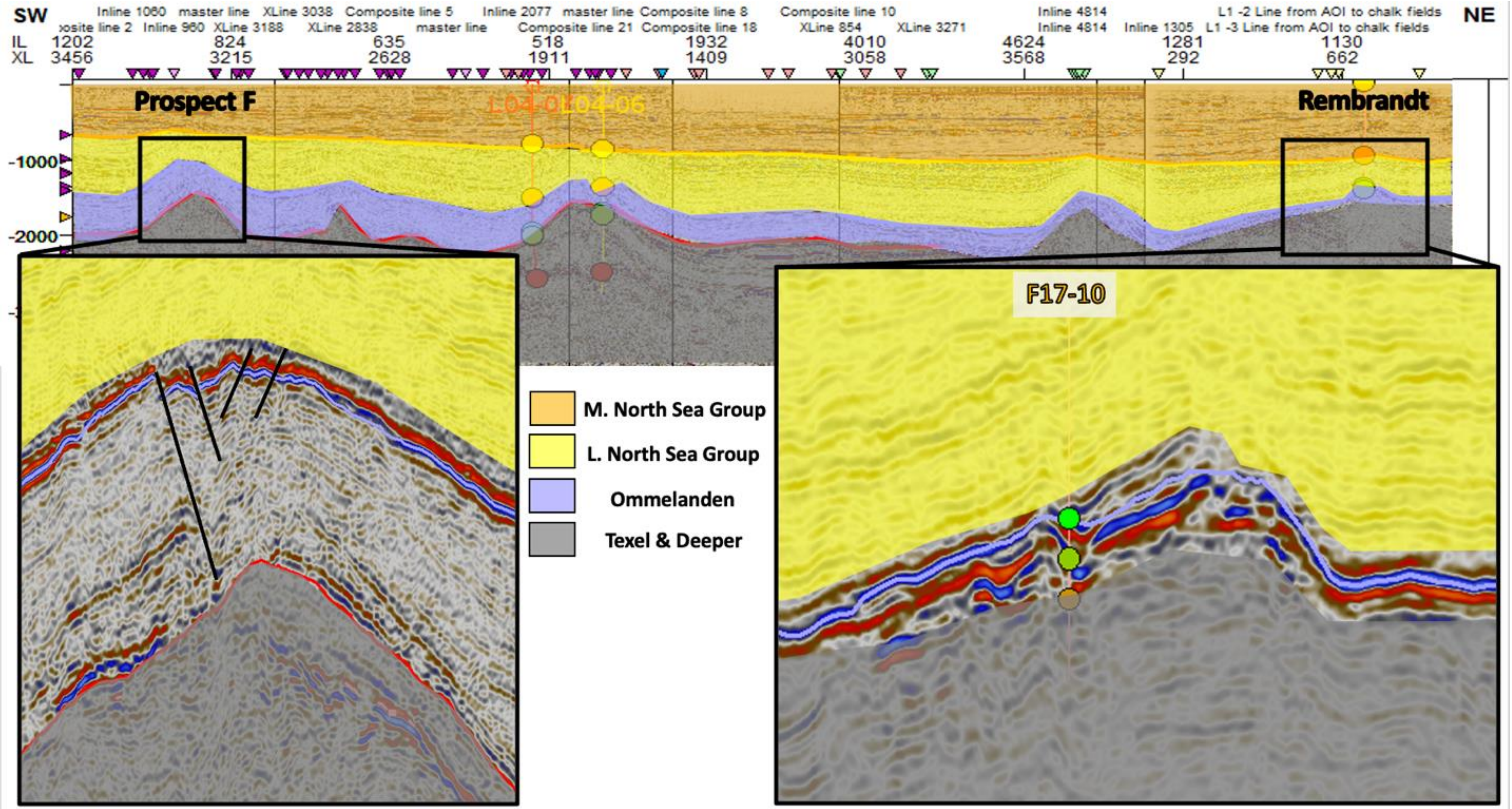

Figure 30: Regional Seismic line connecting prospect F with the Chalk field, Rembrandt.

4.7.2. Prospect G

4.7.2.1. Summary

- **Name:** Prospect G (Rachel Ruysch)
- **Salt Structure Type:** Salt pillow
- **Targeted Chalk Type:** Allochthonous
- **Structural Analysis:** the structure is gently pushed by a sizable salt pillow and the master seal, Middle North Sea reflector, is not breached and as such has potential as explained in section 4.4 (figure 31).
- **Amplitude Analysis:** section X highlights the presence of amplitude anomalies on the southeastern flank of the prospect G (figure 26).

4.7.2.2. Reservoir

Volume attributes were extracted across the focus area and the Ommelanden high potential zones determined in the previous section. The zone was further investigated through the extraction of seismic crosslines and inline to see if the RMS volume attribute and variance can provide further information on reservoir quality. Fig. 32-b shows that within the zone, the Ommelanden has low RMS values, to potentially represent better reservoir quality, while to the north of the line (towards the crest of the structure), higher amplitudes representing tighter Ommelanden is detected. The variance line in Fig. 32-c shows many discontinuities above and below the Ommelanden but non that go through it.

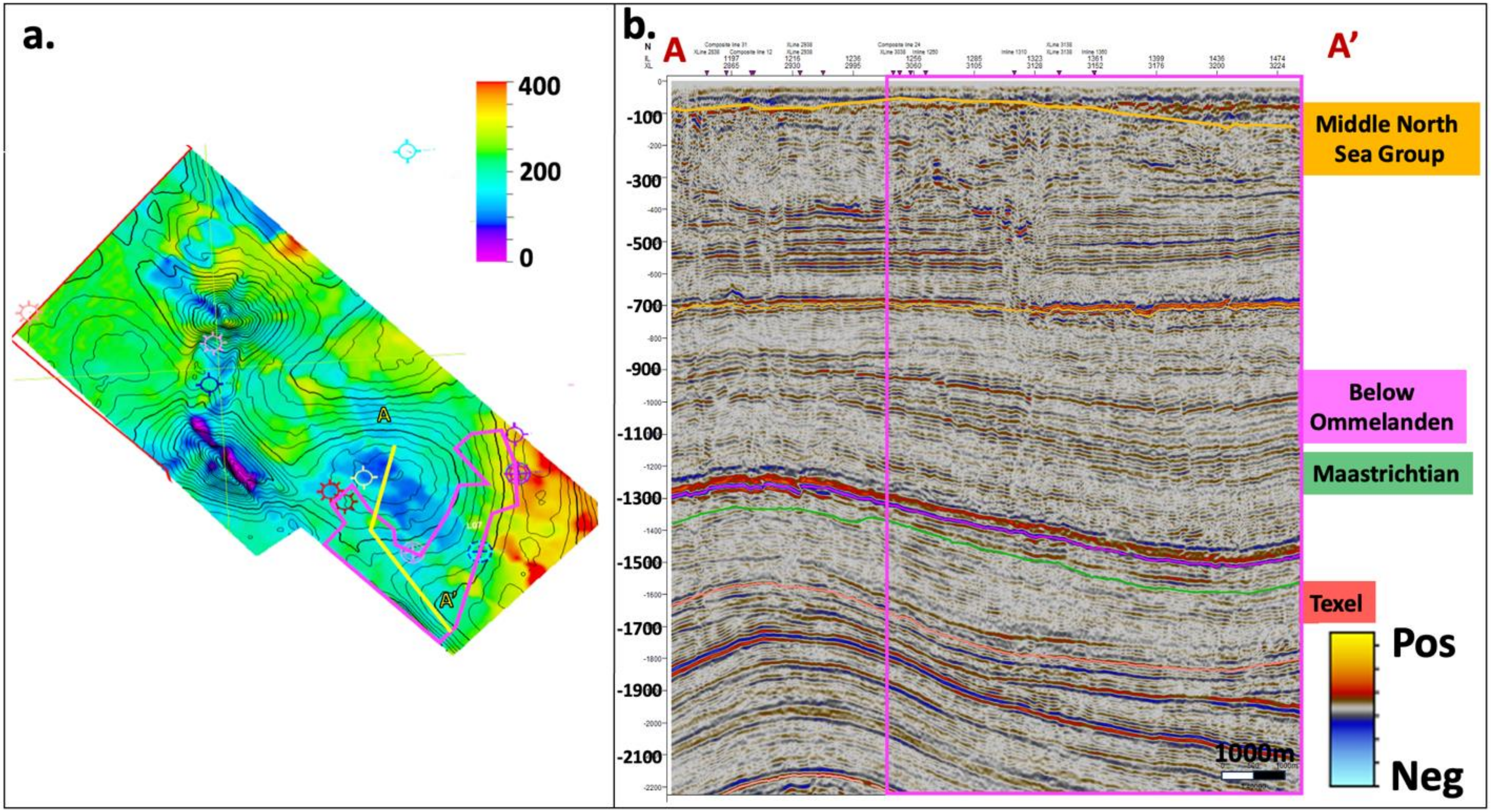

Figure 31: Prospect G transect lines. (a) Ommelanden thickness map with seismic line passing through Ommelanden high potential zone on the flank of prospect G. (b) south-north seismic line going through the southern flank of the structure, across the high potential zone.

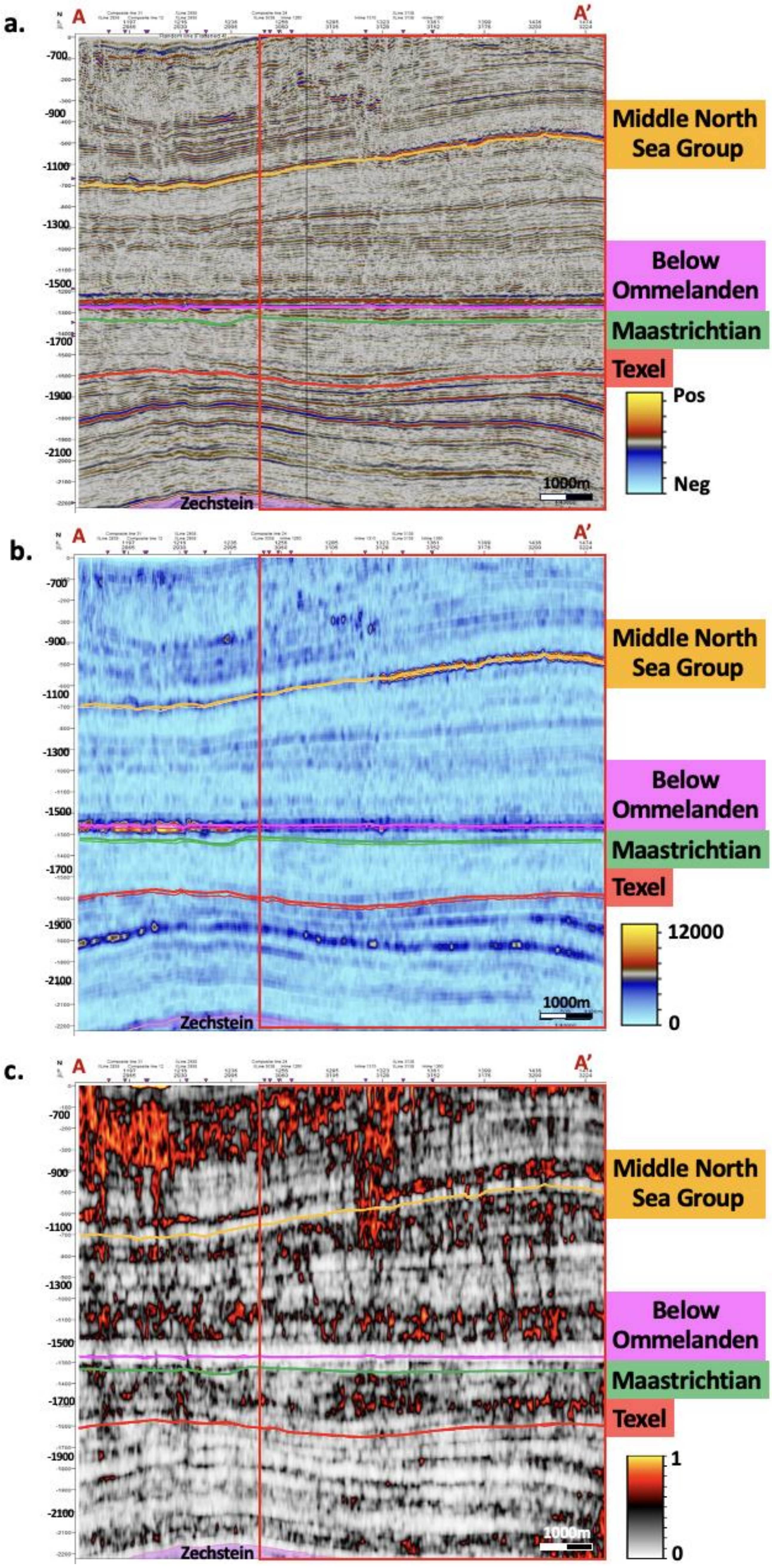

Figure 32: Prospect G flattened transect lines on Ommelanden. (a) same seismic line flattened on Ommelanden surface. (b) RMS volume attribute line. (c) Variance volume attribute line.

4.7.2.3. Trap

From figure 32, we can see that the Ommelanden at the top of the structure of has high RMS values (figure 32-a), which would indicate a tight Ommelanden and as such postulates a good lateral up dip seal (figure 33). Furthermore, the North Sea group as an upper seal appears to be competent from the variance extraction (figure 32-c), specifically since discontinuities in the North Sea group appear to be mainly confined within the layers. Only a few anomalies appear to extend discontinuities across multiple sections. Those appear draping in from the shallow surface, above the interpreted Middle North Sea horizon because of near surface disturbance.

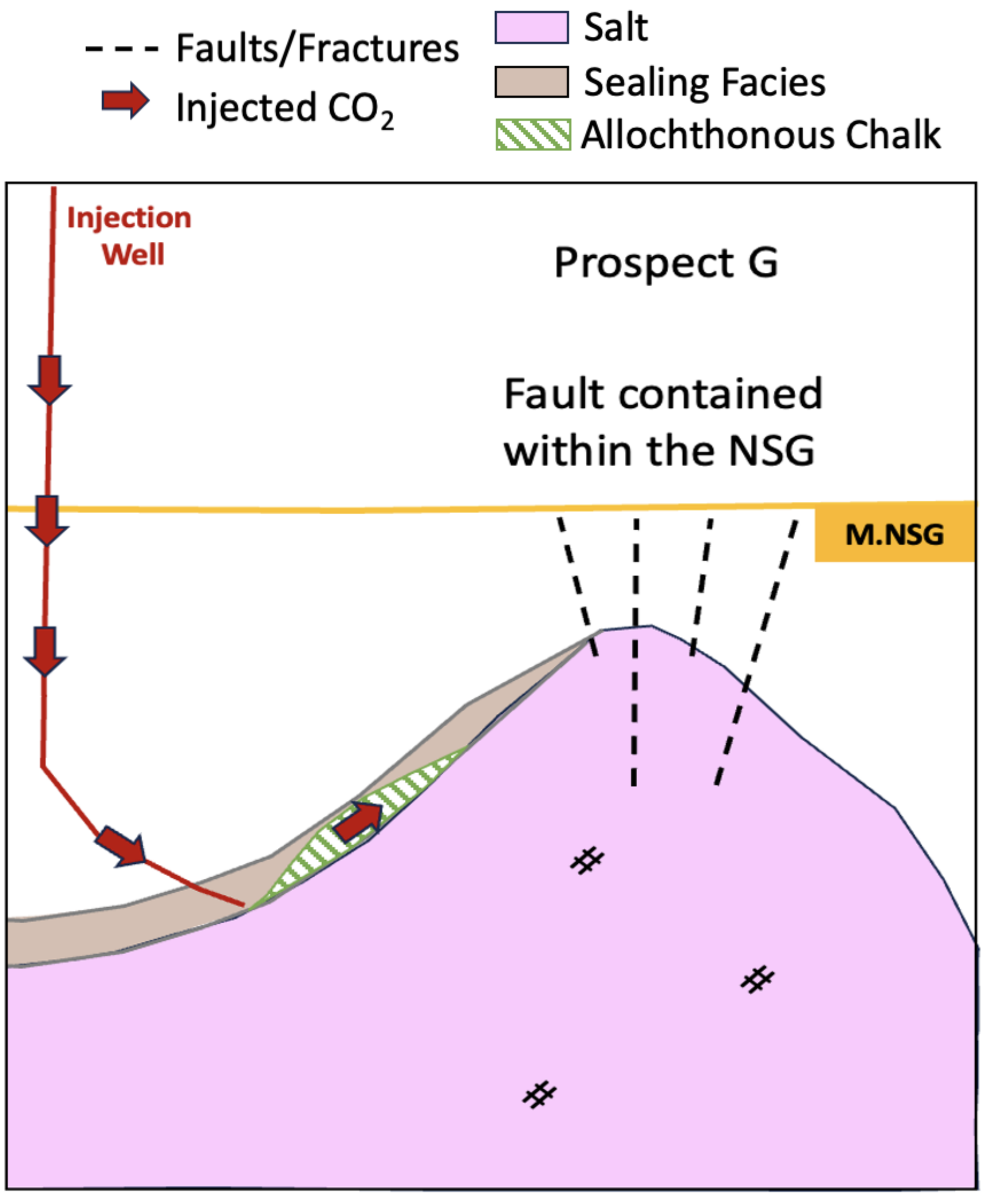

Figure 33: Schematic of prospect G trap configurations

4.7.2.4. Seal

The seal can be evaluated generally through the variance image produced in figure 32-c and pressure data from regional maps. The seismic lines extracted around this prospect do not show discontinuities extending from the Chalk to the shallow subsurface. Furthermore, regional maps in the area show the Chalk to be overpressured, which means that regionally it is overlain by an effective seal (van der Es, et al. 2022). The lower North Sea group claystones are continuous and have an average thickness of 584m. In some zones they display typical polygonal faulting, but these faults are localized within the shale due to post burial dewatering. The stress induced fractures or faults are most bound within the clays and don't reach the overburden, therefore, they don't affect the integrity of the seal.

4.7.2.5. Prospect G vis-à-vis Rembrandt Field

A regional seismic composite line was extended from prospect G to the closest proven permeable Chalk interval, in the Rembrandt field. The target in the Rembrandt field was the Chalk at the top of the structure while the target in prospect G is the purple highlighted box at the flank of the structure (figure 34). In prospect G, we see minor discontinuities at the top of the structure coupled with a strong reflector while the zone of interest in the southeastern flank shows a dimmer reflector. This appears to be lesser in extent in comparison to Rembrandt's discontinuous and evidently faulted reflector.

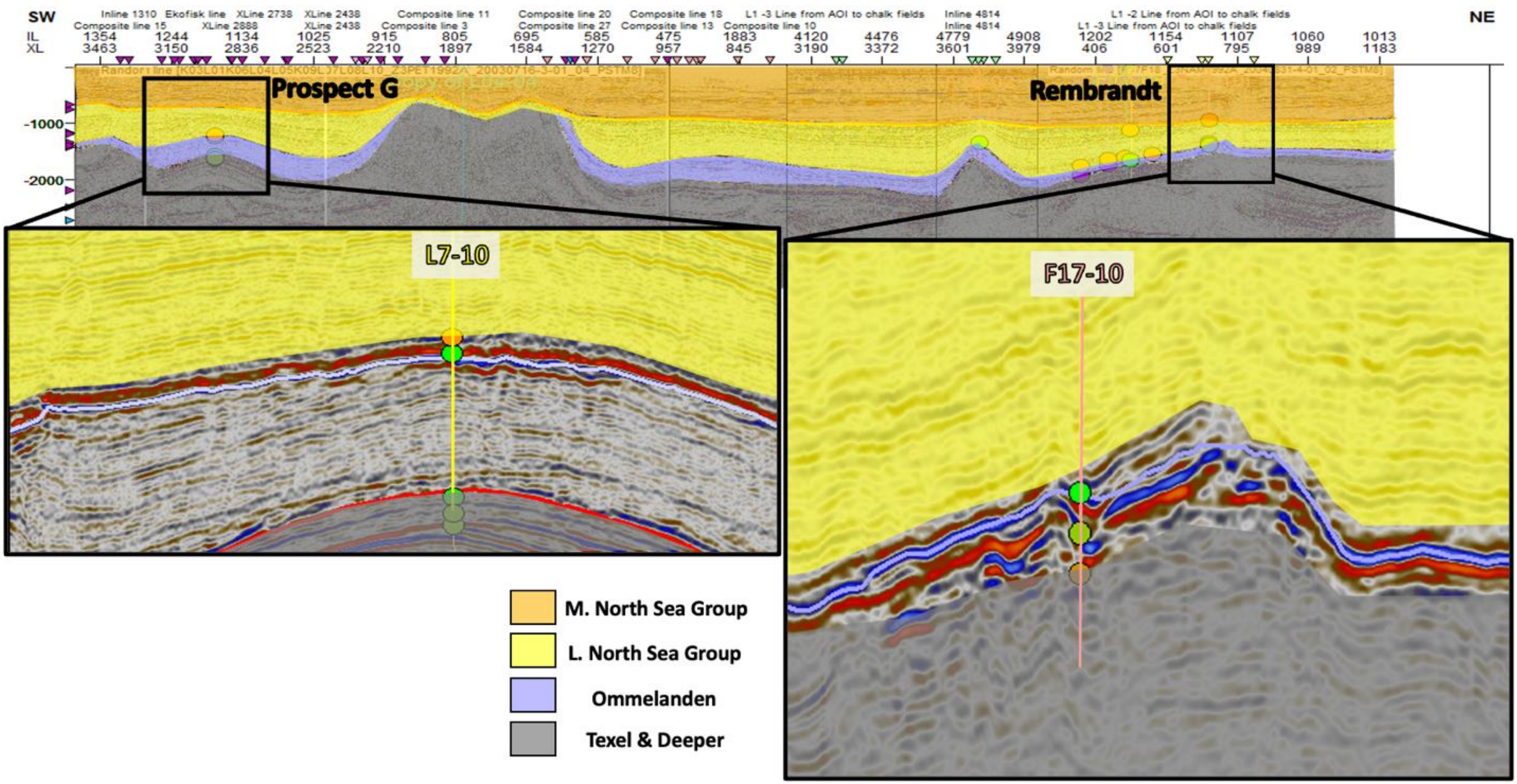

Figure 34: Regional Seismic line connecting prospect G with the Chalk field, Rembrandt.

5. Discussion

Prospect Evaluation

Both prospects have their challenges and opportunities and table 5 highlights their variations.

Table 5: Comparison between the prospects. Highlighted in **red** are risk inducing properties.

Criteria		Prospect F	Prospect G
Halokinesis	Salt Structure	Pillar	Pillow
Reservoir Property	Depth (shallowest point)	-900 m	-1200 m
	Type	Autochthonous	Allochthonous
	Thickness	**Uncertain** (>100)	100-300
	Amplitude Anomaly Size	**Small** (3190.5 km^2)	Sizable (33,768.6 km^2)
	Ommelanden Reflector Disturbance	Significant	**Minor**
	Ommelanden Variance disrupted	Significant	**Minor**
Seal	Middle NSG reflector	Intact	Intact
	Variance disrupted within M.NSG	**High risk**	Low risk
Rembrandt Resemblance	reflector response visually	Very Similar	slightly Similar
	detectable fractures	clearly visible	**Not clearly visible**

As both prospects represent two types of depositional chalk that are fundamentally different, it is challenging to compare both at the same scale. Prospect F has autochthonous chalk that is analogous to all the proven fields in the Dutch offshore while Prospect G targets an undiscovered chalk type in the Dutch offshore, allochthonous which inherently adds risk. The diapir is defined to be an elongated salt structure while the pillow's planform would be round (Jackson et al., 2017). Fundamentally, both types successfully create faulting and fracturing necessary to enhance the Chalk's permeability in the subsurface. In this study specifically, the pillar intruded to a shallower depth in comparison to the pillow and as such led to the development of more fractures (to be discussed in the polygonal faulting section ahead). As such, this would de-risks the reservoir of Prospect F and adds risk to the seal as these faults might extend to it and compromise it. The uncertainty in thickness for Prospect F arises from the inability to correctly trace the Maastrichtian surface across the crest of the structure due to the intruding salt pillar while Prospect G only developed a gentle structure because of the salt pillow push upward which led to the extraction of a clear thickness estimation. Prospect G also has a sizable anomaly on its flank that is an order of magnitude higher than that of Prospect F. In term of reservoir enhancement indications from the seismic, Prospect F shows the most promising signs with clearly fault disrupted reflectors and variance. Furthermore, when comparing both prospects with the proven reservoir in Rembrandt, visually Prospect F resembles Rembrandt seismic character more than Prospect G.

General Guidelines for Chalk Prospecting

The consideration of chalk as reservoir for carbon storage will require future studies to de-risk many currently existing uncertainties. A key future focus area is to investigate other locations that have 3D seismic coverage and salt domes. Figure 35 recommends high potential locations in the blocks J, L, and M because its most proximal to the Dutch onshore and due to the high-pressure regime present in northern blocks E, F, and G.

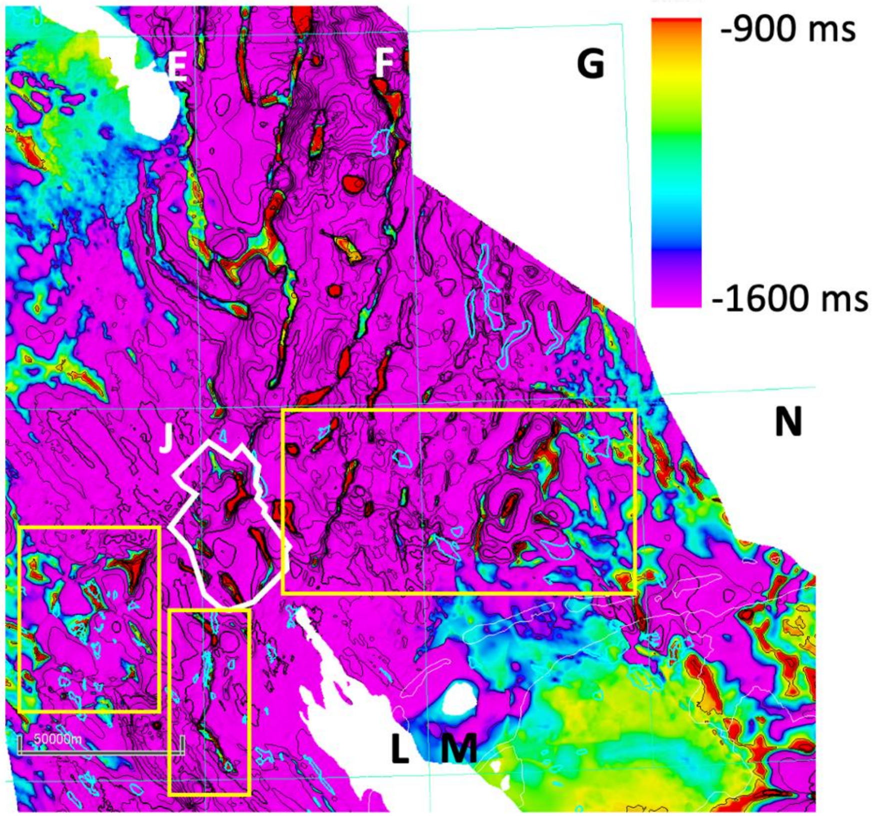

Figure 35: Map of Top Zechstein TWT map. Areas for future investigations highlighted in yellow boxes.

It can be clearly observed from the Top Zechstein regional map that halokinesis has a distinct pattern over the Dutch offshore. These Patterns are said to be that of early phases of salt structuration act as a template that influences subsequent phases of halokinesis, even if the forces differ (Jackson et al., 2017). Two trends can be identified, NE-SW and NW-SE in the area of interest and southward. The one influencing the area of interest in this study might be due to deep seated faults that are remnants of the NW-SE suture zone from the early Paleozoic, when the Netherlands was in the Caledonian foreland near the triple junction of three continents (De Jager 2007). The NW-SE direction appears to affect the regional trend of halokinesis which might be in connection to the conjugate faults of the earlier established trend (de Jager, 2007).

It was established that all the discovered Chalk field are on top of salt domes and have enhanced permeabilities due to halokinesis induced faulting (figure 8). As such, when considering Chalk as a reservoir for storage, the very first step to screen for a location is by choosing a location with Zechstein salt domes.

Table 6: Traffic Light Assessment of the Chalk play for carbon capture and storage.

Criteria	Chalk Gp.	Methods to de-risk
Depth		Well Tops
Porosity		Analogue fields, Well results
Permeability		Core porosity-permeability relationship
Thickness		Well Biostratigraphy
Halokinesis		Regional Salt Mapping
Fractures		Variance, Ant Tracking
Attribute Seismically Detectable		Inversion, Forward modeling
Reservoir Extent/ Volume		Seismic sequence stratigraphy, well results, analogue studies
Petrophysical Logs Availability		-

Reservoir extent challenges and trap

A major challenge for Chalk exploration and its development for petroleum has been the ability to determine the developed reservoir extent. The most recent discoveries of Rembrandt and Vermeer have been explored based on seismic anomalies and subsequent drilling results confirmed their validity EBN (2023. Pers. Comm.). However, the challenge remains to estimate the extent and distribution of the reservoir, specifically when the reservoir or the fractures enhancing its permeability are sub-seismic resolution. Furthermore, saline aquifer storage is desirable because it unlocks potential beyond structural constraints, however, due to the nature of Chalk and its reliance on fracturing from halokinesis, the reservoir development is condensed within structural closures. Down dip extensions of the enhanced reservoir interval will drastically lack permeability and will not be viable as pathways for the CO2 plume to migrate upwards without mechanical enhancements. As the Chalk reservoir development is bound to within structures created by inversion or halokinesis, the trapping configuration should be structural and like petroleum. If the reservoir is developed on the flank of the structure, then it would constitute a combination trap with a structural tilt element and a stratigraphic deterioration of reservoir facies towards the top of the trap.

Halokinesis induced faulting in the seal

The variance extraction maps show clear differentiation than faulting induced by the salt pillow and that induced by the salt pillar. In the case of Prospect G (pillow salt), we see chaotic pattern covering the area on top of the circular diapir while in Prospect F (salt pillar) it is more concentrated to the crest of the stretched elliptical diapir with chaotic in the center and radial towards the periphery (figure 36).

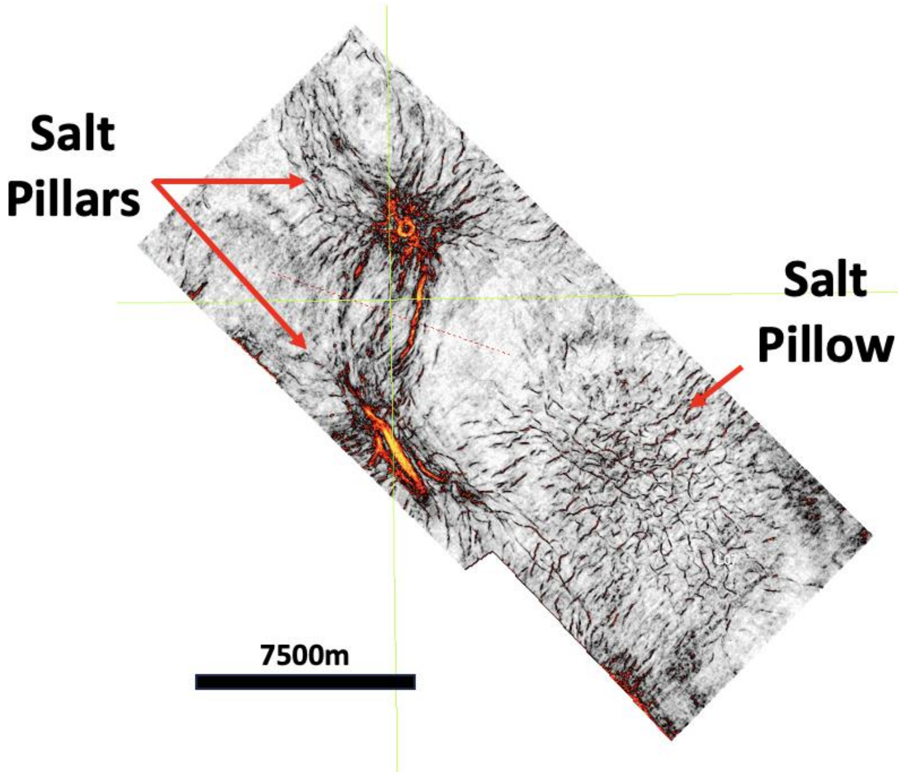

Figure 36: Maps showing radial faulting as a product of halokinesis in the area of focus.

A study by Zhang and Alves (2023) that investigated halokinesis induced faults in the K block (to the east of the study area) has recognized similar features on seismic cross sections (figure 37). Zhang and Alves conclude that halokinesis has gone through multiple stages of growth that influenced the stratigraphy since the late Permian. This is evidenced by thinning in the of strata between top Zechstein and top Chalk, which resembles the scenario experienced by Prospect F (Zhang et al., 2023). The salt pillow in Zhang and Alves study formed later during the late cretaceous inversion event which is evidenced by thinning in the North Sea group overlaying the Chalk (Zhang et al., 2023). This is also like the case encountered with Prospect G in this study area. In conclusion, it would be recommended to conduct a detailed study investigating the times of structuration between the various types of salt domes, nature of faulting induced, as well as the stresses that led to their formation and their impact on fault reactivation risk and seal integrity.

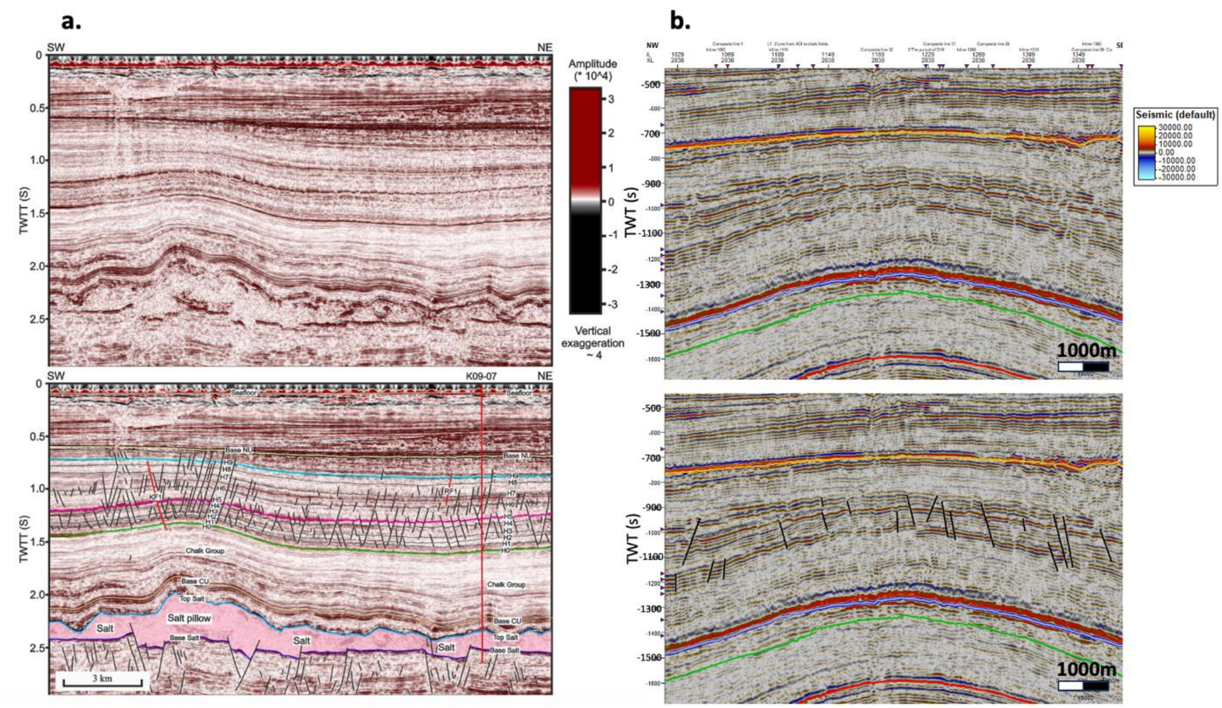

Figure 37: Seismic profiles showcasing polygonal faulting in the Nort Sea group. (a) Example from Zhang and Alves (2023) in an area in K block, just east of this project's focus area. (b) crossline passing through the Prospect G.

Comparison to clastic reservoirs

The advantage that arises from targeting clastic reservoir is their wide distribution and the existence of prolific legacy petroleum characterization studies. The challenge with the Chalk group in the Dutch sector is that it is a young play that has only been encountered in a handful locations and has been operationally challenging. The first challenge that faces the Chalk and sequestration in carbonate rocks in general is the question of CO_2 reactivity with the reservoir inducing weakening and compromising the storage site. Bonto et al. (2021) reviewed the extensive work has been done on studies done to understand CO_2 storage in the Chalk in the neighboring Danish sector. These studies include flooding tests performed on core samples to investigate the thermo-hydro-mechanical-chemical behavior of the Chalk in the presence of CO_2 saturated aqueous solutions. The conclusion was that although the behavior of the samples is mixed, most of the flooding tests did not support further weakening due to water injection or significant changes in petrophysical properties (Bonto, et al. 2021).

Another challenge that the Chalk portfolio for carbon storage faces is the geologic complexity of permeable Chalk and the fact that the main permeability stems from fractures. The Chalk has been consistently marked as a casing point due to well control issues faced during drilling. For carbon storage, a technically challenging reservoir might not be the safest option for safe storage.

6. Conclusions

This study has demonstrated a workflow to evaluate and assess the Chalk Group in the Dutch offshore as a potential reservoir for CO_2 storage. The Chalk has been found to be relatively unexplored in the Dutch offshore compared to other sectors in the North Sea (figure 3). To determine a suitable location of Chalk prospectivity, it is important to observe two regional trends: Chalk reservoir pressure and halokinesis. Overpressure zones offer little room for injectivity and the presence of salt and halokinesis is necessary for Chalk reservoir development. Once a suitable area is selected, the quality of the seismic and availability of well data will determine the ability to map and delineate various depositional Chalk types (Autochthonous or Allochthonous).

The study relied on 4 wells that partially logged the Chalk and two wells that contained biostratigraphy data to discern intra-Chalk zones. Two prospects were identified in the focus area to have potential for CO_2 storage, Prospect F identified as an autochthonous Chalk opportunity structurally trapped on top of a salt pillar and Prospect G as allochthonous Chalk stratigraphically isolated on the flank of a pillow salt structure. Both prospects have their own technical challenges as well as opportunities highlighted in table 5, but to mature them further work must be done to de-risk the whole play as well as particulars such as reservoir properties, integrity of the top seal, and trap configuration.

The highest reservoir potential zones in the Chalk that have proven to be productive are the Danian Ekofisk and Maastrichtian Ommelanden. Distinguishing these zones on seismic lines without the presence of high quality well logs and biostratigraphy data poses a key challenge. Another challenge is extending these well data points laterally across a seismic volume.

A specific challenge for the allochthonous play is that it has not been proven in the Dutch offshore nor documented in any well penetration. To de-risk this, studying and following evaluation workflows utilized on allochthonous fields in the UK sectors is recommended.

The Chalk in the Dutch offshore is underexplored and as such its potential is indeterminate until it is further demystified by future studies, most integral is reprocessing the seismic data for the Chalk zone. Also, creating a tectono-stratigraphic understanding of key basin inversion events affecting the Chalk and the role of pressure and compaction on reservoir properties. Furthermore, it is key to utilize well logs, when available with adequate quality, to quantify seismic amplitude anomalies and relate them to reservoir properties through seismic inversion and forward modeling. Finally, replicating the workflow in this study to other prospective areas and the creation of a portfolio of autochthonous and allochthonous prospects will lead to the ability to clearly assess and risk the feasibility and viability of this play as a reservoir or to store CO_2 or a seal for deeper Jurassic reservoirs.

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