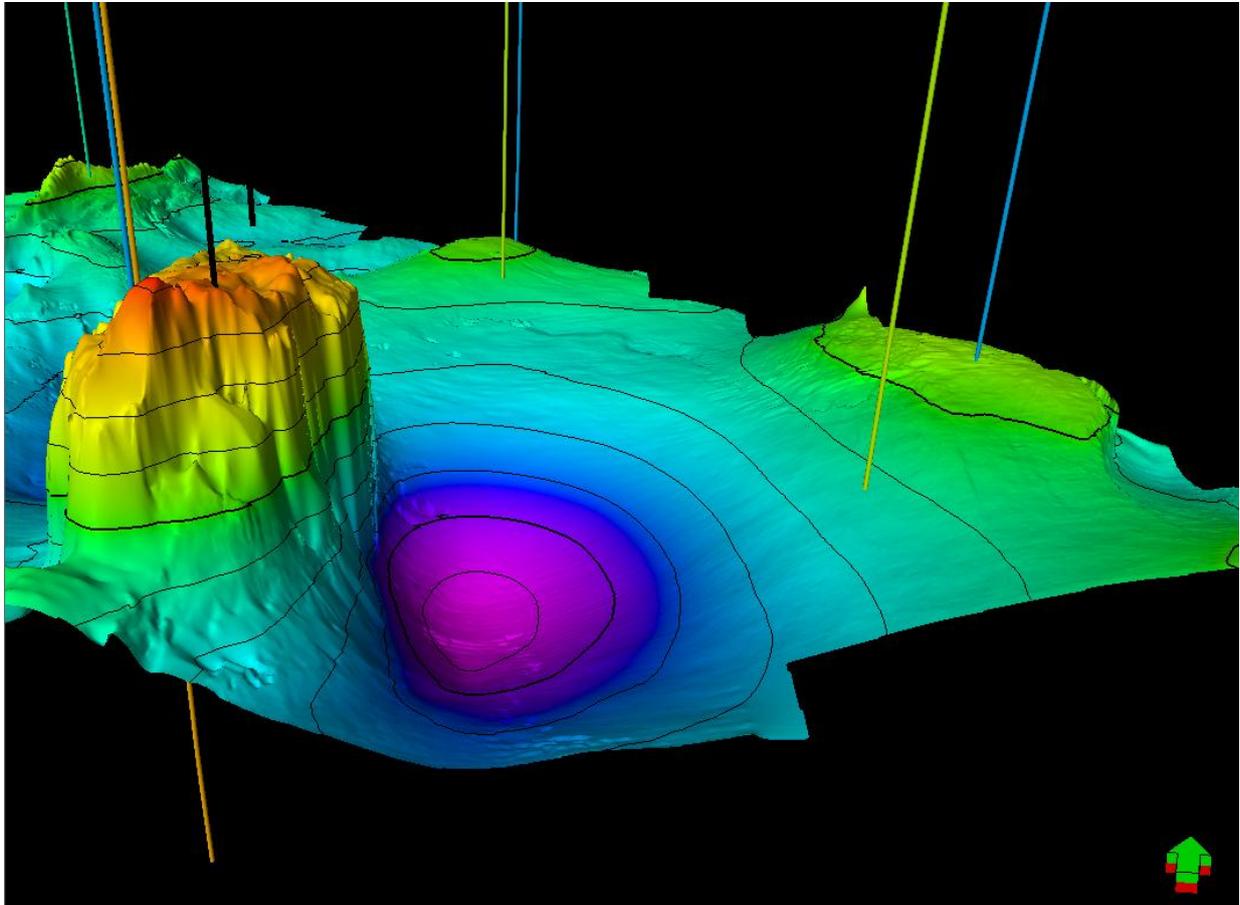


Prospectivity analysis of the northern Dutch Central Graben



Internship

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Summary

For this project, a prospectivity analysis of the B quadrant in the northern Dutch offshore has been carried out. The recently released Entenschnabel (ES02) dataset was used for this analysis; this is a 3D dataset of the northern Dutch offshore and through the German Entenschnabel into the southern Danish Central Graben and was obtained by Fugro in 2002. Seismic mapping of nine key horizons such as the base Chalk, base Schieland Group and top Zechstein resulted in the division of the geological model into eight layers. These layers were used as input for the time-depth conversion which was conducted using the Velmod 2 velocity model. After the first nine horizons were completed, more detailed mapping was carried out on play level. Four source rocks are probably present in the study area: the Jurassic Clay Deep Member and Posidonia Shale Formation, the Westphalian Maurits and Klaverbank Formations and the Namurian Geverik Member. The Posidonia and Clay Deep Member are probably only mature in the Central Graben; the Carboniferous source rocks may well be mature in the Step Graben in the west of the study area. Six plays were identified: the Chalk, Vlieland Sandstone, Scruff Greensand, Lower Graben, Lower Buntsandstein and Rotliegend play. Only the Scruff Greensand and Lower Graben plays have been proven successful in the study area by the F3-FA field. The most prospective plays are probably the Scruff Greensand and Vlieland Sandstone plays; in addition, a number of leads have been identified in the Chalk. The three most prospective leads are the Amethyst, Beryl and Bloodstone leads. The Amethyst lead is a fault-dip closure on top of the B16 salt wall in a Chalk reservoir which is probably fractured. Carboniferous source rocks probably provide charge which may migrate into the chalk via the large normal fault which runs along the salt wall. Bright spots in the Tertiary indicate that hydrocarbons may be present. The Beryl lead is a combined Scruff/Vlieland Sandstone lead located in the center of the B17 block. The closure consists of steeply dipping flanks against the northern flank of the B17 diapir which are truncated by the Chalk Group. Charge for this lead probably comes from Posidonia Shale and/or Clay Deep Member, which are probably mature in the Central Graben. Bright spots over the B17 diapir hint at charge. The Bloodstone lead is speculative: the Vlieland Sandstone has not been encountered by any wells in the study area, but may be present near structural highs. The trap of this lead consists of a four-way dip closure in the west of the B14 block.

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1. Introduction

The North Sea is a mature petroleum basin: exploration and production of hydrocarbons has been going on for the last 60 years and it is likely that the greatest discoveries have been made. However, as the quality of seismic datasets continues to increase and evermore parts of the North Sea are covered by 3D seismics, plenty of smaller discoveries are probable to be made. This study has been conducted in one of the areas where 3D seismic was recently released: the B quadrant of the Dutch northern offshore.

The eastern part of the B quadrant covers part of the Dutch Central Graben, which contains a very thick sequence of mostly siliciclastic sediments. The large normal faults which bound the Central Graben have been active since the Carboniferous, either during extensional regimes or as inverted faults during tectonically active periods. The presence of a thick layer of Zechstein salt in the subsurface makes for even more complex and interesting geometries and provides plenty of opportunities for hydrocarbon exploration. In 2002, Fugro acquired the ES02 survey (fig 1); a 3D seismic dataset was obtained which tied producing Danish oilfields through the German 'Entenschnabel' blocks to the Dutch F3-FA, F2-A-Hanze and B17 discoveries.

This study is a regional evaluation of the Dutch part of the survey and was conducted for EBN. Using Petrel software, 9 major lithostratigraphic horizons were interpreted throughout the study area. Locally more horizons were interpreted. These horizons were then converted from time to depth. Specific questions which we wanted to be answered were:

- Is it possible to update existing well postmortems with the newly gained information from this study?
- Describe each possible play in the area
- Evaluate the exploration potential per play by generating playmaps and listing possible leads plus volume

2. Data & literature

For this study, a ~50x40 km 3D seismic dataset from the Entenschnabel survey was available. This survey was shot by Fugro in 2002 and extends over the German and Danish borders towards the north-east. However, due to the nature of the German legislature, the German part of the survey is not in the public domain. 11 wells are present in the study area, of which 5 are located on top of the B17 salt diapir. An overview of the encountered formations in the wells, the available well logs and other information is given in table 1. Mud logs, checkshot data, composite logs etc. were obtained from the TNO website www.nlog.nl. In addition to the seismic and well data, interpreted surfaces of 9 key horizons were available. These interpretations were done by TNO and are based on a number of 2D seismic lines (fig. 2). TNO well top interpretations were also available for all wells in the study area. This dataset is from the NCP-1 project which is a large on-and offshore mapping project completed in 2006 by TNO. An updated project (NCP-2) should have been completed in 2010; in this update, newly released 3D seismic data is used to map the eight major lithostratigraphic units in greater detail. However, the Northern Dutch Central Graben part of the NCP-2 project is not yet available on www.nlog.nl so any comparisons that will be made in this study are with the NCP-1 project. In addition to the seismic dataset and interpretations which were already loaded into the project, I have used the following books, publications and reports:

- First of all, most of the geological background can be found in Geology of the Netherlands (2007). This book consists of a compilation of key papers concerning the structural, paleogeographical, sedimentological and climatic evolution of the Netherlands during the Paleo-, Meso- and Cenozoic.
- In 2007, TNO build a very extensive velocity model for the Dutch subsurface consisting of 8 key lithostratigraphic layers. For each of these layers, a V0k function was constructed in order to conduct time-depth conversions. For the layers below the Chalk Group, I used this model in the time-depth conversion I carried out.
- In 2006, another large project which TNO together with six sponsors undertook was the Petroplay project. The objective was to assess the prospectivity of the pre-Westphalian in four key regions in the Netherlands, one of which is the northwestern offshore. This report is confidential.
- Chevron and Zetaware Inc. undertook an extensive study in 2012 in which they assessed distributions, maturities, expulsion and migration of all source rocks in the A and western B blocks. This report is confidential.
- In the Central Graben of the B18 quadrant, the Amber prospect has been tested by Gaz de France. A prospect review was written in 2004 in which, among other things, distribution and maturities of Jurassic source rocks were modeled. This report is confidential.
- Panterra and TNO conducted an extensive study in 2010 titled 'Remaining hydrocarbon prospectivity of the Dutch Central Graben'. For this report, seismic mapping, basin modeling lead identification etc. were conducted in the Jurassic of the Central Graben area. This report is confidential.
- Field descriptions of the F3-FA field by NAM and EBN were used to illustrate the only successful example of a petroleum system in the study area. Both of these reports are confidential.

- Petro Canada conducted a study on the possible presence of a gas-bearing sandstone in the Upper Rotliegend section of well B17-04 in 2009. This report is confidential.
- Besides these confidential reports, a large number of documents found on www.nlog.nl have been consulted. These may be biostratigraphical reports, lithological descriptions, checkshot data, composite logs etc.

3. Methods

3.1 Seismic interpretation

Initially, nine seismic horizons were mapped out in the seismic survey. These key horizons represent the boundaries between major stratigraphic groups in the Dutch offshore. I used the existing NCP-1 interpretations as a guide and further validated my picks at well sites. Figures 4 and 5 show examples of representative picks; together, they show all horizons except the Posidonia Shale. Table 1 shows the approach to the seismic interpretation of each horizon, with density of the cross- and inlines and the areas where the horizons have been interpreted. Figure 4 shows a schematic overview of the wells in the study area and the stratigraphic horizons they encountered. The nine horizons I picked are:

- The base of the Upper North Sea Group (NU), picked on a broken, positive reflector in a transparent section
- The base of the North Sea Supergroup (N), picked on a clear negative, continuous reflector at the base of a set of slightly less distinctive reflectors
- The base of the Chalk Group (CK), picked on a bright positive reflector. If the Rijnland Group is absent, this horizon unconformably overlies older deposits
- The base of the Rijnland Group (KN), picked on a bright positive reflector which unconformably overlies older deposits
- The base of the Schieland Group (S), picked on a moderately bright positive reflector, which is surrounded by more transparent reflectors
- The base of the Altena Group (AT), picked on a very clear negative reflector overlain by very transparent seismic and underlain by slightly higher amplitude reflectors
- The base of the Upper Germanic Trias Group (RN), picked on a moderately bright reflector in a very continuous 'layercake' overlying the chaotic Zechstein section
- The top of the Zechstein Group which in most of the study area forms the base of the Lower Lower Germanic Trias Group (RB), picked on a moderately bright and continuous positive reflector at the top of the the transparent Zechstein Group
- The Base of the Zechstein Group (ZE), picked on a very bright positive reflector. Below the reflector, lamination can generally be distinguished; above the reflector there is a section of varying thickness with very transparent seismic. This section occasionally contains bright reflectors at random angles

After these nine key horizons were picked, I zoomed in on the different plays. From top to bottom, I picked the following horizons:

- The base of the Ommelanden Formation (CKGR, only in the Central Graben area), picked on a relatively faint negative reflector at or <100 ms above the base of the Chalk Group
- The top of the Vlieland subgroup (KNN), picked on a moderately bright negative reflector which often shows an angular unconformity with lower reflectors. A more detailed description is given in the chapter 'Vlieland Sandstone play'
- The base of the Vlieland subgroup, which is identical to the base Rijnland Group interpretation

- The base of the Clay Deep Member (SGKIC), picked on an occasionally very faint, negative reflector. This pick is based on checkshot data in well B14-01
- The base of the Scruff Greensand Formation (SGGS), picked on a moderately bright, positive reflector <100 ms below the base Clay Deep horizon
- The base of the Kimmeridge Clay Formation (SGKI, partly overlaps with the base of the Schieland Group). If the Lower Graben Formation is present, it is picked on a faint positive reflector in a set of three, evenly spaced negative reflectors. If the Lower Graben Formation is not present, the reflector has an increased amplitude
- The base of the Lower Graben Formation (SLCL, partly overlaps with the base of the Schieland Group), picked on a bright, positive reflector
- The Posidonia Shale Formation (ATPO); due to the limited thickness, top and base could not be distinguished so it is interpreted as a single reflector. The picked reflector is based on a seismic section from the Amber prospect review by GDF Suez (fig. 12), which ties the German B18-01 well to the Dutch part of the Entenschnabel survey
- The base of the Keuper Formation (RNKP), only in the Step Graben), picked on the upper, moderately bright, positive reflector in a set of two, separated by a moderately bright, negative reflector
- The base of the Upper Muschelkalk (RNMUU, only in the Step Graben), picked on the lower, positive reflector described above
- The base of the Röt Formation, which is identical to the base Upper Germanic Trias Group interpretation
- The base of the Solling Formation (RNSO), picked on a relatively faint, positive reflector ~100 ms below the Base Röt horizon. The pick has been tied to well B17-02; outside the Step Graben, the seismic in the Triassic section occasionally becomes very transparent and no reliable mapping could be carried out in these areas (mainly the Thor transform zone and the area near wells B14-02 and B13-02)
- The top of the Lower Volpriehausen Sandstone Member (RBMVL), picked on a very faint, positive reflector ~120 ms below the base Solling Formation horizon. Similar to the base Solling, no reliable mapping could be carried out in the Thor transform zone and near wells B13-02 and B14-02
- The base of the Upper Rotliegend Group (RO). A different approach than for the other horizons was followed in the construction of this horizon. First, the base Permian Unconformity was mapped out in the Step Graben, where it was visible as a low-angle truncation of a faint reflector which runs parallel to the base Zechstein Group. In the area with interpretation, the interpreted lines were interpolated. In the areas where the unconformity was not visible, a 150 ms isopach below the base Zechstein was used to construct the horizon
- The probable base of the Maurits Formation (DCCU). The interpretation of this horizon is discussed in more detail in chapter 'source rocks'
- The probable base of the Klaverbank Formation (DCCK). The interpretation of this horizon is discussed in more detail in chapter 'source rocks'

3.2 Time-depth conversion

A short description of the steps involved in the time-depth conversion will be given here. The interpreted (TWT) horizons were first converted to surfaces in order to completely fill the grid of the study area. For the North Sea Supergroup and Chalk Group and top and base Zechstein this was not a problem as these horizons cover the entire study area. However, the Mesozoic layers are not present throughout the study area and the horizons had to be merged with the directly overlying horizons where they are absent. Also, to preserve the 'layer cake' model, horizons are not allowed to cross one another.

I used two different methods for the time-depth conversion (table 2). For all layers except the Zechstein, I used a $V0k$ function. From the Velmod 2 project, $V0$ maps and k values of all layers are available. Initially, the resulting depth surface of the North Sea Supergroup consistently came out 30-70 m shallow with regard to the well top data. Therefore, I used the time-depth data of the wells in the study area to construct my own $V0$ maps for the North Sea Supergroup and Chalk and Rijnland Groups. By definition, residuals were reduced to zero. However, at the end of the project I found out that the $V0$ map of the Chalk in the Central Graben contained negative values which do not make sense geologically. The Chalk in the Central Graben was as a result only 500 m thick, versus 1300 m when the Velmod 2 project was used. This effect is only apparent in the Central Graben since on the flanks, well coverage is better and the $V0$ map shows more normal values in the order of ~ 2000 m/s. I found this out after all the play and source rock maps were made however, so I did not have time to update these. The leads and structures are still valid, only the actual depths may vary slightly.

In the end, the problem of the systematically shallow North Sea Supergroup with regard to the well tops was also solved. The Entenschnabel seismic dataset is not positioned correctly and should be shifted downward by ~ 36 ms. This deepens the constructed depth horizon by ~ 40 m, largely offsetting the residuals at the well tops. A table listing the residuals at various well tops is shown on the next page.

For the Zechstein layer, I used an interval velocity instead of $V0k$ models. Because salt does not compact upon burial, seismic velocities do not increase with depth and therefore, interval velocities may be used to convert the time grids to depth. The interval velocity was set at a constant 4500 m/s.

North Sea Supergroup	Well	Depth residual (m)
	B17-04	-35,83
	B17-01	-8,85
	B18-03	-4,93
	B14-02	-3,07
	B14-03	11,07
	B18-06	0,81
	B17-03	-57,52
	B13-02	9,42
	B14-01	-3,5
	B17-02	15,48
	B18-02	-8,58
Chalk Group		
	B17-04	57,95
	B17-01	42,75
	B18-03	-2,2
	B14-02	-0,55
	B14-03	6,95
	B17-03	47,3
	B13-02	3,42
	B14-01	-9,09
	B17-02	20,76
	B18-02	-18,11

Rijnland Group	Well	Depth residual (m)
	B17-01	38,75
	B18-03	13,83
	B14-02	23,52
	B17-03	39,3
	B17-02	41,18
	B18-02	-6,25
Schieland Group		
	B18-03	-35,36
	B14-02	-1,57
	B14-01	-46,37
Upper Germanic Trias Group		
	B14-02	21,01
	B17-02	26,57

4. Stratigraphy (after *Geology of the Netherlands, 2007*)

4.1 Pre-Silesian

The basement of the Dutch subsurface consists of undefined weakly metamorphic, moderately deformed Caledonian rocks which have been encountered in only two wells. South of the Netherlands, these rocks surface in the Belgian Ardennes where they have been described as fine siliciclastics. One of the wells which encountered the Caledonian succession was the A17-01 well which is located ~40 km west of the study area. Here, a thick Upper Devonian succession consisting of silty claystones of lacustrine or floodplain origin overlies an Early Devonian granite body. It is overlain by a succession of fluvial sandstones, conglomerates and claystones which belong to the Old Red Sandstone. The Mid North Sea High area, north-west of the study area, also contains carbonate platforms in the Upper Devonian strata.

Overlying these deposits are Early Carboniferous fluvio-deltaic sand- and siltstones. Locally coals have been deposited in floodplains. These deposits have been encountered in wells A14-01, E2-01 and E2-02 as well as in wells A9-01 and B10-01 which lie just over the German border. Provenances of the sediments deposited in this fluvio-deltaic setting were the Mid North Sea High and areas north of here.

4.2 Silesian

During the Silesian, the continents Gondwana and Laurussia collided, resulting in the formation of the Variscan orogenic belt. North of this belt, a foredeep basin originated. Except for the London-Brabant Massif, the area of what is now the Netherlands was located in this foredeep. Subsidence was very high in the basin and accommodation space was continually created. In the north, meandering rivers entered the basin in a low-relief setting. These rivers were bordered by swamps, where coals developed. This Namurian succession is probably present in the western half of the study area. Sometime during the Namurian, the western bounding fault of the Central Graben probably became active in the study area. During the Westphalian, these swamps probably became more widespread in the study area. Unfortunately, the Westphalian succession has been removed during the Early Permian except for a small area near the B17 salt diapir. In well B17-04, the Westphalian sediments which have been encountered are an alternation of sand-, silt- and mudstones with occasional coal streaks down in the succession.

4.3 Permian

A combination of inversion-related uplift associated with the Asturian inversion during the Westphalian C and thermal uplift during the Early Permian caused deep erosion of Carboniferous sediments. The Early Permian is thus represented by a large hiatus in the Netherlands. During the Middle and Late Permian, the Netherlands was part of the Southern Permian Basin, an E-W trending complex of sedimentary basins ranging from the east of the UK to Poland. During the Middle Permian, volcanic activity took place in the Dutch Central Graben, related to wrenching movements along deep-seated faults in the Dutch Central Graben.

The Permian is divided into three groups: the Lower and Upper Rotliegend Groups and the Zechstein Group. The Lower Rotliegend Group in the Central Graben consists of a 150 m thick succession of

tephra and basaltic lava flows which are interbedded with clay- and sandstones. Overlying these strata are the clay- and siltstones and evaporites of the Silverpit Formation which have been encountered by the B17-04 well. The coarser sandstones and conglomerates of the Slochteren Formation were not deposited in the study area; the northern limit of sand deposition is situated in the north of the J, K and L blocks. However, sands from the northern edge of the Permian Basin may reach the northern edges of the study area, as is shown by some wells in the A blocks which have drilled thin Permian sands. The Late Permian is characterized by the deposition of the Zechstein evaporites. Five cycles which are related to relative sea level variations are present; each cycle comprises an evaporite layer which was deposited when sea level was relatively low and a carbonate layer when sea levels rose. All of these cycles are present in the study area and the total Zechstein thickness is >1000 m. During later periods, sediment loading caused the salt to mobilize, creating a highly complex pattern of salt pillows, diapirs and salt walls which are closely related to major faults.

4.4 Triassic

During the Early Triassic, sedimentation continued in an area similar to the Southern Permian Basin. A large regression caused this sedimentation to occur in a continental setting. During the Middle Triassic, the connection with the Tethys Ocean towards the east was re-established. Later, uplift of the Fennoscandian Shield towards the north returned the region to continental conditions and during this time, fluvial systems built out towards the south. Towards the end of the Triassic, a phase of Early Kimmerian extension mobilized the Permian salt which was present in the subsurface, leading to further fragmentation of the depositional basins.

The Triassic lithostratigraphy consists of the Lower (RB) and Upper Germanic (RN) Trias Groups. RN contains the Lower Buntsandstein (RBSH), Volpriehausen (RBMV), Detfurth (RBMD) and Hardegsen (RBMH) Formations. The Lower Buntsandstein is up to 400 m thick in the Dutch northern offshore and consists of fining upwards, cyclic alternations of lacustrine sandstones and claystones. The formation is topped by the 5 m thick Rogenstein Member, a limestone oolite bed. Overlying the Rogenstein Member is the Main Buntsandstein subgroup. The Volpriehausen, Detfurth and Hardegsen which belong to this subgroup are fining-upward sequences with basal sandstone at the bottom and clay-siltstones at the top. These units are separated by tectonic pulses. The Volpriehausen Formation reaches thicknesses of 200 m in the Central Graben; the Detfurth Formation is approximately half as thick with thicknesses of 60-100 m. The Hardegsen Formation is up to 200 m thick in the Dutch Central Graben.

The Upper Germanic Trias overlies the Hardegsen Formation; formations contained within this group are the Solling (RNSO), Röt (RNRO), Muschelkalk (RNMU) and Keuper (RNKP) Formations. The Solling Formation is separated from the Detfurth Formation by the Hardegsen Unconformity and overlies various older deposits in the Netherlands; in the Central Graben area, it rests on the Hardegsen Formation. The Solling Formation exhibits large thickness variations because it was draped over older topography. In the Dutch northern offshore, it is up to 125 m thick and it consists of a thin basal sandstone overlain by a succession of claystones and siltstones. However, thick eolian sandstone sequences which have been deposited in small depocenters created by salt migration may occur locally, as has recently been revealed by De Jager & Geluk (2012). A <100 m thick sequence of eolian Solling sandstone is the producing reservoir for the L9-FF field. On top of the clay- and siltstones of

the Solling, an up to 300 m thick halite sequence of the Röt Formation has been deposited. This evaporite succession may have been mobilized during later times.

The Muschelkalk Formation is divided in three distinct sequences: two alternating sequences of carbonates and siliciclastic sediments separated by an evaporitic succession. The Lower Muschelkalk is up to 150 m thick in the Dutch Central Graben. The Middle Muschelkalk comprises an alternating succession of thick halite packages separated by thinner marl layers which together reach a thickness of over 100 m in the Dutch Central Graben. The Upper Muschelkalk is ~125 m thick in this area.

The topmost formation in the Triassic is the Keuper Formation. This formation is separated internally by the Early Kimmerian Unconformity and it consists of the Lower Keuper Claystone, a 200 m thick alternating sequence of claystones and thick dolomite and sandstone layers. Overlying these deposits is a thick (>400 m) succession of halite, anhydrite and claystone of the Main Keuper Evaporite, the ~100 m thick Middle Keuper Claystone and the ~100 m thick Red Keuper Evaporite. The Red Keuper Claystone is separated by the Early Kimmerian Unconformity from the Red Keuper Evaporite. Together with the Upper Keuper Claystone, these deposits covered most of the paleorelief created during the Kimmerian Unconformity.

4.5 Jurassic

During the Jurassic, three lithostratigraphic groups were deposited in the Netherlands: the argillaceous Altena Group, the continental Schieland group and the marine Scruff Group.

The Altena Group was deposited during the Early Jurassic (Hettangian-Bajonian). In the study area, the Altena Group contains the Sleen, (ATRT), Aalburg (ATAL), Posidonia (ATPO) and Werkendam (ATWD) Formations. After the Early Kimmerian extensional phase which resulted in an unconformity in the uppermost Triassic, a marine transgression took place. During this transgression, deposition of the 20-45 m thick Sleen Formation took place. After the transgression, deposition of the thick Aalburg Formation, consisting of up to 700 m of dark-grey to black claystones took place. Overlying the Aalburg is the Posidonia Shale Formation, a 30 m thick bituminous shale which was deposited during an Oceanic Anoxic Event, a period when basin stagnation caused massive preservation of organic matter. This event lasted some 5-7 million years and when the basin was well aerated again, the silty mudstones of the Werkendam were deposited.

During the Bajocian, thermal uplift in the central North Sea caused deep incision of the Altena Group in the Dutch Central Graben. The Werkendam Formation is present locally in the Central Graben; outside this area, incision was deeper and the top of the Altena Group is formed by the Aalburg Formation. The area remained a structural high of non-deposition until the Callovian when sedimentation started along the axis of the northern Dutch Central Graben. From this period onwards until the end of the Early Cretaceous, rifting took place in the Dutch Central Graben. Differential fault block movement related to oblique slip in an overall transtensional regime caused a complex pattern of changing depocenters. A high sediment input and the mobilization of thick evaporite sequences in the subsurface further complicated the paleogeographical evolution of the area.

Sedimentation in the Callovian started with the Lower Graben Formation (SLCL). The fluvial plain deposits of the Lower Graben were draped over existing relief and thus show large thickness

variations from a few metres to ~560 m. During the Oxfordian, a relative sea level rise caused a shift to a lacustrine and swamp-dominated environment in which the fine-grained Middle Graben Formation was deposited. A further sea level rise caused a marine incursion during the Late Oxfordian. South of the study area, the stacked, prograding coastal-barrier sand complex of the Upper Graben Formation (SLCU) was deposited. Going northwards, this formation grades into the marine claystones of the Kimmeridge Clay Formation (SGKI). This formation was deposited as a thick section in the Dutch Central Graben which developed into a principal depocenter during the Kimmeridgian.

During the Portlandian, a regression caused local deposition of the Scruff Greensand Formation (SGGS) in the study area. This massive, well-sorted sandstone was deposited on a shallow-marine shelf on the flanks of the Dutch Central Graben. Shoaling and reworking caused an enrichment of coarse-grained sediments. Towards deeper parts of the Dutch Central Graben, the Scruff Fm grades into finer-grained claystones of the Kimmeridge Formation. Conformably overlying the Kimmeridge and Scruff are bituminous claystones of the Clay Deep Member (SGKIC) which was only deposited in the B18 quadrant. This sequence developed after basin stagnation and it is the southernmost occurrence of the Clay Deep Member as source rock.

During the Late Jurassic, two tectonic regimes probably existed side by side in the study area: rifting and sedimentation in the Central Graben and uplift and erosion on the adjacent structural highs. Jurassic sediments have not been deposited at all in the Step Graben high; north and north-west of the Dutch Central Graben, the Jurassic sequence has been tilted and eroded. Here, a very pronounced angular unconformity with the overlying Rijnland Group developed.

4.6 Cretaceous

During the Early Cretaceous, a transgression took place across north-western Europe. Gradually, previously small, unconnected basins flooded and formed into a single basin. During this time, the Rijnland Group was deposited. This clastic sequence consists of the Vlieland Sandstone, Vlieland Claystone and Holland Formations. The Vlieland Sandstone consists of shallow-marine, fine-medium sandstones which have been deposited close to the shoreline. Intense bioturbation, winnowing and wave action have largely removed any sedimentary structures. The thickness and distribution of the Vlieland Sandstone is highly erratic because of the complex paleotopography during the Early Cretaceous. Later in the Early Cretaceous, the Vlieland Claystone Formation was deposited in a fairly deep marine environment. This sequence is slightly to strongly calcareous and the upper part of the Vlieland Claystone consists of the Vlieland Marl Member.

Outside the Central Graben, the Vlieland Claystone and Holland Formations are separated by an unconformity, showing up on seismic as truncations of the Vlieland Claystone Formation by the strong, continuous reflector of the base of the Holland Group. This unconformity may have developed during one of the regressive pulses during the Barremian during which the sea must have retreated so far that the structural highs became areas of non-deposition. The Holland Formation is a sequence with a uniform thickness of several tens of meters which contains marls and marly claystones which have been deposited in a fairly deep marine setting.

Conformably overlying the Holland Formation is the Chalk Group. This very thick sequence of limestones has been deposited throughout the North Sea and it is divided into three formations: the

Texel, Ommelanden and Ekofisk Formations. The Texel Formation comprises a <100m thick sequence of white limestones which are topped by the Plenus Marl Member, a dark-grey, calcareous, laminated, bituminous claystone several meters thick. This bituminous marl has been deposited during a period of stagnation and anoxia which is correlated with the world-wide Oceanic Anoxic Event II. Overlying the Texel Formation is the Ommelanden Formation which consists of fine-grained, sometimes argillaceous limestones. Several intraformational unconformities developed within the Ommelanden Formation; one of these is very clearly visible on seismic north of the Step Graben in block B14. Thicknesses of the Ommelanden Formation are approximately 1000 m. The Ekofisk Formation was deposited during the Danian (65-60 Ma) and was deposited under similar conditions as the Ommelanden Formation. However, locally, redeposition by gravitational mass flow near salt domes occurred. Its thickness is less than 100 meters.

During the Paleocene Laramide phase, inversion reactivated much of the Triassic and Jurassic faults. This caused deep erosion in the uplifted former basins, at some places removing all Chalk and the top of the Jurassic sequences. In the study area, inversion seems to have been minor. The Chalk Group is present everywhere and does not thin over the Central Graben. Instead, it is thinnest in places where the Late Jurassic sediments are lying the most shallow, indicating that these locations were already structural highs during Late Jurassic times.

4.7 Tertiary

During the Tertiary, the North Sea Supergroup was deposited throughout the North Sea basin. It is divided into the Lower, Middle and Upper North Sea Groups. These three groups are separated by tectonic events: the Lower and Middle North Sea Groups by the Late Eocene Pyrenean tectonic phase and the Middle and Upper North Sea Groups by the Early Miocene Savian phase. During both of these phases, uplift resulted in sub-aerial conditions during which erosion of the underlying sediments took place.

Of importance for petroleum geology is the Landen Formation, the first sediments to be deposited after the Laramide phase. It is a transgressive sequence which consists of silt- and claystones, with coarse-grained sediments being supplied from the south-east of the Netherlands (Rhenish Massif). Since it covers all of the North Sea, it may act as a top seal for any hydrocarbons trapped in the Chalk Group. Overlying the Landen Formation are intercalations of clay-, silt- and sandstones. The (near) Base Miocene Unconformity is a typically heavily fractured horizon, which is likely caused by the extreme high sediment input of the overlying Pliocene and also the onset of regional overpressure. During the Neogene, the Eridanos river complex drained part of Scandinavia, northern Germany and the Netherlands. On seismic, large fore-sets can be detected at depths of 500-1000 ms TWT. Some of the sandy packages in the Neogene contain economic gas which is either generated biogenically in situ or is thermally generated in deeper sections and migrated upwards in places where the Landen Formation is faulted.

5. Source rocks

Four possible source rocks may be present in the study area. These are:

- Namurian type II or type III oil and/or gas-prone coals and/ or shales
- Westphalian type III gas-prone coals
- Posidonia type II oil-prone shale
- Clay Deep type I/II oil-prone shale

This section will separately discuss these four source rocks. Presented source rock distributions are derived from the regional mapping which was carried out for this project. Maturities have been inferred using depth (no indications for inversion) and former analysis/ reports. In 2012, Chevron and Zetaware Inc. undertook an extensive study in which they assessed distributions, maturities, expulsion and migration of the four mentioned source rocks. Also, basin modeling was carried out by GDF in 2004 for the Amber prospect review. Source rocks which were modeled in this study are the Clay Deep Member and the Posidonia Shale Formation. A third study which has been used is the report which presents the Petroplay study, carried out in 2004 by TNO. For this project, a large-scale petroleum geology potential assessment of the pre-Westphalian in the Netherlands was carried out. Finally, I also consulted a Panterra study which was carried out in 2010. The title of this study is 'Remaining hydrocarbon prospectivity of the Dutch Central Graben'; for this study, regional mapping of Jurassic source rocks as well as basin modeling was carried out.

Before discussing the different source rocks a short section dealing with migration pathways of Carboniferous gas into the Mesozoic reservoirs will be presented. Then, the Namurian, Westphalian and Jurassic source rocks will be discussed in turn.

5.1 Migration paths for Pre-Permian charge

Gas which has been generated in Carboniferous source rocks must somehow pass through the volcanics of the Lower Rotliegend Group, the fine-grained deposits of the Silverpit Formation and the salt of the Zechstein Group in order to reach overlying reservoir intervals. The migration of this gas is thus dependent on open faults and salt windows. This section will discuss the mapping of the base and top of the Zechstein evaporites and the subsequent identification of salt windows in the study area.

Seismic sections through salt are generally difficult to interpret due to their transparent character and lack of internal layering. The large contrast in acoustic impedance between salt and clastic sediments results in a very clear reflector at the base and/or top of a salt body. In addition, so-called 'floaters', carbonate layers within a salt sequence, may show up as clear reflectors at random angles within the salt.

In some parts of the study area, identifying the top and base of the Zechstein salt is ambiguous because of the depth and the complex geometries at this level. Especially in the Central Graben, the base of the Triassic is located at ~10 km; at these depths, the quality of the seismic becomes very low (fig. 6) and confidently identifying a discontinuous reflector such as the base of the salt is very difficult. In other places such as in the vicinity of the B13-02 fault blocks, the seismic is much too discontinuous and transparent to track the top and base of the salt. This is also the case near the

Thor transform zone north of the B17 salt diapir where the north-south trending edge of the Central Graben deviates towards the north-west.

The locations where salt windows are present are shown in figure 30. Two large areas where salt has withdrawn completely are present towards the southern end of the B13 and B14 blocks. An E-W seismic section showing these salt windows is shown in figure 7. The absence of salt can be inferred from the layered blocks which are truncated by the transparent Triassic section above. In addition to these large salt windows, several smaller ones have been inferred in the Step Graben and north-west of the B14-01 well. In the center of the Dutch Central Graben, it is nearly impossible to detect anything on seismic (fig. 6). In places, the fuzzy seismic is disturbed further by steeply dipping multiples. In the Central Graben, I expect the salt has withdrawn completely and migrated into the large diapir directly to the west. A deep rim syncline with thick Chalk and Rijnland Group sediments is located in between the diapir and the graben. Both of these observations indicate that major salt withdrawal must have taken place and the very thick Mesozoic sequence in the Central Graben will probably have exerted so much pressure on the underlying salt that all of it may have migrated into the salt diapir.

However, even when salt windows are present, the Lower Rotliegend layers probably pose a barrier to gas migration. Offsets created by faulting are needed to create a flow path through these layers. Candidates are the bounding faults of the Central and Step Grabens. Overall, ample opportunity for Carboniferous gas to migrate into younger sediments seems to exist, except for the Step Graben; here, a thick salt layer probably forms a substantial barrier to gas flow.

5.2 Namurian Geverik Shale

In the Chevron source rock study, the Geverik Shale Member is discussed as a possible source rock in the AB area of the Dutch offshore. This Namurian source rock with an age of 325 Myr was deposited on the northern edge of the Variscan foredeep basin. Sediments derived from the Ringkobing-Fyn High and Caledonian uplands towards the north were deposited by meandering rivers in the northern Dutch offshore area. Relief was low, so swamps were abundant and the Geverik Member is coal-bearing. Chevron claims that this indicates that the Geverik member is more likely to be a type III gas source than a type II oil source. Basin modeling results from the same report show the Geverik in the Central Graben area to have been charging continuously since the Late Cretaceous, with a sharp increase during the Quaternary.

It is not clear whether the B17-04 well penetrates the Geverik Member. On www.nlog.nl, the latest lithostratigraphic subdivision of the well shows it to TD in the Westphalian Maurits Formation. However, a source rock study conducted by Wintershall claims that samples from these depths belong to the Namurian Geverik Member. I decided to follow the definition on www.nlog.nl; this means that the Geverik Member is not encountered in the study area.

Combined with poor imaging at these depths makes it impossible to identify the Geverik on seismic. It is probably located at depths larger than 4000 ms in the Step Graben and even deeper in other parts of the study area. Therefore, we will have to rely on the Chevron source rock study in the A blocks where it lies shallower and is easier to identify for the distribution of this source rock. The large-scale tectonic evolution during the Namurian was of gentle subsidence with occasional uplift of isolated massifs at the fringes of the foredeep, so probably, the Geverik Member is present in the north of

both the Step and Central Grabens where it was deposited near the northern edge of the Carboniferous basin. Erosion at the Base Permian Unconformity is not expected to have removed the Namurian. In the center of the Central Graben, it is located very deep (>10 km) so here, it is probably overmature. In the Step Graben though, it may still be located in the gas window (fig. 8). This is supported by basin modeling from both the Chevron and Petroplay studies. A gas show in the Buntsandstein of well B14-02 may be charged by this source rock (I did not find any evidence for this gas show outside of the Chevron report though). In the area near the B14-02 well I have identified several large salt windows through which this gas could have migrated to the Mesozoic reservoirs. Higher in the stratigraphy near the B14-02 well, shallow gas has been identified on seismic. Apart from its possible biogenic origin, this shallow gas might also be charged by the Geveik Member.

5.3 Westphalian Klaverbank & Maurits Formation

The second source rock in the AB area which was assessed in the Chevron study is the Westphalian. During the Westphalian, high sedimentation rates balanced subsidence in the Variscan foredeep. In the study area, deltaic-shallow-water sedimentation in the Westphalian A was replaced by swamp-dominated sedimentation during the Westphalian B and C. During this period, the Klaverbank and Maurits Formations were deposited as floodplain deposits with coal layers and coarser-grained channel infills. These coals are likely to be type III gas sources.

In the study area, only well B17-04 has penetrated into the Carboniferous where the top of the Maurits Formation was encountered. However, the well was drilled through 2500 m of Zechstein salt so in addition to a significant velocity pull-up, the seismic is very transparent; a seismic tie is thus very difficult to make. The base of the Zechstein can vaguely be distinguished on seismic. From here, V0 maps of the Velmod 2 project were used to calculate Rotliegend and Limburg Group seismic velocities. These velocities were then used to calculate TWT values for the well tops identified in the B17-04 well. This way, an approximate well tie to seismic could be made.

Since only one well has tested the Carboniferous section in the study area and this section is located at a depth of >4500 m in the Step Graben (>7000 m in the Central Graben), it is very difficult to assess the type and distribution of Carboniferous formations. Only in the Step Graben, a relatively confident mapping exercise can be carried out. Here, several large fault blocks can be distinguished; the upper part of these blocks shows transparent seismic sections with an occasional high-amplitude reflector (fig. 10). The top of this section seems to be eroded during the Base Permian Unconformity and the section between the base Permian and this reflector ranges in thickness from 200-500 ms.

Below this section, a pair of bright reflectors (upper = X, lower = Y) can be recognized throughout the Step Graben. These reflectors are ~200 ms TWT apart and although they show some variations in amplitude, they have been mapped with relatively high confidence in between the B17 and B16 diapirs up to the edge of the Central Graben north-west of the B17 diapir. North of this zone, the distribution of these reflectors is patchier and much less certain. East of the B17 diapir, on the western flank of the Central Graben, the presence of reflector X is inferred by flattening the seismic on the base of the Zechstein. However, this interpretation is highly speculative.

Based on the seismic character and the B17-04 well tie, reflector X and Y may be the base of the Maurits and Klaverbank Formations, respectively. The high amplitudes of these reflectors may then be caused by the high acoustic impedance contrast between coals and shales or sandstones. The

Klaverbank and Maurits Formations have been deposited during the Westphalian A, B and C as swamp deposits with occasional coarser-grained channel infills. The coal seams are only decimeters thick but can often be correlated over large distances in the Carboniferous basin. This shows how flat the basin was during the Westphalian.

Figure 9 shows the modeled maturity of the Westphalian source rocks by Chevron. Well B17-04 showed a vitrinite reflectance at the top of the Carboniferous of 1.01-1.40. North of the Step Graben, vitrinite reflectance values are likely to be much higher (>1.5%) and in the Central Graben, the Westphalian is likely to be overmature. In the Step Graben, modeling showed that the Westphalian has been generating gas since the Eocene. High sedimentation rates and rapid burial in the Plio-Pleistocene has induced a large pulse of gas generation in the last few million years.

Geochemical analyses of four samples from the Maurits Formation in the B17-04 well were conducted by Wintershall in 2001. Very high TOC values of 40-50% were found in the coal-bearing intervals; however, the Hydrogen Index is relatively low with values ranging from 88 to 111. The S1 (~0.5 mg/g) and S2 (~45 mg/g) values of the samples show that the Maurits Formation has very limited source rock potential left.

5.4 Posidonia Shale

The Posidonia Shale Formation is a ~30 m thick, bituminous shale deposited during the Toarcian. Anoxic bottom water conditions during an Oceanic Anoxic Event caused enhanced preservation of organic matter arriving at the sea floor. The Posidonia Shale is the principal oil source rock in the West Netherlands Basin (Geology of the Netherlands) and is only present here and in the Central Graben; both of these were basins during Jurassic times. The Posidonia has not been drilled in any wells in the study area; however, Posidonia Shale was encountered in well B18-01 which was drilled just north of the German border near B18-02. No well data is available so the pick of the Posidonia on seismic is not certain. I based this on a low-resolution figure from the GDF Amber prospect evaluation in which the Posidonia Shale Fm is traced from B18-01 south-west into the Dutch Central Graben (fig. 12).

I interpreted the Posidonia Shale Formation to be present only in the Central Graben; on the west flank the source rock probably pinches out underneath the Kimmerian Unconformity. It is very difficult to map out the Posidonia Shale, possibly because of its limited thickness or because it is a less pronounced reflector compared to the Posidonia Shale further south. At a depth of ~4 km, the seismic resolution away from wells is lower than the 30-m thick shale layer. It makes mapping the formation very ambiguous and this becomes clear when comparing the GDF Posidonia model with my interpretation. In the Amber prospect evaluation by GDF, the Posidonia is interpreted to be present well into the B14 block while in my interpretation, it is not present there. The Chevron source rock report shows an even larger area of Posidonia Shale than GDF, while in the Panterra study, the source rock is not present at all in the study area.

In the Panterra study 'Remaining hydrocarbon prospectivity of the Dutch Central Graben', a basin modeling effort of the Posidonia Shale has been undertaken (fig. 11). For this basin modeling, vitrinite reflectance data from six wells throughout the F quadrant were available. One of these wells is F03-01 which is penetrating the F03-FA field. The depth and VR data of this well are shown in table 3. These data show that at the location of the F3-FA field, sediments enter the oil window at depths

of ~2000 m. A map showing temperatures at well locations at a depth of 2500 m depth which is available on nlog.nl confirms these values; all wells in the study area fall in the range 85-105°C while the top of the oil window is at 60-70°C.

Based on the mentioned temperature map and the Vitrinite reflectance measurements on well F03-01, I estimated the range of the oil window at depths of 2000-4000 m. Oil generation in the Posidonia Shale Formation probably re-initiated on the structural highs since the Miocene due to the high sedimentation rates and rapid burial after the Mid-Miocene Unconformity. In the Panterra report, the basin modeling suggests that the Posidonia Shale reached maturity and generated hydrocarbons during the Latest Jurassic and Early Cretaceous in the deep parts of the Central Graben. The Chevron source rock study claims that moderate generation took place since the Early Eocene with a sharp increase since the Pliocene-Quaternary. Basin modeling conducted for the Amber prospect review by GDF-SUEZ suggests that oil generation in the Posidonia Shale ceased during the Latest Cretaceous.

Overall, there seems to be a large uncertainty in the presence and maturity of the Posidonia Shale Formation. The differences in distribution may be explained by the limited thickness of the layer and a changing seismic character, complicating the seismic mapping. A number of factors may be responsible for the differences in modeled maturity: different heat flow scenarios may be used and for each study, basin modeling methods may have differed. In addition, not all studies were conducted at the same scale. The Amber prospect review only dealt with the B quadrant, while the Chevron source rock study was conducted on the entire AB area with the exception of the B18 and the east of the B14 and B17 blocks.

Figure 13 shows the present-day maturity of the Posidonia Shale Formation based on my seismic interpretation and velocity model. Over a large part of the area, the Posidonia seems to be currently in the gas window; only on the fringes of the Central Graben is the Posidonia generating oil. In the Panterra study, the Posidonia was deemed to have no gas potential due to its being a type II source rock, but the gas present in the F3-FB field seems to disprove this claim.

5.5 Clay Deep Member

The Clay Deep Member is part of the Kimmeridge Formation and represents one of the southernmost occurrences of the Kimmeridge 'hot shale' occurrences which are described in Geology of the Netherlands (2007). In Denmark, it is the generally accepted source rocks of most of the oil fields in Denmark. In the absence of a reliable synthetic seismic section, my pick of the Clay Deep Member is based on a well tie in well B18-02 where ~130 m of Clay Deep Member has been deposited. The relatively clear negative reflector in a transparent section in figure 14 shows the pick for the SGKIC. The Clay Deep Member is present throughout the Central Graben, and extends for some distance westwards north of the B17 salt diapir (fig. 15). Two other wells have encountered the Clay Deep Member: well B14-03 (8 m) and B18-03 (55 m).

An evaluation of source rock potential in a large number of Dutch offshore wells by Wintershall (2000) included a sample from the Clay Deep Member in well B18-02. A TOC of 5.16 was found; together with a Hydrogen Index (HI) of 428, the Clay Deep in the B18 block was deemed an excellent source rock. Unfortunately, it is not mature in well B18-02; the S1 and S2 values of the analyzed sample from this well are 0.67 mg/g and 22.10 mg/g, respectively. The S1 is a measure of the volume

of hydrocarbons previously generated and the S2 represents the remaining hydrocarbon potential in the source rock. Values of 0.67 and 22.10 mg/g thus indicate that the Clay Deep Member probably just entered the oil window at this location.

Figure 14 shows the modeled vitrinite reflectance values of the Clay Deep Member. This figure is from the Amber prospect review by Gaz de France. On the flanks of the Central Graben, VR values of 0.5 are modeled, while the VR of the Clay Deep Member rises to just above 1.0 in the center of the basin. The Chevron source rock study claims the Clay Deep Member is immature in the entire Step Graben and on the flanks of the Central Graben; however, no modeling of the Central Graben itself was done in this study. In the Panterra study, the Clay Deep Member is not considered a source rock and it has not been modeled.

The modeled Clay Deep maturity from this study is shown in figure 14. Overall, the source rock seems to be more mature than in the GDF study. Calculated depths of the Clay Deep Member are roughly 2000 m on the structural highs and >5000 m in the center of the basin. The depth grids which were used by either the Chevron or Gaz de France study are not known, so it may be that the difference in maturity arises from a different velocity model. When comparing the NCP-1 project depths of for instance the base of the Schieland Group with the depth grid from this study, differences are in the order of hundreds of meters. This is a problem for the entire study area: wells have generally been drilled on structural highs so in the deeper parts of the basin, well control is lacking. In this way, obtained depth grids specifically in the deeper basins cannot be compared to actual depth data. A more detailed discussion of this issue can be found in the section 'Time-depth conversion'.

Regardless, it is obvious that the maturity of the Clay Deep Member and the top of the oil window in the study area are by no means certain; the different reports show a large range in maturity and timing of generation, but if the Clay Deep Member has such excellent TOC and HI values in the entire study area, it seems likely that somewhere along the flank of the Central Graben it is mature.

6. Chalk Play

1. Introduction

The Chalk play consists of Late Cretaceous Chalk reservoir sealed by either Tertiary shales or intraformationally sealed by tight chalk. This Chalk group consists of a succession of marine, bioclastic limestones, which are occasionally marly. In some parts of the Central Graben, the Chalk has been eroded to some degree due to Early Tertiary inversion. It is difficult to detect any such phenomenon in the study area, though. The chalk thickness is highly variable showing the strong differences in relief at time of deposition. The Chalk Group consists of three formations: the Texel, Ommelanden and Ekofisk Formation. Any of these may act as a reservoir; only three chalk fields have thus far been discovered in the Netherlands. These are the onshore Harlingen gas field, the Hanze oil field and the recently discovered F17-10 oil field.

The Harlingen field was discovered in 1982 and contains gas in the top of the Ommelanden Formation in a structural trap configuration. The top of the Chalk in the Harlingen area has been eroded during the Early Tertiary inversion phase and is unconformably overlain by the sealing Paleocene Landen Formation. Porosities in the Harlingen field are abnormally high at porosities of ~40%. Causes for this may be the early filling of the reservoir which preserved porosities as the chalk was buried and leaching during the time when the chalk was exposed to the atmosphere.

Both the F17-10 and Hanze fields are situated on top of a salt diapir and contain hydrocarbons in the faulted and fractured Ekofisk Formation. The Hanze structure has a hydrocarbon column of 118 m and is probably charged by fill and spill from the F3-FB field. The source rock for both fields is the Posidonia Shale Formation. Basin modeling shows that the source rock generated oil during the Early Cretaceous in the Central Graben. On the flanks of the Central Graben, the Posidonia Fm also generated oil during the Tertiary. In deeper parts gas generation also started filling up the F3-FB field.

6.2 Reservoir

The Chalk Play is an unconventional play in the sense that reservoir characteristics are less laterally continuous than in sandstone reservoirs. Porosities are usually fairly high in chalk (especially in the Paleocene Ekofisk Formation) but very often, permeabilities are extremely low. Three processes may improve reservoir characteristics in chalk: reworking of the chalk via mass movements at the sea floor, leaching and/or weathering of lithified chalk and faulting/fracturing of the chalk. The latter process has created good reservoir sections in both the Hanze and the F17-10 field. Leaching and weathering have locally enhanced porosities and mainly permeabilities in the Amber prospect which has been tested by the B18-06 well. The Amber prospect is a stratigraphic trap within the chalk. These traps are difficult to track because they are not always present on structural highs (unlike sand reservoirs). The third process leading to enhanced chalk reservoir properties, redeposition of chalk, has not been proven in the Netherlands and it remains to be seen whether this concept is viable in the area. It has proven successful in the Danish Half-Dan field.

6.3 Seal

I assume the Early Tertiary Landen Formation to be the seal to all Chalk structures. The F2-A-Hanze and F17-10 fields prove the top sealing capacity of this formation. It is debatable whether the Landen Formation is an effective seal for gas, since both fields show overlying gas accumulations in the Upper Tertiary and have found very low gas-oil ratios in the oil field (i.e. gas may have leaked out). In addition, a relatively large number of bright spots and chimneys in the Tertiary can be observed in the study area, hinting at gas leakage from below. The lower part of the Landen Formation consists of claystones and is present throughout the North Sea.

6.4 Source rock & migration

An overview of the different source rocks and their maturities is given in section 'Source rocks'. This section will discuss the migration pathways into the chalk. Since the Posidonia and Clay Deep are only present and mature in the Central Graben, respectively, only Chalk structures adjacent to the Central Graben are expected to be susceptible to charge from the Jurassic section. Migration paths from Posidonia-charged oil would run through Lower Graben Fm sandstones upward along the flanks of the Central Graben. In order to reach the Ekofisk Formation from there, oil would have to travel through fractured or faulted sections. Unfortunately, there seems to be little evidence of any faulted chalk sections in the study area. Figure 16 shows the different major faults which are offsetting the chalk. Of course, sub-seismic fractures cannot be accounted for and seismic imaging along the steep salt diapirs is not optimal. Another potential problem in migration routes into the chalk are the presence of Clay Deep Member and Vlieland Claystone Formation. Both of these have been proven to be effective seals in the F3-FA field and may provide a barrier to migrating oil or gas.

6.5 Drilled structures

Nine wells have penetrated the chalk in the study area. A number of chalk structures have already been tested by these wells. Dry hole post-mortems will be shortly discussed in this section:

- B18-03: This well has been drilled in the B18-FA field so the focus was not on the chalk section. The absence of hydrocarbons in the chalk which was tested within closure is likely the apparent good sealing capacity of the Clay Deep Member which is the top seal of the B18-FA field (Scruff Greensand Formation).
- B18-06: The well found the Amber prospect to be dry. The prospect concept was based on an amplitude anomaly possibly related to enhanced porosities and permeabilities. A possible cause for the dry hole is the inability of hydrocarbons to migrate through thick chalk towards the top of the Ommelanden Formation, where the reservoir is located. In addition charge may have been focused away from this prospect already in the Jurassic, if hydrocarbons preferentially migrating updip through Jurassic sands would then migrate straight upwards through thick Jurassic shales and tight chalk.
- B18-02: This well failed to prove hydrocarbon presence in the Chalk because of very low permeabilities in the Chalk which was drilled by the well, even though porosity was relatively high (25%). Thus, no reservoir is present and any hydrocarbons probably would not be able to migrate through the tight Chalk. The well does penetrate a structural high of both the top and base of the Chalk so it is probable that migrating hydrocarbons from Jurassic source rocks in the Central Graben were focused on this high.
- B14-01: Similar to well B18-02, permeabilities in the Chalk are extremely low while porosities are high. No indications for fracturing are found; the migration route for Jurassic source rocks

in the Central Graben is likely to be long and tortuous. If the Clay Deep Member is mature in the smaller basins north-west of the Central Graben, migration would be less difficult.

- B13-02: The lack of oil or gas shows in this block seems enigmatic. A pronounced chimney is visible in the North Sea Supergroup above the B13-02 well which hints at the presence of hydrocarbons. The well did not encounter any hydrocarbons in the Tertiary section, though. If there is gas in the B13-02 structure, it probably originated in Carboniferous source rocks since the Clay Deep Member and Posidonia Shale Formation are both only gas-mature in the Central Graben. In addition, oil from the Clay Deep Member might have migrated to the B13-02 block.
- B14-02: Idem to B13-02
- B17-02: In the Step Graben, no Jurassic source rocks are present. Charge in the Chalk would have to rely on migration from Carboniferous source rocks through the Zechstein and Triassic sequences. No hydrocarbons were encountered in the Chalk. The reason for this is probably a lack of charge, since the Chalk does not appear to be fractured in the Step Graben and there is a thick underlying Triassic section with a lot of fine-grained layers which probably form a barrier to migration
- B17-03: The only well which has an oil show in the Chalk is located on top of the B17 salt diapir. The source rock for this oil is most probably the Posidonia Shale in the Central Graben towards the east. Charge would have migrated upward along the western flank of the Central Graben and have continued on the east flank of the salt diapir. The Chalk on top of the piercement has been fractured which is the most probable cause for the good reservoir characteristics in the Chalk. In this way, it is similar to the F2-A-Hanze field which is also positioned on top of a diapir in a section of fractured chalk. I cannot find information about whether a drill stem test has been conducted. As far as I know, no hydrocarbons have been produced from the Chalk section of the B17 diapir. Several wells did encounter shallow gas at depths of 400-1000 m

6.6 Remaining prospectivity

In figure 1, outlines of top Chalk structures are shown. A number of structures have already been tested but some prospectivity may remain. Wells B14-01 and B17-02 penetrated the top of the Chalk structures, thereby eliminating any chances of hydrocarbon presence higher up in the trap. Wells B13-02, B18-02 and B18-03 did penetrate large structural closures, but failed to test the top of the structures. The tops were typically located up to a hundred meters higher up in the structure. These invalid tests thus leave some chance of remaining prospectivity in the structures. Finally, there are some structural closures which have not been tested at all yet. These will be discussed below.

- The Aventurine lead: a four-way dip closure north-west of the B14-01 well which has an area of 17.5 Mln m² and a maximum closure height of 61 m. Chances of finding hydrocarbons in this structure are probably low since any charge would probably have passed via the saddle point in between this structural closure and the B14-01 structure which was dry. Furthermore, there is no mature source rock underlying this region.
- The Amethyst lead: overlying the salt wall in the B16 quadrant is a chalk section with a structural closure. However, since this structure is located on the western edge of the Entenschnabel survey, it is difficult to assess generation and migration of hydrocarbons into this reservoir. Still, it is very unlikely that any Jurassic source rocks are present west and south of the diapir since the Jurassic section is only present in the Central Graben towards the east. Above the diapir, shallow gas can be detected on seismic. This is probably charged from Carboniferous source rocks in the Step Graben. The gas probably migrated along the normal fault on the east side of the B16 diapir.
- The Agate lead (fig 17): north-west of the B17 salt diapir, an amplitude anomaly is visible below the top of the Chalk. Locally, a brightening of the positive reflector can be seen.

However, since the acoustic impedance of chalk is higher than the overlying shales, the presence of hydrocarbons would cause a dimming of the reflector by lowering the impedance contrast. Thus, a brightening probably indicates an increase in acoustic impedance and may be related to a chert layer or a zone of extra tight chalk. The reservoir quality is thus highly dubious. The presence of mature source rocks is proven by shallow gas, though

- The Aquamarine lead (fig. 17): south-east of the B17 diapir, a steep, structural closure of the chalk may be present underneath the Landen Formation. Similar to the Agate lead, hydrocarbons have been generated in the adjacent Central Graben and are proven to be present by the occurrence of shallow gas in the vicinity.
- The block west of the B13-02 fault block with a closure against the N-S trending normal fault of this block has not been tested. The structure has an area of $\sim 20 \text{ Mln m}^2$ and the maximum closure height is 180 m. In order for this structure to be successful, charge must have come from the north or west. Further towards the north (into Germany) Clay Deep may be present and mature. The Carboniferous (Namurian) charge potential has not been evaluated.

Overall, the main risks for Chalk prospects in the study area are:

- 1) Lack of charge; the Clay Deep Member may be mature only in the Central Graben and the Posidonia Shale Fm is mature everywhere, but not present in blocks B14 and B17. Basin modeling based on the new depth maps would be able to resolve maturities for the Clay Deep Member. In case the SGKIC is only mature in the Central Graben, only adjacent structures are expected to be connected to a mature source rock. Of these structures, most have proven to be dry except for the B17-03 well which is located on top of the B17 diapir. In case the SGKIC is mature outside of the Central Graben, most structures may be connected to a direct migration route. Carboniferous charge has not been evaluated.
- 2) Lack of good reservoir qualities; although almost all wells in the study area drilled through the Chalk section, only a few report reservoir characteristics. Chalk was often not a target of the well so extensive logging data may be absent. Wells B17-01, B18-02 and B14-01 drilled through Chalk with good porosities but found very low permeabilities. No K measurements have been taken though, so the chalk in these wells is estimated to be tight. The only wells which encountered a good reservoir in the Chalk are B18-06 which was drilled on the Amber prospect and well B17-03 which was drilled in a section of fractured chalk on top of the B17 diapir. Regarding the Amber prospect, an amplitude anomaly suggested locally enhanced porosities. A number of different RMS extractions directly below the top of the Chalk did not show any conformity to structural highs in the study area. Therefore, I do not expect the untested structures to show improved reservoir characteristics in the Chalk. Sections with good reservoir characteristics may occur within the chalk (i.e. Amber prospect), however, they are very difficult to identify. In order to do this correctly and throughout the chalk section in the whole study area, a large number of horizons would need to be tracked within the chalk. This is not the focus of this study so I have not investigated this in more detail. Currently, a detailed mapping exercise within the chalk of the B blocks is being carried out at TNO.
- 3) Lack of migration paths; as shown in the Amber prospect, migration towards the top of the Chalk may present an additional problem. The F3-B18 field shows there are excellent seals in between the Lower Jurassic and the Upper Cretaceous. Assuming charge would

reach the Rijnland or Schieland Groups which directly underlie the Chalk on top of the flanks of the Central Graben, the hydrocarbons must still migrate upwards through the chalk for several hundreds of meters. However, most of the wells in the study area have shown the Chalk to be very tight which may prevent oil or gas from reaching the sections with good reservoir characteristics. Also, the Vlieland Claystone Formation and Clay Deep Member which are extensively present near the Central Graben may prove to be barriers to hydrocarbon migration.

6.7 Amber prospect

Well B18-06, located in the Central Graben, was drilled by GDF in order to test the Amber prospect. This prospect consists of a stratigraphic trap of the Ommelanden Formation underneath the unconformity with the overlying Ekofisk Formation. This trap is located on the eastern flank of the Central Graben. The prospect is related to an amplitude anomaly (fig. 19) which seems to match enhanced porosities in the Ommelanden Formation. Weathering and leaching are proposed as the main mechanisms behind these high porosities. From impedance-porosity crossplots of 16 wells in the area, pre-drill porosities of 40-45% were derived; these porosities were confirmed by the well data.

There may be two source rocks responsible for charge into the Amber prospect. One of these is the Early Jurassic Posidonia Shale Formation. This has been buried deeply in the Central Graben area and is only present on the eastern flank. The Posidonia ceased generating oil during the Late Cretaceous and has been generating gas since the Early Tertiary. Any generated HC's would have to migrate westwards along the western flank of the Central Graben to reach the structural high just east of the B17 salt diapir. From there, sub-seismic fractures in the lower section of the Chalk would be required for the HC's to migrate upwards and at the top of the Ommelanden Formation, the gas would have to travel eastwards towards the stratigraphic trap. The migration route is shown in figure 18.

Another possible source rock is the Clay Deep Member. This source rock may have been generating oil since the Late Tertiary only in the deeper parts of the basin. The proposed migration path for the oil is along the western flank of the Central Graben towards aforementioned structural high and from there it would migrate along the same pathway as the gas generated from the Posidonia Shale Formation.

The pre-drill POS of the prospect was estimated at 8.5% (mainly due to the uncertainty of the charge) and unsurprisingly, the well proved dry even though a good reservoir was encountered. Probably, this is because of the absence of sub-seismic fractures in the chalk of the rim syncline just east of the B17 diapir. This would hamper the vertical migration through the Chalk, preventing hydrocarbons from reaching the prospect. This is supported by the lack of shows: if a seal failure would be responsible for the dry well, some gas or oil shows would be expected. An additional cause for the failure of the prospect could be that gas from the Posidonia Shale Formation failed to make it through the thick Jurassic shale section in the western flank of the Central Graben. The Clay Deep or Early Cretaceous Vlieland Shale may have been responsible for this.

7. Vlieland Sandstone play

7.1 Introduction

The Vlieland subgroup (KNN) contains the Vlieland Claystone Formation (KNNC) and the Vlieland Sandstone Formation (KNNS). It is an Early Cretaceous sequence which is part of the Rijnland Group (KN). This reservoir/seal pair forms the Vlieland Sandstone play. Source rocks for this play may be the Clay Deep Member, Posidonia Shale Formation and possibly deeper, Carboniferous source rocks. Oil fields with a Vlieland Sandstone reservoir are the Helm, Helder, Hoorn, Kotter and Logger fields.

The base of the Vlieland subgroup is visible on seismic as a very bright positive reflector, often unconformably overlying older deposits of Triassic or Jurassic age. However, the Rijnland Group is very thin in many parts of the study area so it often is difficult to pick away from well control. Because the Holland Formation unconformably overlies the Vlieland subgroup (fig. 20), the top of the latter is relatively easy to pick in areas where the Rijnland Group is thickly developed. Outside these areas, it is very difficult to distinguish the two subgroups. Based on the fact that the Holland subgroup signifies the start large, continuous transgression, I think this formation has a more or less uniform thickness throughout the study area. I have thus picked it on the bright negative reflector directly underlying the base of the Chalk; the layer which varies in thickness below this horizon is interpreted as the Vlieland subgroup. This makes sense since the sediments of the lower Rijnland Group were draped over the existing relief which was created during the tectonically active Late Jurassic.

7.2 Well correlation

Only three wells have encountered the Vlieland subgroup: wells B17-02, B18-02 and B18-03 (fig. 21). No Vlieland sandstone is present according to nlog.nl, but inspecting the GR logs, both the B18-02 and B18-03 wells show a ~5 m thick sand body at the base of the Vlieland subgroup. This thin zone may be interpreted as Vlieland Sandstone. Even though GR readings are very low in the Vlieland subgroup of the B17-02 well, the section is entirely argillaceous. The low GR readings are probably related to relatively high calcium carbonate contents in the claystone.

7.3 Reservoir

The Vlieland Sandstone Formation in the Central Graben area contains one possible reservoir: the Friesland Member which comprises progradational shoreline sandstones interbedded with restricted marine mudstones. This depositional setting causes the sandstones to form elongated, shore-parallel sand bodies which may be separated by mudstones, deposited during sea level highstands.

An anomalous, bright reflector is present at the base of the Vlieland subgroup in well B18-02. By performing an amplitude extraction on this reflector, I have tried to map the extent of this amplitude anomaly. The results are shown in figure 22; though the results of the amplitude extraction are ambiguous, this anomaly seems to be present in the area between wells B18-02, B18-06 and B18-03 and may represent a basal sandbody such as the one identified on the well logs of the B18-02 and B18-03 wells.

In other parts of the study area, the Friesland Member may also be present. This is difficult to assess because of poor well control, but the depositional model of the Friesland Member may provide a

clue to where the sandstone facies of the Vlieland subgroup could be expected. Because the sandstones of the Vlieland subgroup were the first sediments to be deposited after the Late Jurassic thermal doming event and their depositional environment was coastal, they may be expected in areas that were near structural highs during the Early Cretaceous.

7.4 Seal

The Vlieland Claystone Formation is the top seal of the Vlieland Sandstone play. The sealing effectiveness of the formation is unproven as there are no fields in or near the study area where it acts as a top seal. The F3-FA field is probably sealed by the SGKI and SGKIC. Additionally, pressure information of the F3-FA field suggests that the Chalk is sealing; in this case, the F3-FA field would be significantly underfilled because the closure by the Chalk seal is much greater. The other nearby fields F2-A-Hanze, B13-FA and B16-FA contain hydrocarbons in stratigraphically and structurally younger formations and have no relation to the sealing capacity of the Vlieland Shale. Further south, in the P blocks, the Vlieland Claystone Formation is an effective top seal for both oil and gas.

Despite the fact that the KNNC is not a proven sealing formation in nearby fields, it has potential to act as a top seal in the B14/17/18 blocks. In the B14 block, it directly overlies Jurassic sediments of the Schieland and Scruff Groups above an angular unconformity. If there are sandstones within these sequences which have had access to hydrocarbons, unconformity traps thus created may be sealed by the KNNC. Alternatively, the KNNC may be a top seal for Scruff sands which are not effectively sealed by the Clay Deep Member.

Based on the well logs, the Vlieland Claystone seems to have good sealing capacities. The KNNC has a thickness of only 14 m in well B17-02 but is made up of pure claystone. Uncertainty arises from the low GR readings in the log though; this could be explained by high calcium carbonate contents but no mention of this is made in the composite well log. If calcium carbonate would be present, this might detriment sealing capacities. In wells B18-02 and B18-03, the KNNC is much thicker: 45 m and 84 m, respectively. Here, it consists of a fining-upwards sequence of silt-claystones with a thin sand body at the base. Overlying this sequence in well B18-02 is the Vlieland Marl Member, a fining-upwards sequence with a thickness of ~80 m. It is unclear how far the KNNC continues westwards because of the transparent seismic and the highly faulted Jurassic-Cretaceous section near well B18-02. In wells B17-02 and B18-03, the KNNC is overlain by sediments from the Holland Group.

Overall, I think the effectiveness of the Vlieland Claystone Formation as top seal will be very limited due to the following reasons:

- A number of large faults run through the KNNC in the east of block B18; if it is not known whether these faults are sealing. Shale- shale juxtaposition is required to create sealing across these faults, this is not unlikely based on the limited sandpackages in the KNNC. Shale smearing is another possibility, also very possible seeing the amount of shale in the section.
- Thin KNNC in combination with fault offsets can pose a risk for the sealing capacity. In areas of thin KNNC, top seal effectiveness is a larger risk than in areas with thick KNNC.
- Calcareous sections in the KNNC instead of high GR shales might detriment sealing capacity

7.5 Source rock and migration

There are a number of potential source rocks which may charge the Vlieland Sandstone Formation (if it is present in the study area). These are the Clay Deep Member, Posidonia Shale Formation and possibly older, Carboniferous source rocks. Based on basin modeling done by Panterra (see chapter 'source rocks') and assuming no inversion has taken place, I have inferred the top of the oil window to be located at a depth of 3000 m. Locations where the Clay Deep Member and Posidonia Shale Formation are below this depth are shown in figure 23. In the sandy facies of the Vlieland Sandstone Formation which may fringe the Central Graben, migration of generated hydrocarbons may be relatively straightforward, as the Clay Deep Member directly underlies the Vlieland Sandstone Formation. In addition, the Posidonia Shale Formation is mature in this area, adding further options for hydrocarbon migration into Vlieland Sandstone reservoirs. Further towards the west, the Clay Deep Member may be oil mature in the small depocenters; oil generated here may have migrated towards the crests of the structural highs bordering these mini-basins and entered the Vlieland Sandstone which might be present here.

7.6 Drilled structures

Of the three wells which have encountered the Vlieland subgroup, only two have found a thin sandstone interval. In wells B18-02 and B18-03, a thin sand body is present at the base of the sequence, but at both locations, the well tested a valid closure at this level and the reservoir proved to be dry. Well B17-02 shows a very shaly facies which I do not expect to change towards the Step Graben, since the Rijnland Group as well as the underlying Triassic sediments have a very uniform thickness, indicating that no major tectonic movements took place during the deposition of these sediments.

7.7 Remaining prospectivity

Any further prospectivity of the Vlieland Sandstone play is completely dependent on the inferred presence of Vlieland Sandstone in the study area. The Vlieland Sandstone Formation has been shown to possess excellent reservoir qualities ($\phi = 0.17-0.26$, $N/G = 0.80$) elsewhere in the Dutch offshore. If the structural highs in the north-western part of the study area were indeed fringed by beach sands during the Early Cretaceous, the Vlieland Sandstone might be present here. Assuming this is the case, I have identified three leads:

- 1) The Bloodstone lead; this four-way dip closure just south-east of the B13-02 well is bounded towards the north-west by a large normal fault. The presence of sediments from the Rijnland Group is by no means certain; if they are present, there is a chance that the sandy facies of the Vlieland subgroup is present. The structural high lies adjacent to a small depocenter where the Clay Deep Member may be early oil mature; additionally, the presence of shallow gas may hint at mature Carboniferous source rocks in the area.
- 2) The Bauxite lead; this small four-way dip closure south-east of the Bloodstone lead may contain coarse-grained sediments of the Vlieland subgroup. Charge may have come two adjacent depocenters where the Clay Deep Member may be early oil mature. Additionally, gas may have originated in deeper, Carboniferous source rocks.

- 3) The Beryl lead; a pinch-out trap underneath the Holland Formation at the northern edge of the B17 salt diapir. It lies adjacent to the Central Graben so charge should pose no large problems; the presence of hydrocarbons is proven by the occurrence of shallow gas in the sequences overlying the diapir. Sealing layer may be the shaly facies of the Vlieland subgroup or the Holland Group.

8. Scruff Play

8.1 Introduction

The Scruff play is located in the Late Jurassic Scruff Greensand Formation which consists of glauconitic sandstones deposited in a shallow marine setting. Hydrocarbons trapped in the Scruff are probably generated from the Posidonia Shale Formation or Carboniferous source rocks below the Zechstein evaporites. The top seal for the play is the Clay Deep Member and possibly the Vlieland Claystone Formation.

One oil and gas field with a Scruff reservoir is located within the study area. The F3-FA field is a salt-cored, domal structure which is dissected by a large, NNE-SSW fault zone. This field contains gas and oil in the Lower Graben and Scruff Greensand Formations. A detailed field description can be found in appendix 3.

8.2 Well correlation

A number of wells have encountered the Scruff Greensand Formation in the study area: wells B13-02, B14-02, B14-03 and B18-03. In addition, wells F03-01 and F03-08 have encountered gas-bearing SGGs intervals. A well correlation is shown in figure 24. In wells F03-08, F03-01, B18-03 and B14-03, the SGGs is overlain by fine-grained sediments of the Clay Deep Member and Vlieland subgroup. In the west of the B quadrant, the Clay Deep Member and Early Cretaceous section are absent, probably due to erosion and inversion; this is clearly visible in angular unconformity between the Scruff and Chalk Groups in the east of the B14 block. Here, the Scruff sands are directly overlain by the Late Cretaceous Chalk Group.

8.3 Reservoir

In a re-evaluation of the F3-FA field by EBN (2005), the reservoir geology of the Scruff Greensand encountered in wells B18-03, F03-01 and F03-08 is described in great detail. It is a shallow marine sandstone reservoir with extremely abundant sponge spiculae. The formation was deposited in a shallow marine, starved environment, indicated by the abundance of glauconite particles in the sediment. Evidence for relative sea level changes during deposition of the Scruff Greensands comes from thin sandstone beds. These are interpreted as minor storm beds, most likely deposited in between storm and fair weather wavebases. The spiculae in the Scruff Greensand Formation were produced as sponges in a lower shoreface setting. Backwash shelf currents carried the sponge particles towards deeper waters. Figure 25 shows a schematic overview of the depositional setting of the Scruff.

Three coarsening-upwards para-sequences have been observed in the F3-FA field wells. These are bounded by laterally extensive shales or flooding surfaces, reflecting increases in relative sea level. The abundance of spiculae in the Scruff Greensands is a critical factor controlling the porosity of the reservoir. Even small relative sea level changes will probably cause a significant lateral shift in depositional environment and as a result, the reservoir characteristics of the Scruff may vary very locally. Because the reservoir was deposited in elongated bands parallel to the paleo-shoreline, it laterally shales out into the Kimmeridge Clay Formation towards deeper parts of the paleo-basin.

This is illustrated by well B18-02; here, a thick package of Kimmeridge Clay (proven by two biostratigraphy reports) is directly overlain by the Clay Deep Member. When tracking the base Scruff horizon from well B18-03 to B18-02, the Scruff Greensand Formation should be present in well B18-02, though. This observation fits with the depositional model for the Scruff. Apparently, no structural high was present near the well location during the Volgian. However, the B18-02 exploration well was drilled on a domal structure. When looking deeper in the seismic, it becomes apparent that the dome is situated above a salt swell which only became active after the Volgian. Thus, during deposition of the Scruff Greensand Formation, the area was located deep in the basin. Somewhere in between well B18-02 and B18-03 (and B14-03 towards the west), the Scruff Greensands shale out into the Kimmeridge Clay Formation.

A different way of assessing the extent of the Scruff sand facies in the study area may be by investigating where erosion was taking place during deposition of the Scruff. During the Volgian, blocks B13 and B14 were structural highs; the erosion which took place here provided the material which makes up the coarse-grained Scruff Greensands in this area. Further east towards the Central Graben, apparently, no structural highs were present during the Volgian and the time-equivalent Kimmeridge Clay was deposited (Roel Verreussel, personal communication). The coarse-grained Scruff which has been encountered in well B18-03 indicates that erosion probably took place somewhere in the F03 quadrant. The area where the Scruff is expected to be shaly and of low reservoir quality is shaded in the Scruff play map (fig. 26).

The highly complex tectonic evolution of the Dutch Central Graben area during the Late Jurassic is highlighted by the highly variable thickness variations in the Upper Jurassic section. One of the clearest examples of this is seen in the B13-02 fault block. In the B13-02 well, an anomalously thick (175 m) section of Scruff Greensand has been encountered directly beneath the Chalk. These sands were probably deposited in a small (~4x3 km) depocenter which developed as a result of faulting. These faults may be related to salt movement in the Zechstein section which (probably) lies directly beneath the Upper Jurassic sediments.

8.4 Seal

The principal seal of the Scruff play is the Clay Deep Member. This bituminous shale sequence has been deposited directly on top of the Scruff sands. The formation has been encountered in wells B14-03, B18-02 and B18-03. In addition, a ~50 m thick section of Clay Deep Member is present in wells F03-01 and F03-08, where they probably form the seal of the gas contained in the Scruff Greensand Formation. The excellent sealing capacity of the Clay Deep Member has been proven in field F15-A; here, gas is contained in Solling and Scruff sands under very high pressures of ~650 bar. In the B18 quadrant, the Clay Deep Member is present everywhere the Scruff Greensand Formation

is present except for one important exception. On the south flank of the inverted structural high near wells B14-01 and B14-03, the Upper Jurassic section is strongly tilted. As a consequence, the Scruff Greensand terminates a small distance from the Clay Deep along the flank. Here, the sands are directly overlain by the Chalk. Any hydrocarbons which would have migrated upwards through the Scruff on this flank would be dependent on the Chalk as top seal which is considered to be riskier.

In the area near wells B13-02 and B14-02, no Clay Deep Member has probably been deposited. The Scruff Greensand Formation is here also directly overlain by the Chalk. Even though measurements in the F3-FA field demonstrate that the Chalk could be an effective top seal, this is probably not the case in this area because of the presence of very large faults which run through the entire stratigraphy.

8.5 Drilled structures

Figure 26 is the constructed play map for the Scruff, showing the depth of the base of the Scruff, faults and the tested and untested structures. The area which I expect to be shaly and of low reservoir quality is shaded in grey (see 'reservoir' section).

The following structures have been tested:

- B14-02; this well proved dry in the 60 m thick Scruff interval. A problem is the lack of a top seal: the Scruff sands are directly overlain by Chalk which might very well be heavily fractured since the well has been drilled in between two very large faults. The most probable cause for the lack of hydrocarbons in the Scruff section of the B14-02 well is a lack of charge, though. Migration pathways from the Posidonia Shale which is located far towards the south-east may be problematic. Alternatively, charge may have come from Carboniferous source rocks more directly underlying the B14-02 well or the Posidonia Shale Formation which may be present and mature in the German subsurface towards the north-east. Still, one would expect to have at least an oil or gas show if this were the case and if the structure proved dry due to an ineffective Chalk top seal.
- B13-02; idem to B14-02
- B14-03; this well has been drilled on a tilted section of Schieland Group sediments which are separated from the overlying Chalk by an angular unconformity. The well proved dry; however, there is significant updip potential of ~160 m. It is thus questionable whether this well was a valid test. The section is located favorably with respect to mature Posidonia Shale in the Central Graben; however, the timing of the oil generation of the Posidonia is critical. Probably, the Posidonia ceased generation hydrocarbons during the Late Cretaceous. The thinning of the Chalk on top of the high indicated that during the Late Cretaceous, this was already a structural high so hydrocarbons which may have been generated by the Posidonia Shale might have migrated towards the stratigraphic trap. The top seal of the Scruff is Chalk however, which may very well be a problem because the Chalk is not an effective seal.
- B18-02; this well has been drilled on a structural high which came into existence only during the Cretaceous. Therefore, the Scruff is not present here but the time-equivalent shales of the Kimmeridge Clay Formation have been deposited here. Thus, this structural high probably does not contain any good quality reservoir rocks in the Scruff interval.

- B18-03; this well is located within the F3-FA field and ~1 km towards the south, gas is contained within the Scruff of the F03-01 and F03-08 wells on the upthrown side of a normal fault. In the B18-03 well no hydrocarbons are present in the Scruff though. This field clearly illustrates that there is potential in the Scruff; hydrocarbons probably originated from the Posidonia Shale formation in the F3 block, but may also have been generated from Posidonia Shale in the B18 quadrant. Gas in the Scruff in the F wells is probably trapped by the Clay Deep Member, so the effectiveness of this claystone is proven. However, there is no updip potential in the B18-03 structure.

8.6 Remaining prospectivity

All Scruff structures except for two have been tested in the study area. However, three of the structures have significant updip potential: 160 m in well B14-03, 280 m in well B13-02 and 300 m in well B14-02. A gas chimney is visible above the B13-02 field so there must be hydrocarbons present somewhere in the subsurface. The Scruff updip of the B13-02 well would be an excellent candidate for this gas; the alternative is gas which is contained within the Chalk. At the same time, the fact that a chimney is visible indicates that the top seal is leaking. This may be a fractured Chalk section above the Scruff Greensands. Elsewhere in the study area, there is very little potential; two structures have not been tested yet.

These structures are located just north of the B17 diapir. One of the structures is a four-way dip closure which is probably related to tectonic movements in the Thor transform zone; the other structure is located on a northwards dipping section and is bounded by the B17 diapir on the southern side. Both structures are overlain by a thick Clay Deep section so an effective top seal should be present. Migration of any hydrocarbons may have come from the Posidonia Shale Formation in the east along the western flank of the Central Graben. However, there may be a problem with the reservoir quality because of the shaling-out effect in the Scruff Greensands towards the center of the basin. It may very well be that there is no Scruff sandstone present at the location of these structures and that instead, time-equivalent claystones of the Kimmeridge Clay have been deposited.

9. Lower Graben play

9.1 Introduction

The Lower Graben play is the second Jurassic play in the Dutch offshore. Reservoir for this play is the Lower Graben Formation which consists of fluvial sands and finer-grained floodplain deposits which have been deposited during the Middle-Late Callovian. Hydrocarbons probably originated from the Posidonia Formation below the reservoir interval and/or from older, Carboniferous source rocks. The top seal is the Kimmeridge Clay which attains thicknesses of hundreds of meters in the Dutch Central Graben. Structural as well as stratigraphic traps may exist in the study area in the Lower Graben Formation. One oil and gas field with a Lower Graben reservoir is located within the study area: the F3-FA field. A detailed description of this field is given in appendix 3, so here, it suffices to state that gas of uncertain origin is contained in the Lower Graben sandstones in wells F03-01 and F03-08 and an oil-bearing Lower Graben section has been encountered in well B18-03. The source rock for this oil is probably the Posidonia Shale Fm in block F3, B18 or the German Entenschnabel as the other oil prone source rock the Clay Deep Member is located hundreds of meters shallower than the Lower Graben Formation. Any Carboniferous source rocks probably are been overmature for oil . They may possibly have generated gas.

9.2 Well correlation

In the study area, only two wells have encountered the Lower Graben Formation: well B14-01 and B18-03. Other wells have not encountered the formation because it was eroded or not deposited in the first place (B14-03, B17-02, B13-02) or because they did not penetrate that deep (B18-02, B18-06). In well B14-02, 39 m of Middle Graben Formation silt- and claystones have been drilled but because of the very bad quality of the seismic near this well, it could not be established whether any Lower Graben sands may be present in the vicinity.

9.3 Reservoir

The Lower Graben Formation consists of a sequence of sandstones interbedded with silt- and claystones which are very locally calcareous. The Lower Graben Formation was deposited during the Callovian when sedimentation re-initiated after the thermal uplift during the Middle Jurassic. Extensional rifting first created accommodation space along the center of the rift, so the Lower Graben clastics are limited to the Dutch Central Graben area. The Lower Graben Formation has been deposited in a fluvial plain setting which blanketed the existing relief as subsidence continued. The reservoir is probably compartmentalized; coarse-grained channel infills are separated by finer-grained floodplain deposits. The channel infills have a highly asymmetrical geometry; they are probably elongated along the axis of the Dutch Central Graben because this was the drainage direction at the time of deposition. Because of the presence of isolated sand bodies in a silt-claystone matrix, there probably is potential for stratigraphic traps in the Lower Graben Formation.

The Lower Graben play concept is discussed in Abbink et al. (2006) where a new subdivision of the Upper Jurassic stratigraphy is introduced. Figure 29 sums up the most important play elements: the Posidonia Shale source rock charges into the isolated sand bodies of the Lower Graben Formation which are sealed by intraformational seals and the Kimmeridge Clay overlying the whole sequence. However, Abbink et al. seem to assume that subsidence was strongest in the center of the graben.

This is not necessarily the case, since often, extension occurs along one or several half-grabens where only one flank is tectonically active. In this scenario, the highest density of sand bodies is expected to be not in the middle of the graben, but at the edge (fig. 30).

The thickness of the Lower Graben Formation may provide a clue about where the most subsidence occurred during the Callovian. The Lower Graben Formation is thickest along the center of the Central Graben. It thus seems that the most subsidence took place here and that both the eastern and the western fault of the Dutch Central Graben were active during the Callovian. This implies that the most sand bodies in the study area are expected in the center of the Dutch Central Graben. Figure 31 shows a W-E cross-section running across the fluvial graben axis. No individual channels are visible. Better reservoir characteristics (more specifically, higher N/G ratios) may be found in the center of the Dutch Central Graben.

9.4 Seal

It is not entirely clear what the top seal of the Lower Graben Formation is. In Abbink et al. (2006), the Lower Graben Play is discussed. For reasons not mentioned in the paper, the authors claim that the Vlieland Claystone is the top seal for this play. However, the Lower Graben Formation is nearly everywhere overlain by the Kimmeridge Clay Formation which shows up as a predominantly silty claystone in most well logs in the study area. Furthermore, the B18-03 well contains oil in the Lower Graben Formation while the Scruff Greensand Formation overlying the Kimmeridge Clay Formation is dry. This proves the effectiveness of the Kimmeridge Clay as top seal in this field. Based on the composite well log of the B18-03 well, the Kimmeridge Clay lithology in this area seems to be identical to other parts of the study area, so here, the Kimmeridge Clay is probably also an effective seal. Thicknesses of the formation range from 100 to over 600 everywhere the Lower Graben Formation is present. In the F3-FB field, intra formational seals in the Middle Graben Formation also seem to have sealing capacities. The Middle Graben Formation is not present north of the F3-FA field, though.

9.5 Source rock and migration

Geochemical analyses of oil and gas in Lower Graben reservoirs in the Dutch offshore have been linked to the Posidonia Shale Formation and Carboniferous source rocks, respectively. Posidonia Shale is present right below this formation, so in the vicinity of mature Posidonia, charge risk for this play is generally low. Clay Deep charge is more difficult, it is likely immature outside of the Central Graben and needs to 'down-charge' the deeper Lower Graben Fm; such a conduit maybe possible along major faults. For gas charge from the Carboniferous the same difficulties are applicable as for all plays.

9.6 Drilled structures

The Lower Graben Formation has been encountered only in two wells in the study area: in well B18-03 it contains an economically exploitable volume of oil and in well B14-01, where it has proven to be dry. Interestingly, based on the TWT maps, the well seems to have a significant updip potential of ~80 ms. After the time-depth conversion, this difference reduces to only 14 m which indicates that the well was indeed a valid structural test. The large difference between the time and depth

structure arises from the large difference in overlying high-velocity chalk thicknesses between both locations.

9.7 Remaining prospectivity

When purely looking at structural traps, only one structure has not been tested in the Dutch part of the Entenschnabel survey area (fig. 32). This is the four-way dip closure near the B18-02 well; this well has a TD in the Kimmeridge Clay Formation. However, just over the German border north of the B18-02 well, the B18-01 well has probably tested the Lower Graben Formation within this structure. No data about this is available ; the only information regarding well B18-01 can be found in the Amber prospect review by GDF SUEZ where a NE-SW section through the well is and it has drilled the Lower Graben while the well is indicated as dry.

When taking the depositional model of the Lower Graben Formation into account, a possibility for stratigraphic trapping seems to exist. The formation has been deposited as elongated channel infill bodies surrounded by a matrix of flood-plain deposited silt- and claystones. The highest chance of finding hydrocarbons in the Lower Graben Formation is probably along the axis of the Central Graben, where the formation is thickest. Here, a tens of meters thick section of Werkendam Formation shales separates the Lower Graben Formation from a thin section of Posidonia Formation. This may complicate charge of the Lower Graben Formation.

10. Lower Buntsandstein play

10.1 Introduction

The Lower Buntsandstein play consists of a number of reservoirs which are very similar in distribution and character. These are the Basal Solling sandstone, Lower Detfurth Sandstone and Lower Volpriehausen Sandstone Members. All three sandstones form the base of large fining-upwards sequences which are separated by tectonic pulses. Superimposed upon these large-scale cycles are smaller scale alternations which are controlled by Milankovitch cyclicity and thus climate-related.

No oil or gas fields with Main Buntsandstein reservoirs are present in the vicinity of the study area; the nearest is the F15-A gas field which was discovered in 1986 and contains gas in a highly overpressured Lower Volpriehausen Sandstone reservoir.

10.2 Well correlation

Only two wells have encountered the Triassic section in the study area: wells B14-02 and B17-02. The well correlation between these two wells is shown in figure 33. Both wells have encountered Solling sandstones, but their thickness and character is very different. Well B17-02 shows a ~85 m thick section of Basal Solling Sandstone with two stacked, ~10 m thick sand bodies. Well B14-02 contains only an 8 m thick Basal Solling Sandstone sequence which consists of a single, clean sand body. Overlying these sands are silty claystones with low GR readings which belong to the Röt Claystone Member. These claystones are unconformably overlain by fine-grained deposits of the Middle Graben Formation; age control of this section is provided by a palynological study done by TNO. Below the Basal Solling Sandstone, a section consisting of the Solling Claystone, Hardegsen Formation and Detfurth Claystone Member has been encountered in well B14-02. These sediments are not present in well B17-02; instead, the Basal Solling Sandstone is directly underlain by a thick section of Volpriehausen Clay-Siltstone Member. Below this, 20-50 m thick stacked sandstone units of the Lower Volpriehausen Sandstone Member have been encountered.

10.3 Reservoir

The topmost reservoir unit in the Lower Buntsandstein play is the Basal Solling Sandstone Member which belongs to the Solling Formation. This formation constitutes the oldest sequence in the Upper Germanic Trias Group and is unconformably overlying the top of the Lower Germanic Trias Group. It is an eolian sandstone which filled in existing relief created by the fourth pulse of the Hardegsen Unconformity. In combination with the fact that locally, salt movement in the subsurface took place during the time of deposition, this causes the Basal Solling Sandstone to have varying thicknesses. This is perhaps best illustrated by the L9 "Fat Sand" field. In 1992, the NAM drilled exploration well L9-7 and found a completely unexpected, 64 meter thick section of Middle Solling Sandstone Member. These eolian sands had been deposited in a mini-basin where accommodation space was driven by movement along a listric fault. Gas was found in the reservoir and the L9 Fat Sand field has proven to be very successful since its discovery (de Jager, 2012)

Below the Solling Formation, the next reservoir in the Main Buntsandstein play is the Detfurth Formation, which contains two sandstone members, separated by a claystone interval. The coarser intervals in the Detfurth Formation were deposited as eolian sandstones, while the claystones were

deposited in a playa lake setting. At its base, the Detfurth Unconformity cuts into the Volpriehausen Formation. Occurrence of the Detfurth Formation is restricted to Triassic lows; in areas which were higher, it has been eroded prior to deposition of the Solling Sandstone. The Detfurth is not present in well B17-02. This indicates that the Step Graben was uplifted to above base level during the fourth phase of the Hardegsen Unconformity. In well B14-02 which lies north of the Step Graben in a structurally complex area, 37 m of Detfurth Formation was encountered. However, of this, only 3 m consists of the Lower Detfurth Sandstone Member while the upper sandbody is not present at all. In the Dutch Central Graben, reservoir qualities of the Detfurth sandstones are very uncertain; often, porosities are destroyed by salt plugging.

The third and oldestst reservoir in the Main Buntsandstein play is the Volpriehausen Formation. The Volpriehausen was deposited after the first pulse of the Hardegsen phase. It is an arkosic, eolian sandstone which has often been cemented by calcite en dolomite, reducing the reservoir quality. In addition, salt plugging of the Volpriehausen sandstone is common in the Dutch Central Graben. In the lithological description of well B17-02, the Lower Volpriehausen Sandstone is described to be a very fine, calcareous sandstone. Occasional anhydrite and claystone layers are also present. The lithological description of well B14-02 is not detailed enough to mention cementation. Based on the 2 wells in the area, the Lower Volpriehausen is expected to have poor reservoir qualities, because of the limited thickness of the layer, the small grainsize of the sandstone and the chalk cementation which has been reported. In both wells, the reservoir interval is several tens of meters thick.

10.4 Seal

The seal for the Main Buntsandstein play may be one of the Röt or Keuper claystone sequences or an intraformational seal in the individual reservoir intervals. This all depends on local stratigraphies; in some fields south of the study area, claystone layers directly overlying the reservoir intervals act as seal (i.e. G16-a); in other fields, the ultimate top seal is the Vlieland Claystone Formation or Clay Deep Member (i.e. F15-a).

10.5 Source rock and migration

Source rocks for the Lower Buntsandstein are located within the Carboniferous section. The inferred presence of Maurits and Klaverbank coals in the Step Graben is extensively discussed in the 'source rocks' section above. Probably, these gas-prone source rocks are currently in the gas window; a problem may be the continuous and relatively thick wedge of Zechstein evaporites overlying the Carboniferous sediments here. These may form a barrier for migrating gas, preventing it from reaching Triassic sediments. However, throughout the B13 and B14 blocks, there are several places where shallow gas seems to be present. Since this cannot have been generated by the Clay Deep Member and the Posidonia Shale Formation is only present in the Central Graben, there are only two origins for this gas: either it is biogenic gas which has been produced in situ, or it originated in Carboniferous sediments of the Maurits and/or Klaverbank Formation.

10.6 Drilled structures

Two wells have tested the Lower Buntsandstein play in the study area:

- B17-02; this well tested a large 4way dip closure in the Step Graben and encountered dry Solling and Volpriehausen reservoirs. The Triassic section in this area is largely undisturbed; structures are broad, gentle swells. The absence of hydrocarbons in the Triassic reservoir sections may be due to a number of reasons: an obvious one is that there are no Carboniferous source rocks present and that the inferred distribution of Maurits and Klaverbank coals is incorrect. Alternatively, gas may have been generated but would have been unable to migrate through the Zechstein evaporites and Silverpit section. The positions of salt windows are shown in figure 34. Seal failure is seen as less likely.
- B14-02; this well encountered dry Solling and Volpriehausen reservoirs in a steeply dipping Triassic section. The structure is a fault-dip closure which has been drilled nearly perfectly on structure. Because of the bad seismic quality below the Zechstein, the presence of Carboniferous source rocks in this area is speculative. If they are indeed present and mature, gas would probably be able to migrate through the Zechstein salt since two large salt windows have been detected on seismic. Of course, fine-grained deposits of the Step Graben Formation, Lower/Upper Rotliegend and Lower Triassic sequences may still have formed a barrier to gas migration. Top seal seems intact with a thick section of intra-Triassic seals overlain by the fine-grained Rijnland Group.

10.7 Remaining prospectivity

Several large Triassic structures have not been tested in the study area. In the Step Graben, the two untested structures are located updip of the B17-02 well, but these are unlikely to contain hydrocarbons because of the limited attic potential. The other structures will be discussed below:

- Emerald lead; this four-way dip closure above the B18-02 salt swell has not been tested. Updip of well B18-02 in the German offshore, exploration well B18-01 has been drilled but this well has also not drilled through the Lower Buntsandstein (fig. 34) so the structure remains untested. It is located at a depth of 5000 m, which is very deep for a Triassic reservoir. Any Carboniferous source rocks are probably overcooked because of their large depths.
- F3-FA lead; because of the bad quality of the 3D seismic dataset which has been shot over the F3-FA field, no appraisal of the Triassic has been conducted. With the better seismic quality of the Entenschnabel dataset I have been able to map the Triassic in this area and a closure seems also to exist at Triassic level. However, since the Lower Buntsandstein is located at depths of ~6000 m, reservoir properties are expected to be very poor.
- B14-01; The crest of this broad structure is in the German sector. The structure cannot be evaluated on the used seismic survey; the only relevant comment is that there may be Carboniferous source rocks present in the Dutch sector of the B quadrant that could fill this structure.
- East of the B17 diapir, an untested Lower Buntsandstein structure is present. This truncation trap against the salt has its crest at a depth of ~3500 m. However, the Carboniferous source rocks may be overmature in the Central Graben.

Overall, I think the remaining Triassic prospectivity is very small, both because of the great depth to which the source as well as the reservoir layers have been buried. In the area where the Carboniferous is not buried to extreme depths (the Step Graben) all Triassic structures seem to have been tested.

11. Rotliegend play

11.1 Introduction

The Upper Rotliegend Group is a very successful reservoir in the Southern North Sea. Offshore, over 67 TCF of gas has been discovered in this interval. The reservoir of the Rotliegend play is the Upper Rotliegend Group which consists of fine-grained clastics and evaporites of the Silverpit Formation in the north and predominantly sandstones of the Slochteren Formation in the onshore and western off-shore area. These clastics were deposited in the Southern Permian basin, of which the southern shoreline ran roughly across the north of Groningen, Friesland and going westwards into the current-day North Sea (fig 35). Occasionally, transgressive phases caused the fine-grained facies of the Silverpit Formation to expand. The Ten Boer and Ameland Members are fine-grained intervals in the sandy Slochteren Formation which have been deposited in this way. The seal of the Rotliegend play is the Silverplit Formation and/or Zechstein salt, which is extensively present and has excellent sealing capacities. Main source rocks are the Westphalian coals.

11.2 Reservoir

The Upper Rotliegend Group is largely undrilled in the Central Graben area where the Rotliegend lies at depths of over 8km. In the adjacent Step Graben, the base of the Zechstein salt is at depths of ~4 km and in the study area, one well has drilled the Upper Rotliegend Group. This is the B17-04 well, which is located directly underneath the large B17 diapir. The well encountered a 184 m thick section of Upper Rotliegend Group in the form of the Silverpit Formation. Ambiguity in the log interpretations and cuttings from the B17-04 well led Petro Canada in 2009 to further investigate whether there could be an overlooked gas-bearing sandstone interval in the Silverpit Formation. However, they concluded that the interval is not a gas bearing interval. Instead, the original interpreter was correct in describing it as a salt rich claystone without any indication for sand.

However, a sandy facies of the Upper Rotliegend may be present in the study area. During Permian times, it was located in between the Northern and Southern Permian basin and during sea level lowstand periods, sand may have been deposited from either direction. This is shown by several wells in the vicinity of the study area: both well A15-1 and B10-02-Sidetrack show several sandbodies in their composite logs. In contrast, well F04-2A south of the study area encountered an alternation of halite and claystone in the Upper Rotliegend Group. Apparently, the F04 block is situated too far south of the northern basin edge to find sand and is situated in the Silverpit Basin.

In addition, the eastern half of the study area may contain sandbodies in the Upper Rotliegend Group. Figure 35 shows a map of the Southern and Northern Permian basins. These were connected by several large channels, of which one ran NW-SE across the study area. Probably, the western proto-Central Graben bounding fault was active during the Permian and caused the channel to be located along what would later become the Central Graben. This also means that, if there is indeed a sandy interval of the Upper Rotliegend in the study area, it will be lying at depths far too great for successful exploration. North of the Step Graben, the Upper Rotliegend might have good reservoir qualities though, since it lies at depths of ~4 km here.

11.3 Seal

The seal of the Rotliegend play is the Zechstein salt (and sometimes the Silverpit Fm). This salt has excellent sealing capacities, as numerous Rotliegend fields, among which the giant Slochteren gas field, have proven. Reasons for the good sealing capacity of salt are the fact that salt does not have any porosity and the relatively low viscosity causes salt to act as a detachment surface on which potentially leaking faults terminate.

In the study area, extensive halokinesis has taken place: two large salt diapirs bound the Step Graben in the east and west. In the Step Graben itself, salt seems to be present as a thick and continuous layer with only some very small windows where the seal may be absent. North of the Step Graben, large volumes of salt have probably withdrawn into the diapirs and there are large salt windows in the area near the B13-02 and B14-02 wells. In the Central Graben area towards the east, the seismic is too transparent and the base of the Zechstein is located too deep to confidently map salt windows in this area. Probably, the salt here has withdrawn completely into the diapirs; in any case, the Rotliegend in this area is located too deep to be prospective. The major regional fault trends bounding the Step and Central Graben have significant offset and are a good option for creating migration conduits from the Carboniferous into Triassic and younger. The salt diapirs and saltwalls typically also develop along these fault trends and hamper the imaging of these major Carboniferous fault trends and their offset.

11.4 Source rocks and migration

There are two possible source rocks charging the Rotliegend play: the unproven Namurian Geverik Shale and the proven Westphalian Klaverbank and Maurits coals. Distributions and maturities of this source rock are discussed in more detail in the chapter 'Source rocks', so this section will be kept relatively brief.

The Namurian Geverik Shale has not been tested in the study area as it is located at depths larger than 4500 m. In the Central Graben area, it is most likely overmature but in the structurally higher Step Graben, the shales may still be within the gas window. The Westphalian coals of the Klaverbank and Maurits Formations (the latter has been encountered by the B17-04 well) may similarly be within the gas window in this area.

In this area, the seismic quality below the Zechstein is still relatively high and a large number of normal faults have been interpreted. If these faults were leaking, they may have provided gas from the Carboniferous source rocks with a migration route into the Rotliegend reservoir.

11.5 Tested structures and remaining prospectivity

Only the B17-04 well tested the Rotliegend play. Results were disappointing, as no reservoir was present in the 184 m thick Upper Rotliegend Group. Figure 36 shows the depth map of the base of the Zechstein in the larger study area (Entenschnabel survey interpretation merged with two grids). Here, it can be seen that there are three large structures which have not been tested yet. One of these is located underneath the salt diapir west of the Step Graben. However, it is possible that this is not a depth structure due to the velocity pull-up of the sub-salt reflectors. Another, smaller structure is located on the boundary of block B13 and B16. Here, the B16-01 well is targeted at an

accumulation of shallow gas so it does not penetrate the Rotliegend. The third structure is located in the B10 block and has been tested by the B10-02-Sidetrack well. Even though this well was dry, there is significant updip potential of hundreds of meters towards the north-east. Just across the German border, the B10-01 well has been drilled, though. This well may very well have targeted the Rotliegend updip of the B10-02-Sidetrack well, and since no producing field was developed there, the Rotliegend here probably proved dry as well.

Overall, it thus seems that limited prospectivity remains in the Upper Rotliegend Group. First of all, the well which tested the Rotliegend did not encounter any sand in the Upper Rotliegend Group so, the south of the study area has a high risk on reservoir presence . Further north, there is a larger chance for Rotliegend sand as Rotliegend sands were encountered in well B10-02-Sidetrack and probably B10-01. The larger structures may not be present in depth but most Rotliegend fields tend to be fault blocks with a limited relief. The current regional mapping may not be sufficient; Rotliegend leads may be very sensitive to time-depth conversion , a more detailed Rotliegend interpretation might help in localizing leads. Reservoir properties are expected to be best in the higher areas; Rotliegend in the Central Graben is too deeply buried to have retained reservoir properties.

12. Interesting features

A number of interesting features can be seen in the Entenschnabel dataset. These features will be discussed in this section.

12.1 Glacial channels

At a depth of ~100 ms TWT, a series of channels can be distinguished on seismic. One very large channel, joined by several meandering smaller streams runs roughly north-south through the study area. These channels were active during glacial periods in the Late Pleistocene when eustatic sea levels had fallen so far that the North Sea was continental. Curiously, the large channel runs almost exactly parallel to the western bounding fault of the Central Graben in the vicinity of the B17 diapir. At the same location where the fault deviates towards the north-west, the channel forms a sharp meander. This seems to indicate that the faults are currently still active; alternatively, the location of the glacial channel may be related to ongoing halokinesis. The different lithology of the channel infills may cause velocity pull-ups or drawdowns in the underlying seismic, thereby disrupting the seismic signal.

12.2 Eridanos foresets

At depths of 400-1000 ms, large, westwards prograding foresets of the Eridanos river complex can be seen on seismic. The Eridanos river drained the Baltic states and discharged into the North Sea during the Miocene, Pliocene and Early Pleistocene where it built a gigantic delta. In a relatively short time, massive amounts of sediments were deposited in the North Sea basin. This caused a pulse of renewed hydrocarbon generation in Jurassic and older source rocks because of the rapid burial of these layers. The foresets are targets for shallow gas exploration; sequence stratigraphy could be used to predict the distribution of sandbodies within the deposits.

12.3 Polygonal faults

The Tertiary sediments of the North Sea are bundled in the North Sea Supergroup. The uppermost member of this group, the Upper North Sea Group, was deposited after the Mid-Miocene Unconformity. The base of this sequence is seen on seismic throughout the North Sea as a high-amplitude, intensely faulted reflector (fig. 35). These faults show up in plan view as polygonal structures and are probably caused by sudden dewatering of clastic sediments with a high initial porosity which are rapidly buried. Paul Stroosma wrote his master thesis at EBN about polygonal structures in 2012. In the D and E quadrants, he recognized over a hundred mounds which had formed on top of some of the larger polygonal faults. These mounds probably originated from expelled sediments in the underlying sequences; the lithology of these mounds is uncertain, as no wells have been drilled through them. However, I have not been able to identify these features in the B quadrant.

12.4 Thor transform zone fault

The western bounding fault of the Dutch Central Graben is obscured by a salt diapir in the B17 block. North of this diapir, a zone with strike-slip movements has been described by Wride (1995), who named it the 'Thor transform zone'. In this zone, a thick wedge of Jurassic sediments truncates deeply into horizontally bedded Triassic sequences (fig. 40). Based on this figure, it seems that during

the Late Jurassic, the entire area must have been uplifted hundreds of meters, during which period the Triassic and Lower Jurassic sediments eroded. Then, the area subsided again and the Upper Jurassic wedge of clastic sediments was deposited where the Triassic was eroded. This explanation requires very significant vertical movements in relatively short timespans and altogether seems a highly unlikely scenario.

However, by flattening the seismic section on the Upper Jurassic horizon, the story becomes much clearer. I propose the following sequence of events:

- During the Carboniferous, a NW-SE normal fault developed. This fault would later form the western bounding fault of the Dutch Central Graben. This is supported by Glennie (2002); in the Millennium Atlas is a figure of Permian sedimentary basins in north-western Europe. This map shows a large, NW-SE channel connecting the northern and southern Permian basins; this channel runs over the large NW-SE fault in the study area
- The Rotliegend and Zechstein sequences were deposited in the Southern Permian basin. The normal fault may have been active in this period; extensive halokinesis and the transparent seismic prevent investigating this further
- The Triassic Germanic Trias Group was deposited in a large, uniformly subsiding basin. During this period, salt mobilization may have taken place due to the increasing overburden of the Triassic sediments
- During the Late Triassic and Early Jurassic, the Dutch Central Graben came into existence. On the western flank, this rifting was accommodated by the large NW-SE, Carboniferous fault. In the Central Graben, fine-grained argillaceous sediments of the Altena Group were deposited.
- The Late Kimmerian Unconformity during the Late Oxfordian- Early Kimmeridgian reactivated the bounding normal fault, tilting and uplifting the Triassic and Early Jurassic sediments. Towards the south-west, the topmost Triassic layers of the Keuper Formation were eroded.
- During and after the Late Kimmeridgian, the basin subsided again and a thick wedge of Kimmeridge Clay, Scruff Greensand and Clay Deep Formation sediments were deposited on the tilted Triassic layers.
- During the Latest Jurassic, another inversion phase took place. Probably, faults north-east of the section in figure 40 were reactivated and tilted the Triassic and Jurassic sequences. In this way, the Triassic sediments rotated back towards their original horizontal position while the Jurassic sequence was tilted towards the south-west. Towards the north-east, the Upper and part of the Lower Jurassic sediments were eroded.
- During the Cretaceous, a large transgression took place which blanketed all existing relief; first a thin layer of clastic Rijnland Group sediments were deposited. Later, a thick sequence of chalk was draped over the entire North Sea.

Sometime during the Triassic, Jurassic and/or Cretaceous, salt will have been mobilized and started flowing. Just south of the section shown in figure 40 lies the very large B17 salt diapir. Rim synclines on the sides of this diapir show that a significant amount of salt migrated into the salt dome during the Early Cretaceous, but it is very well possible that multiple phases of halokinesis took place. Salt mobilization is driven by the increasing overburden of sediments; once the overburden reaches ~1 km, the salt is liable to start flowing. Uplift and erosion such as during the Late Kimmerian Unconformity can reduce the overburden to less than this threshold value, putting a hold on

halokinesis. In the Thor transform zone, it is very difficult to date the mobilization of the salt because of the transparent seismic and the very complex structural history of the area.

12.5 Base Zechstein in Step Graben

In the Step Graben, a relatively thick section of Zechstein evaporites underlies the Triassic sediments. The Zechstein forms a detachment surface for a large number of normal faults which are present in the Carboniferous and Rotliegend sequences below. In many places where these faults terminate in the salt, a local thickening of the Zechstein can be observed. The Zechstein itself is easily recognizable by the transparent seismic with occasional bright reflectors which are present at various inclinations. These so-called floaters are carbonate layers which have been broken up and tilted by the matrix of salt in which they reside.

The base of the Zechstein looks very peculiar in many places in the Step Graben. The evaporites and carbonates of the Zechstein have been deposited in the Southern Permian Basin and conformably overlie clastic sediments of the Upper Rotliegend Group. However, the seismic seems to contradict this. Figure 41 shows three sections in which Rotliegend layers which are orientated sub-horizontally are truncated by the base of the Zechstein, which shows up as a very bright positive reflector, surrounded by a pair of bright negative reflectors. Outside of the Step Graben, the base of the Zechstein has a more traditional expression.

13. Conclusion

13.1 Remaining prospectivity

I have systematically analyzed the six possible plays in the study area. By interpreting key horizons in a 3D seismic dataset I constructed TWT maps of these horizons. These maps were then converted to depth using the Velmod 2 velocity model which is available on www.nlog.nl. On the depth grids, I identified tested structures with their attic potential and closures not yet drilled. Using the inferred presence and maturity of several source rock intervals, faults through these untested structures, migration routes, the presence of shallow gas, probable sandstone distributions based on the depositional environment of the reservoir etc., I attempted to assess the prospectivity of these undrilled closures. Based on the results, I identified a number of leads which are described in the corresponding chapters. Below, I will shortly discuss the main conclusions per play:

- 1) **Chalk play:** chalk usually has high porosities but permeabilities tend to be very low. Processes which may enhance reservoir properties are redeposition, leaching/weathering and fracturing. No hydrocarbons have been encountered anywhere in the Chalk Group in the study area, but the B18-06 well did find a section of Ommelanden Formation with excellent reservoir properties. The well was probably dry due to hydrocarbons being unable to migrate upwards through a thick section of tight chalk towards the reservoir. The B17-03 well on top of the B17 salt diapir seems to have significant attic potential and the reservoir is probably fractured. Shallow gas indicates that charge is present. Besides the updip potential of B17-03, a number of leads have been identified, of which the Amethyst lead on top of the B16 salt wall and the Aventurine lead, a four-way dip closure of some 60 m in the center of the B14 block seem the most prospective
- 2) **Vlieland Sandstone play:** Vlieland Sandstone has not been encountered in the study area so this play is highly speculative. The depositional environment of the Early Cretaceous Vlieland Sandstone is in a prograding shoreline, causing the distribution of the reservoir to be elongated and shore-parallel. The sandstone facies was only deposited in areas which were sub-aerial during the time of deposition and probably, the entire study area was situated too far into the basin to contain these elements. Based on the thickness of the Vlieland Sandstone and position with regard to Early Cretaceous structural highs, three leads have been identified: the Bloodstone lead, situated on a gentle fault-dip closure in the B13 block, the Beryl lead, a steeply dipping closure against the northern flank of the B17 salt diapir and the Bauxite lead, a small, four-way dip closure in the north of the B17 block.
- 3) **Scruff Greensand play:** Scruff Greensands have been encountered in four wells in the study area and their distribution is limited to the Central Graben. The F3-FA field in the south-east of the study area produces oil and gas from the Scruff. The Scruff Greensands have been deposited along a starved shore and contain significant amounts of sponge spiculites. This depositional environment means that the sandstone facies of the Scruff shales out into the Kimmeridge Clay going basinwards. Sections with good reservoir qualities are thus probably restricted to the fringes of the Central Graben. The complex tectonic evolution of the North Sea during the Late Jurassic is illustrated by the B13-02 well, where an anomalously thick (65 m) section of Scruff Greensands have been

encountered. Two leads have been identified: the Bauxite and Beryl leads which are similar to their Vlieland Sandstone counterparts in the Chalk. Both of these contain thin sections of Vlieland subgroup sediments and may have been positioned near a shoreline during deposition.

- 4) **Lower Graben play:** The Lower Graben play has been proven successful in the F3-FA field, where economic volumes of oil are present in the Lower Graben Formation reservoir. The Lower Graben Formation has been deposited in a fluvial depositional environment where rivers ran along the axis of the Central Graben. The reservoir thus consists of channel infills in a matrix of fine-grained floodplain deposits. The density of these channels (with other words, the N/G ratio) is not known but is probably the highest in the center of the basin since subsidence will have been greatest here. The Lower Graben formation is only present in and on the flanks of the Central Graben; consequently, only one untested structure remains. This salt-cored four-way dip closure is situated along the border in the north-east of the B18 block and the top of the structure lies at ~2000 m depth. However, well B18-01 has probably penetrated the Lower Graben Formation updip of the B18-03 well. Nothing is known of this well, but since no producing field is located at the well site, the closure probably proved dry.
- 5) **Lower Bunter play:** Three reservoir levels constitute the Lower Bunter play: the Solling, Detfurth and Volpriehausen sandstones. The Solling, Detfurth and Volpriehausen formations are fining-upwards sequences bounded on the top and bottom by unconformities which developed during consequent phases of the Hardeggen Unconformity. In the study area, only two wells penetrate the Triassic (B17-02 and B14-02) and both of these only encountered the Solling and Volpriehausen sandstones. No hydrocarbons were found. Most of the undrilled structures are too deep for exploration (>5000 m). The one exception is a closure against the eastern flank of the B17 diapir which may contain hydrocarbons in the Lower Buntsandstein. Migration from the center of the Central Graben should not have been a problem; the Carboniferous source rocks may be overmature, though.
- 6) **Rotliegend play:** The Upper Rotliegend Group has been encountered only by the B17-04 well. Unfortunately, no intervals with good reservoir properties were found in the 184 m thick section. Further north in the study area, there may be sandstones present though, since the study area was located near the northern shore of the Southern Permian Basin. No structural closures have been identified in the study area; however, Rotliegend reservoirs are often found in fault-dip closure in rotated fault blocks. These fault blocks seem to be present in the Step Graben and more detailed mapping may very well reveal a number of leads here. Westphalian and Geverik source rocks are likely to be mature in the Step Graben and the presence of large normal faults may provide a migration conduit.

13.2 Other improvements

Besides the systematic overview of tested and untested structures in the B quadrant, a number of improvements have been made over existing maps and databases. These are listed below:

- 1) **TWT maps with regard to Velmod 2.** The use of 3D instead of 2D seismic data has significantly improved the TWT maps of especially the surfaces below the Rijnland Group. In the Central Graben, a large domal structure which was interpreted (or rather, interpolated) in the N N N existing TWT grids of the Altena and Schieland Groups on www.nlog.nl completely disappears when interpreting on 3D seismics. In addition, I have interpreted smaller-order surfaces such as the Kimmeridge Clay Formation and Basal Solling Sandstone Member.
- 2) **Z maps with regard to VELMOD 2.** The refinement of the TWT grids naturally has the same impact on the depth maps which have been constructed from these surfaces. The improved depth maps may have major consequences for source rock maturities, reservoir properties and migration routes.
- 3) **Refining the structural elements.** Until now, only a very coarse map of the Pre-Permian structural elements was available in the study area. The large western bounding fault of the Central Graben has been withdrawn using the 3D interpretations from the Entenschnabel survey.
- 4) **Updates to postmortems.** The improvement of fully 3D interpreted horizons over interpolated ones allowed me to re-analyze existing well reports. For instance, migration routes and the presence of shallow gas may be much better understood with this new data.

14. Acknowledgements

During this project, I have been assisted by many people, without whose expertise I would not have been able to complete my internship at EBN. First of all, I would like to thank Eveline Rosendaal; she was always able to help me out when I got stuck with some problem, even when I did something stupid like inserting correlation coefficients instead of compaction constants in my velocity model :)

I'd like to thank Guido Hoetz for his help with time-depth conversions and general feedback. I would also like to thank the other geoscientists (Bastiaan Jaarsma, Mijke van den Boogaard and Annemiek Asschert) for their helpful discussions and ideas. I am indebted to Dirk Munsterman and Roel Verreussel from TNO who were a great help with the biostratigraphy of several wells. Thanks also to Nynke Hoornveld for all the fun we had during work hours. Lastly, I'd like to thank all other people from the technical department for the interesting discussions and support.

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Appendix 1: Field description F3-FA

The only example of a successful oil and gas field in the study area with economic volumes is the F3-FA field. This field was discovered by NAM in 1971 by the F03-01 well. Three other wells have been drilled through the field: F03-07, F03-08 and B18-03.

Structure

The F3-FA field is located on top of a domal structure (fig A1-1 and A1-2). One large, NE-SW fault cuts across the structure. Several smaller faults with different orientations spring from this large fault. The dome is most likely salt-cored. Figure A1-3 shows a cross-section through the field; the location of this section is shown as the red line on fig. A1-1. From the cross-section, the timing of the development of the dome can be deduced: the Lower Graben Formation has much steeper flanks than the Scruff Greensand Formation. Halokinesis must thus have taken place during Kimmeridgian-Portlandian times.

The most recent 3D seismic dataset over the field covers a ~10x10 km area and was shot in 2004. The northern part of this survey overlaps with the Entenschnabel survey. The data quality of the Entenschnabel is significantly higher compared to the F3-FA dataset and it is now possible to identify the Triassic domal structure underneath the field. However, this Triassic lead lies at depths of ~6000 m, too deep to be prospective.

Reservoirs

Two reservoirs contain hydrocarbons in the F3-FA field: the Lower Graben and Scruff Greensand Formations. Four wells have been drilled through the structure. Well F03-01 and F03-08 lie in the western compartment of the structure and contain gas in the Scruff Greensand Formation in a four-way dip closure configuration. Well B18-03 lies ~1000 m to the north of these wells and contains oil in the Lower Graben Formation in a fault-dip closure. Well F03-07 lies to the east of the fault and has an oil-bearing Scruff Greensand reservoir. All the reservoirs are underfilled. In an appendix from the Panterra study 'Remaining hydrocarbon prospectivity of the Dutch Central Graben', a short field description of F3-FA is given. The report claims that pressure information suggests that the Chalk is sealing. However, no elaboration is given and I have not been able to find this information anywhere.

Source rocks

Two source rocks may have charged the F3-FA structure. These are the Upper Jurassic Clay Deep Member and Posidonia Shale Formation. Towards the south-west, on the other flank of the Central Graben lies the F3-FB field which contains oil, condensate and gas and has probably been charged from the same source as the F3-FA field. Probably, the Posidonia Shale and/or Clay Deep Member are mature in the Central Graben in the F3 block. In addition, results from the current study suggest both source rocks are mature in the B18 block and may have contributed gas and/or oil to the F3-FA field. In the Panterra study, no Posidonia Shale has been modeled in the B18 block.

Appendix 2: Leads

In this appendix, an inventory of all structures in the area is presented. Per play, all wells which have penetrated the reservoir are shown; parameters which are listed are the result of the well, the attic potential, crest and spill point, the type of trap, the approximate surface area of the closure and a very coarse calculation of the STOIP. In addition to the drilled structures, the leads are also shown. Table A2-2 on the next page shows the different play elements and the pros/cons for each lead. Accompanying seismic cross-sections of the most prospective leads can be found in the figures section of this appendix.

Name	Reservoir	Drilled?	HC Status	Crest (m)	Spill point (m)	Max. HC column (m)	Trap type	Area (km ²)	GRV (Mn m ³)	N/G	Por	Soi	Sg	Boi	Bg	STOIP (MMBo)	GIP (BCM)
Agate lead	Chalk	No	N/A	1970	2180	200	Stratigraphic, porosity pod	2,1	88	1	0,25	0,65	0,7	0,752	200	68	3,08
Aquamarine lead	Chalk	No	N/A	1600	2850	700	Stratigraphic, porosity pod	8,7	1044	1	0,25	0,65	0,7	0,752	200	802	36,54
Aventurine lead	Chalk	No	N/A	1959	2020	61	4-way dip closure	17,5	204	1	0,25	0,65	0,7	0,752	200	157	7,14
Amethyst lead	Chalk	No	N/A	1250	2060	>100 m	4-way dip closure	112	16800	1	0,25	0,65	0,7	0,752	200	12913	588,00
Amber lead	Chalk	Yes	Dry	1900	N/A	N/A	Stratigraphic, porosity pod	N/A									
B13-02 W untested	Chalk	No	N/A	1550	2170	290 m	Fault-dip closure	20	1024	1	0,25	0,65	0,7	0,752	200	787	35,84
B18-02	Chalk	Yes	Dry	<1710		>162	4-way dip closure	3,4									
B18-03	Chalk	Yes	Dry	1800		>63	4-way dip closure	5									
B17-02	Chalk	Yes	Dry	1774		12	4-way dip closure	4									
B14-01	Chalk	Yes	Dry	1848		0	4-way dip closure	0									
B13-02	Chalk	Yes	Dry	1496		82	Fault-dip closure	1,6									
B17-03	Chalk	Yes	Oil	1221		100	4-way dip closure	1,6									
Beryl lead	Vlieland Sandstone	No	N/A	2180	2870	650	Pinch-out against salt diapir	9,4	564	0,5	0,2	0,65	0,7	0,75	250	173	9,87
Bloodstone lead	Vlieland Sandstone	No	N/A	2350	2790	200	4-way dip closure	19,7	394	0,5	0,2	0,65	0,7	0,75	250	121	6,90
Bauxite lead	Vlieland Sandstone	No	N/A	2650	2775	80	4-way dip closure	3,6	144	0,5	0,2	0,65	0,7	0,75	250	44	2,52
B18-02/03	Vlieland Sandstone	Yes	Dry	2070		N/A	Fault-dip closure	N/A									
Beryl lead	Scruff Greensand	No	N/A	2510	3270	~600	Pinch-out against salt diapir	3,6	306	0,25	0,18	0,8	0,7	0,75	250	52	2,41
Bauxite lead	Scruff Greensand	No	N/A	2750	3450	~200	4-way dip closure	13	975	0,25	0,18	0,8	0,7	0,75	250	166	7,68
B18-02	Scruff Greensand	Yes	Dry	2390		N/A	4-way dip closure	N/A									
B18-03	Scruff Greensand	Yes	Gas (F03-01)	2330		N/A	Fault-dip closure	N/A									
B14-03	Scruff Greensand	Yes	Dry	2200		160	Truncation by unconformity	2,8									
B14-02	Scruff Greensand	Yes	Dry	2110		400	Fault-dip closure	7,1									
B13-02	Scruff Greensand	Yes	Dry	2040		280	Fault-dip closure	3,6									
Emerald lead	Lower Graben	Yes (B18-01)	N/A	<2400		>300	4-way dip closure	31	3100	0,2	0,15	0,8	0,7	0,75	250		16,28
B14-01	Lower Graben	Yes	Dry	2270		14	Truncation by unconformity										
B18-03	Lower Graben	Yes	Oil	2500		N/A	Fault-dip closure										
Emerald lead	Lower Bunter	No	N/A	<4560		>300	Unclear, probably 4-way dip	31	2800	0,3	0,1	0,8	0,7	0,75	400		23,52
F3-FA lead	Lower Bunter	No	N/A	<5600		>300	Fault-dip closure	114	4560	0,3	0,1	0,8	0,7	0,75	400		43,78
B14-02	Lower Bunter	Yes	Dry	2805		0	Fault-dip closure	0									
B17-02	Lower Bunter	Yes	Dry	3600		70	4-way dip closure	25,7									
B17-04	Upper Rotliegend	Yes	Dry	4116			No closure	?									
B16 diapir	Upper Rotliegend	No	N/A	3700			4-way dip closure salt diapir	53									
B10 plateau	Upper Rotliegend	No	N/A	?			4-way dip closure	?									
B17 diapir	Carboniferous	Yes	Dry	?			No closure	?									

Name	Access to mature SGKIC?	Access to mature ATPO?	Migration route?	Shallow gas?	Reservoir quality	Factors reservoir quality	Effective seal?
Agate lead	Probably not	Possibly	Probably	Yes	Low	Enhanced acoustic imp,	Yes
Aquamarine lead	Probably	Probably	Probably	Yes	Low	Enhanced acoustic imp,	Yes
Aventurine lead	Possibly	Probably not	No	No	Low	No faults, no leaching	Yes
Amethyst lead	Possibly	No	Unclear	No	High	Faulted above diapir	Yes
Amber lead	Yes	Yes	No	No	High	Leaching, porosity pod	Yes
B13-02 W untested	Probably not	No	Unclear	Yes	Unclear	Faulted near diapir	Probably not
B18-02	Yes	Yes	No	No	Low	No faults, no leaching	Yes
B18-03	Yes	Yes	Probably not	No	Unclear	Faults, no well report	Yes
B17-02	No	No	Probably not	No	Low	No faults, no leaching	Yes
B14-01	Probably	Probably	Probably not	Yes	Low	No faults, no leaching	Yes
B13-02	Possibly	No	Probably not	Yes	High	Faulted above diapir	Probably not
B17-03	Probably	Probably	Yes	Yes	High	Faulted above diapir	Probably not
Beryl lead	Probably	Probably	Probably	Yes	Unknown	Highly speculative ss facies	Probably
Bloodstone lead	Probably	Probably not	Probably	Yes	Unknown	Highly speculative ss facies	Probably
Bauxite lead	Probably	No	Probably	No	Unknown	Highly speculative ss facies	Probably
B18-02/03	Yes		No		Yes		Yes
Beryl lead		Probably	Probably	Yes	Unknown	Shoreface depositional envir.?	Probably
Bauxite lead		Possibly	Possibly	No	Unknown	Shoreface depositional envir.?	Probably
B18-02							
B18-03							
B14-03							
B14-02							
B13-02							
Emerald lead	N/A	Probably	Probably	No	Unknown	Distribution tidal channels	Probably
B14-01	N/A						
B18-03	N/A						
Emerald lead	N/A	N/A	Probably	No	Prob. Low	Deep burial, diagenesis	Probably
F3-FA lead	N/A	N/A	Unclear				
B14-02	N/A	N/A	Unclear				
B17-02	N/A	N/A	Unclear				
B17-04	N/A	N/A	Unclear		No reservoir		
B16 diapir	N/A	N/A	Unclear				
B10 plateau	N/A	N/A	Unclear				
B17 diapir	N/A	N/A	Unclear				

Figures



Figure 1; The location of the Entenschnabel Survey is shown in the black outline.
Source: Fugro.com

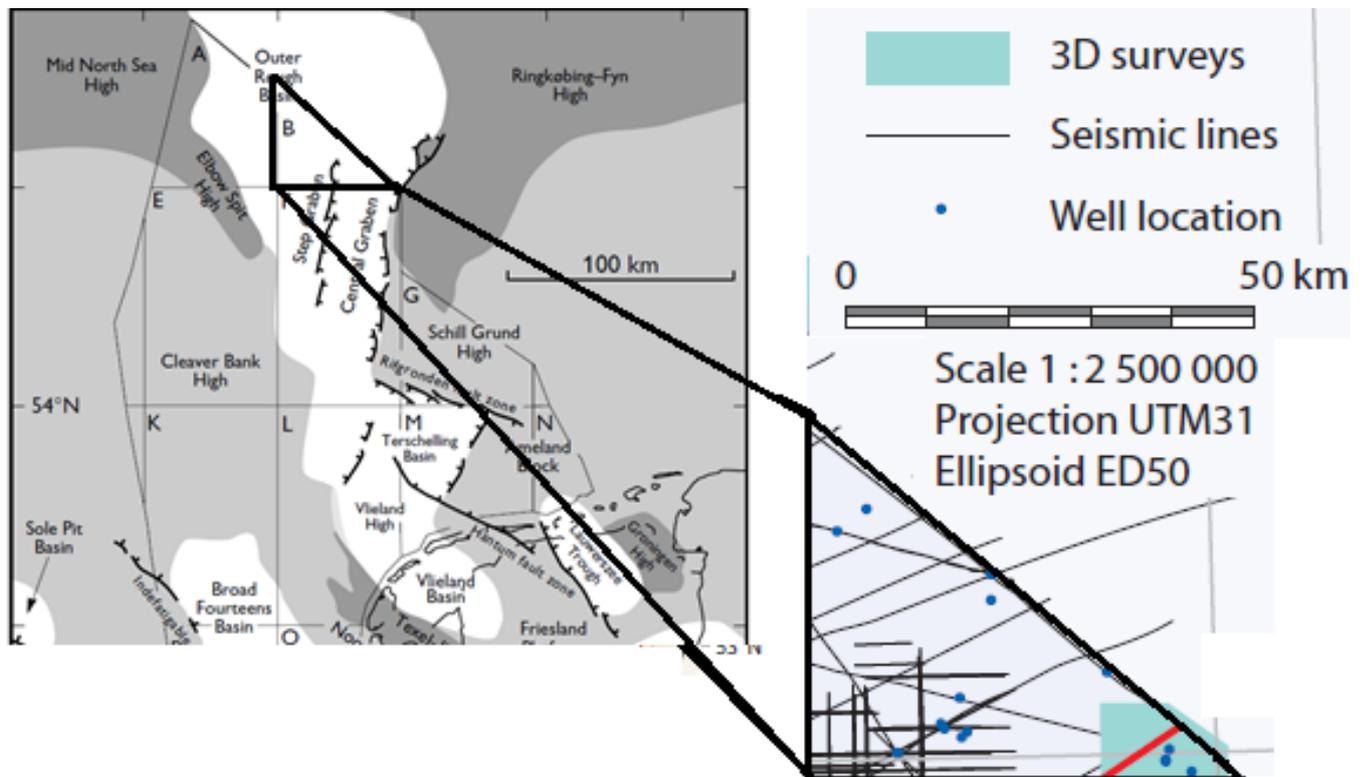


Figure 2; A map showing the location of the B quadrant and existing 2D seismic lines as well as well locations in the study area. Modified from Geology of the Netherlands (2007)

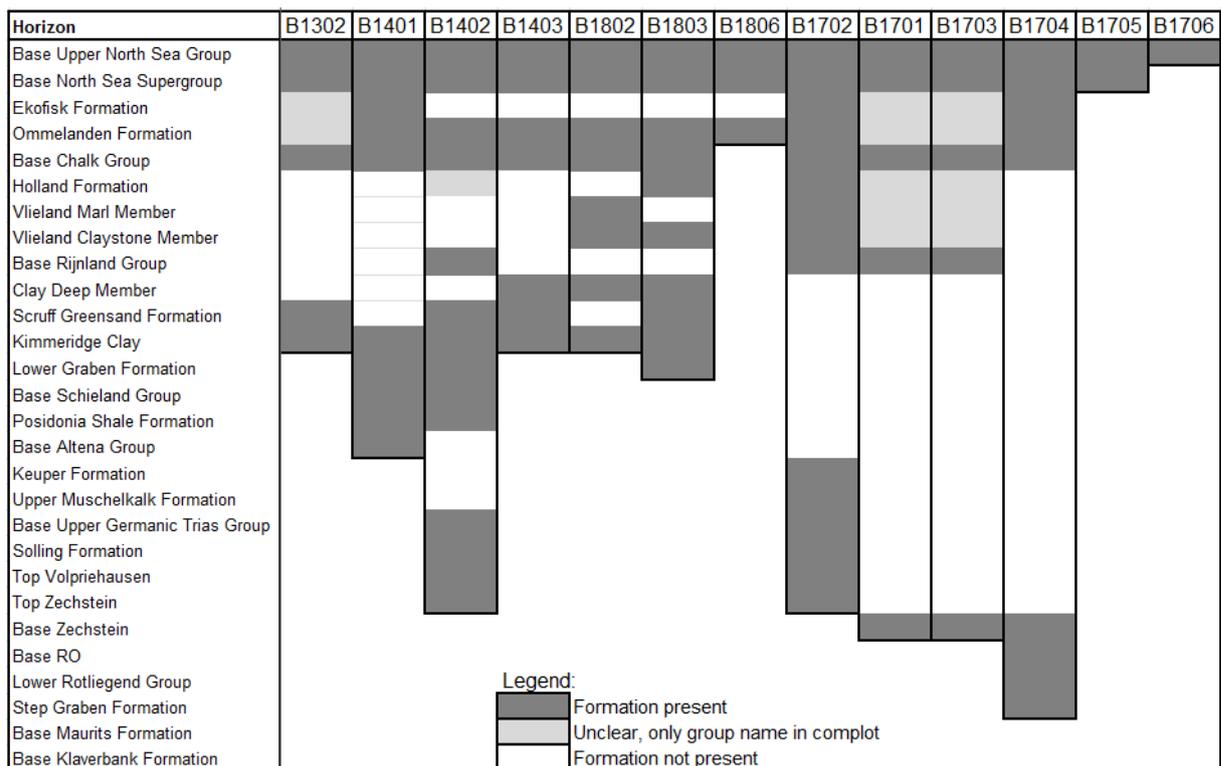
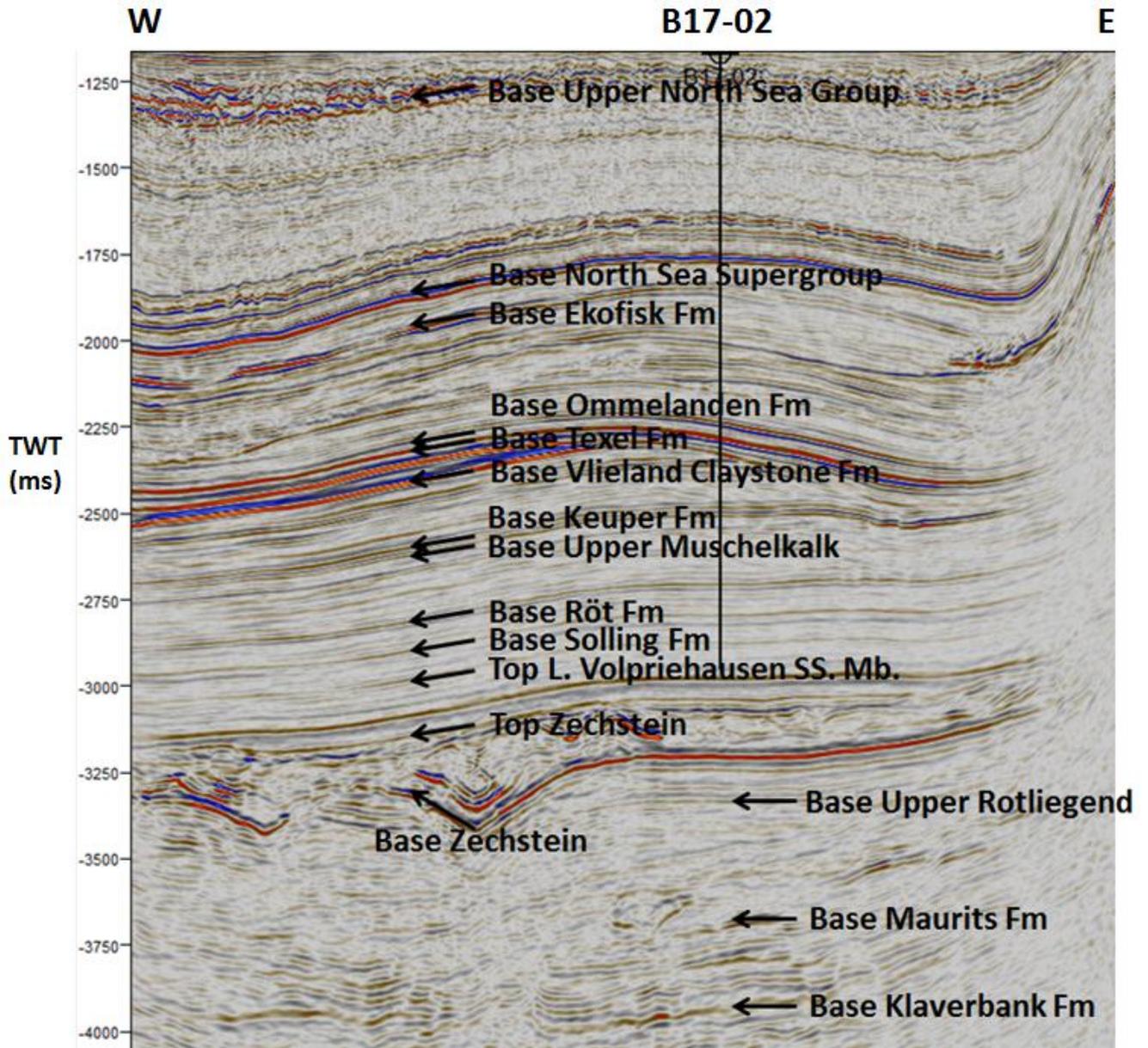


Figure 3; A schematic overview of the formations which were encountered in the wells in the study area. Grey infills indicate horizons which have only been recognized on a higher stratigraphic level

Horizon	Approach interpretation
Base Upper North Sea Group	3D autotracked
Base North Sea Supergroup	3D autotracked
Ekofisk Formation	Every 20th Inline in DCG
Ommelanden Formation	Every 5th Inline in DCG, every 50th Inline in Step Graben
Base Chalk Group	3D autotracked -> every 20 Inline where inconsistent & over diapir
Holland Formation	Every 25th Inline
Vlieland Marl Member	Every 40th Inline
Vlieland Claystone Member	5 Inline
Base Rijnland Group	3D autotracked -> 25th Inline where inconsistent
Clay Deep Member	Variable X and Inlines, NW-SE lines in Thor transform zone
Scruff Greensand Formation	Every 5th inline northern part DCG, variable elsewhere
Kimmeridge Clay	Every 25th Xline
Lower Graben Formation	Every 25th Inline
Base Schieland Group	Variable, density 20-50 X- and Inlines
Posidonia Shale Formation	Every 40th Xline
Base Altena Group	Variable, density 20-100 X- and Inlines
Keuper Formation	Every 10th Inline in the Step Graben
Upper Muschelkalk Formation	Every 10th Inline in the Step Graben
Base Upper Germanic Trias Group	Every 40th Inline, every 20th Xline
Solling Formation	Every 5-10th Inline Step Graben, every 50th Inline DCG
Top Volpriehausen	Every 20th Inline
Top Zechstein	Variable, density 5-200 X- and Inlines
Base Zechstein	Every 100th X- and Inline
Base RO	Variable, 20-40 X and Inline, where not interpreted 150 ms isopach below base ZE
Base Maurits Formation	Every 25th X- and Inline
Base Klaverbank Formation	Every 25th X- and Inline

Table 1 (previous page); The approach which was followed in the seismic interpretation of each horizon in the model (3D autotracking versus manual interpretation) and the density of manually interpreted X- and Inlines

Figure 4; Representative picks of the North Sea, Chalk, Germanic Trias Group, Zechstein, Rotliegend and Limburg Groups on a seismic inline through well B17-02



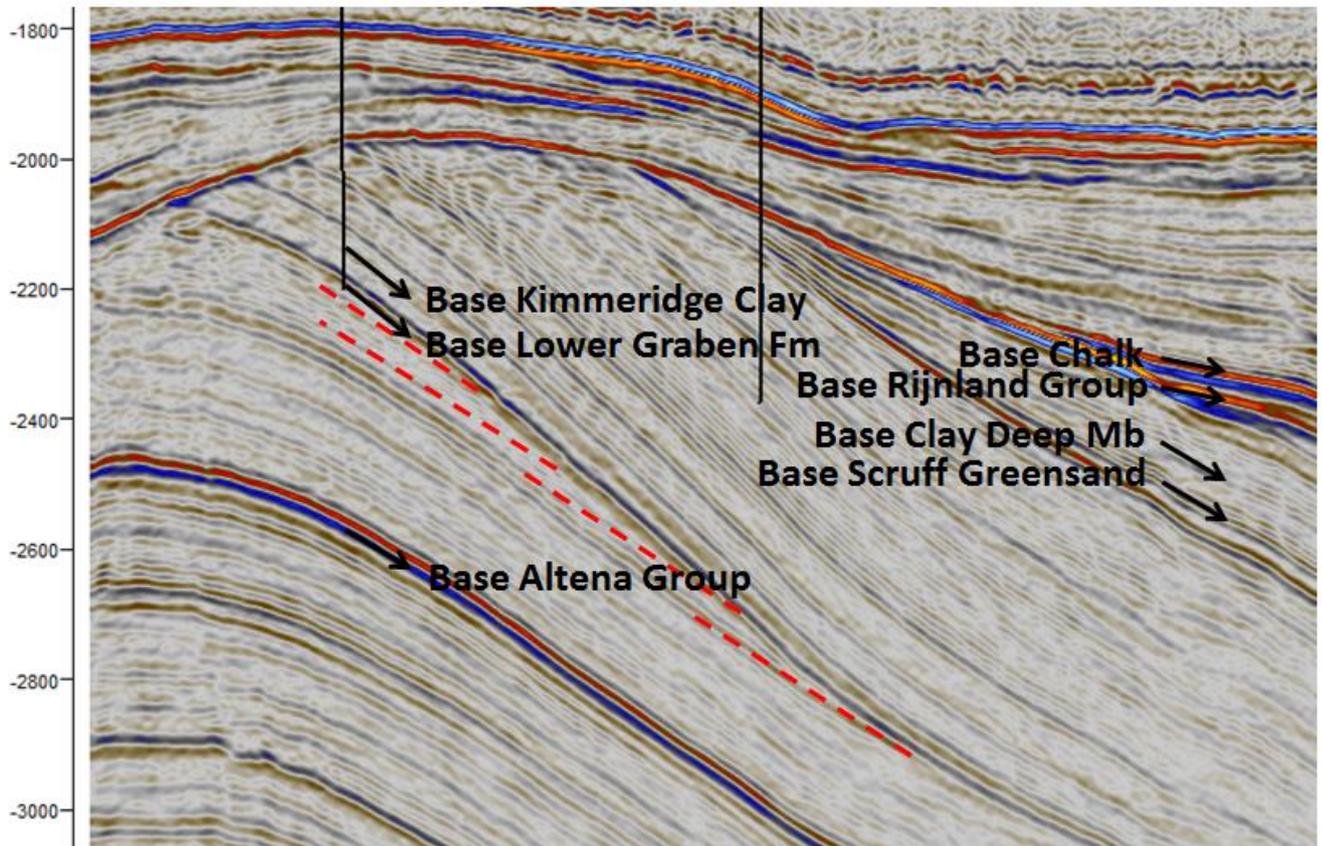


Figure 5; representative picks of the Chalk, Schieland and Altena Groups in a cross-line through wells B14-01 and B14-03. The red, dashed lines show layering in the Altena Group sediments which are truncated by the Lower Graben Formation above

Layer	Method	V0	k
N	V0 + kZ	Velmod 2 V0 map	0,321
CK	V0 + kZ	Velmod 2 V0 map	0,864
KN	V0 + kZ	Velmod 2 V0 map	0,508
S	V0 + kZ	Velmod 2 V0 map	0,805
AT	V0 + kZ	Velmod 2 V0 map	0,601
RN	V0 + kZ	Velmod 2 V0 map	0,374
RB	V0 + kZ	Velmod 2 V0 map	0,417
ZE	Interval velocity	Interval velocity = 4500 m/s	N/A
RO	V0 + kZ	Velmod 2 V0 map	0,364
DC	V0 + kZ	Velmod 2 V0 map	0,273

Tabel 2; The type of velocity model used as well as a description of the used V0 maps and the used values for the compaction constants k

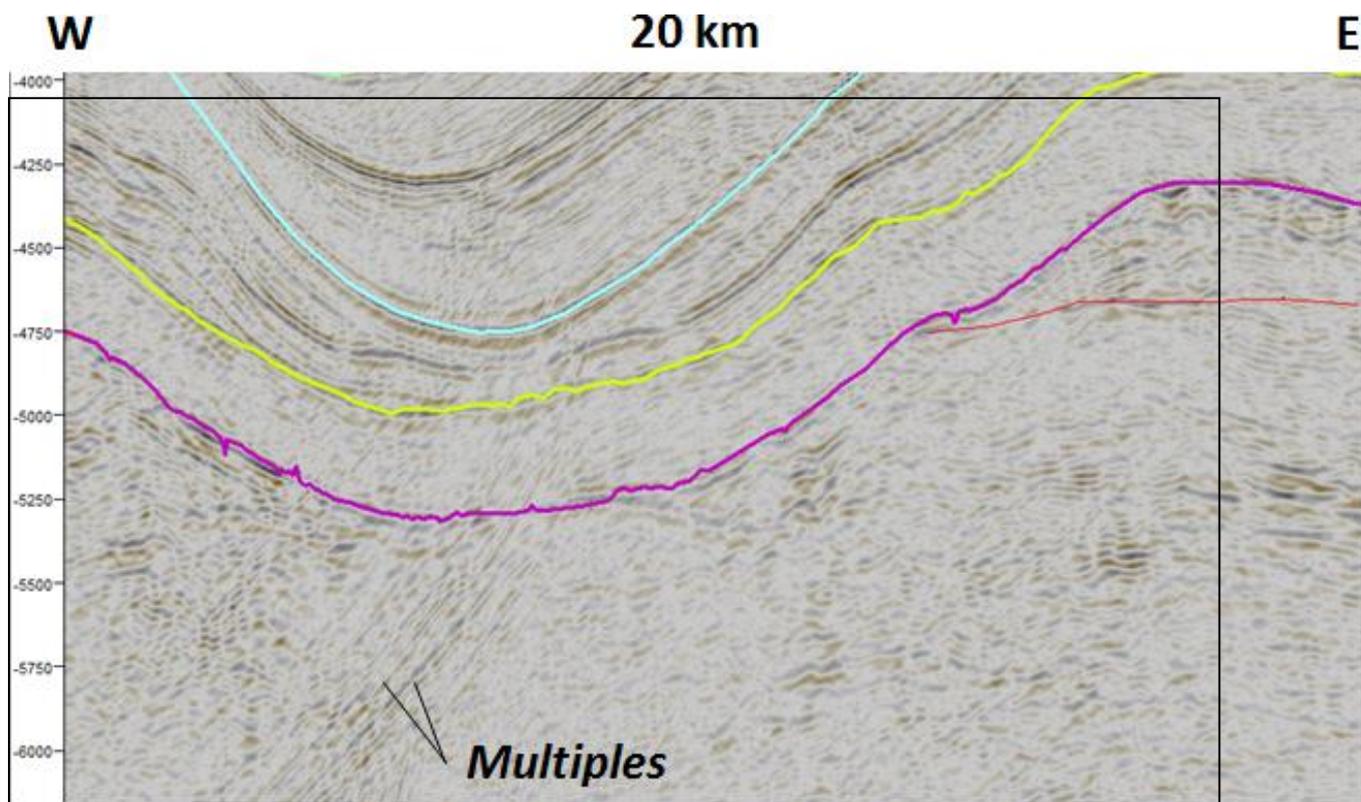


Figure 6; The top of the Zechstein in the Central Graben lies at a depth of >5000 ms. Steeply dipping multiples obscure the already transparent seismic, hindering seismic interpretation at these depths

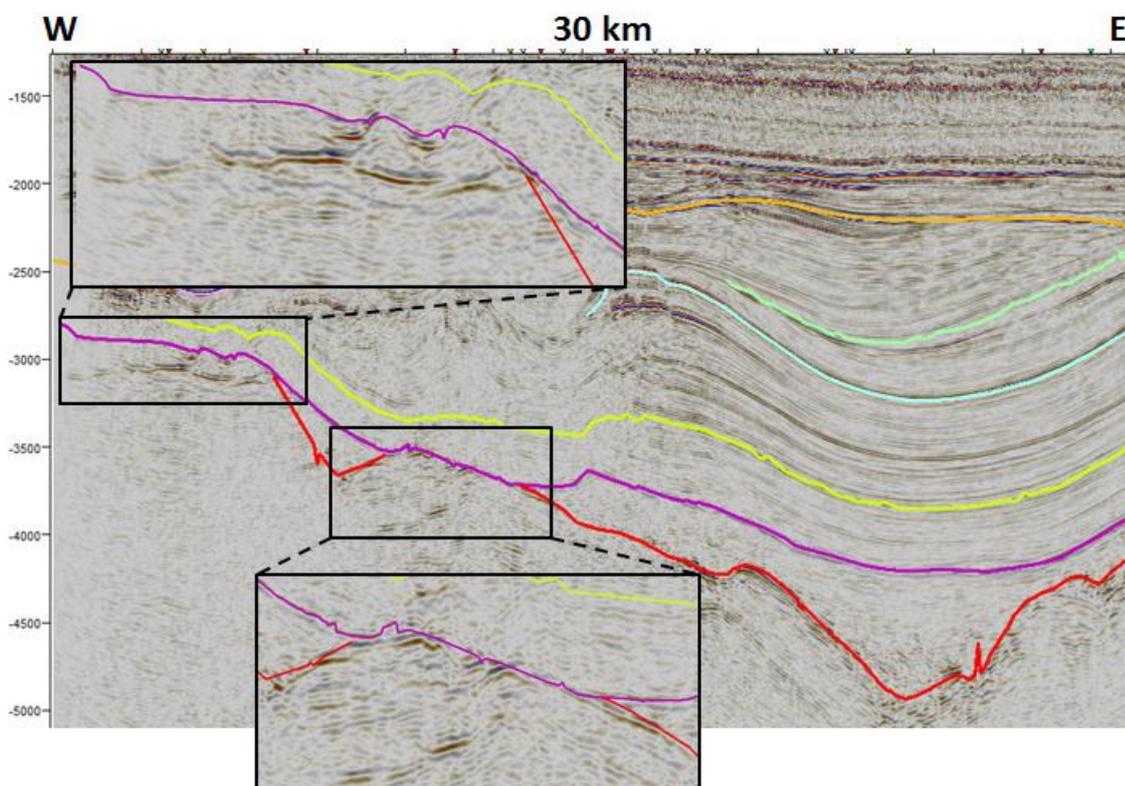
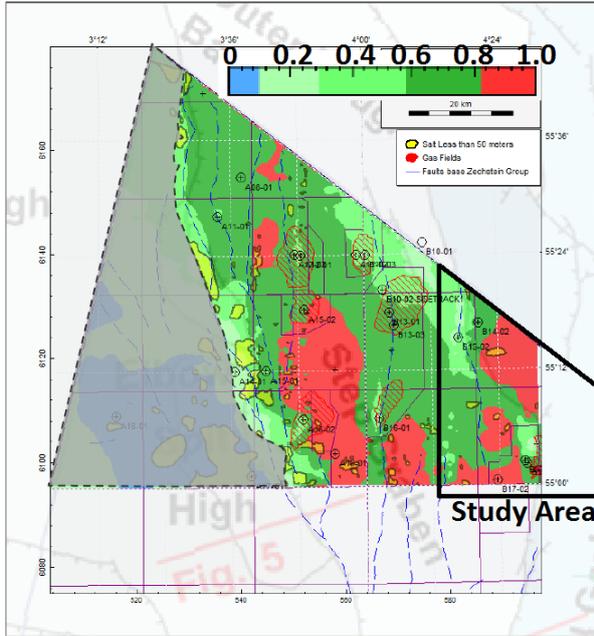


Figure 7; Salt windows have been detected on seismic by tilted layers below the Zechstein salt which are truncated by Triassic layers

Oil Source



Gas Source

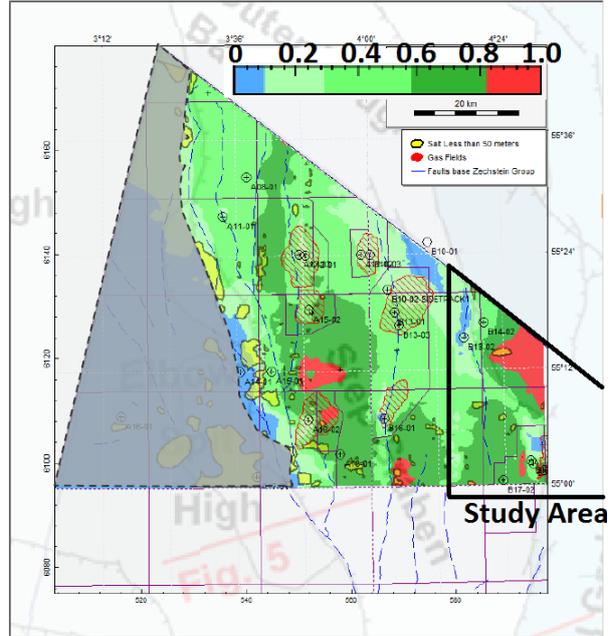


Figure 8; Maps showing the modeled maturity of the Namurian Geverik Member. Since the Geverik Member may be oil and gas prolific, two separate maps are shown. Source: Chevron source rock study, 2009

Ro

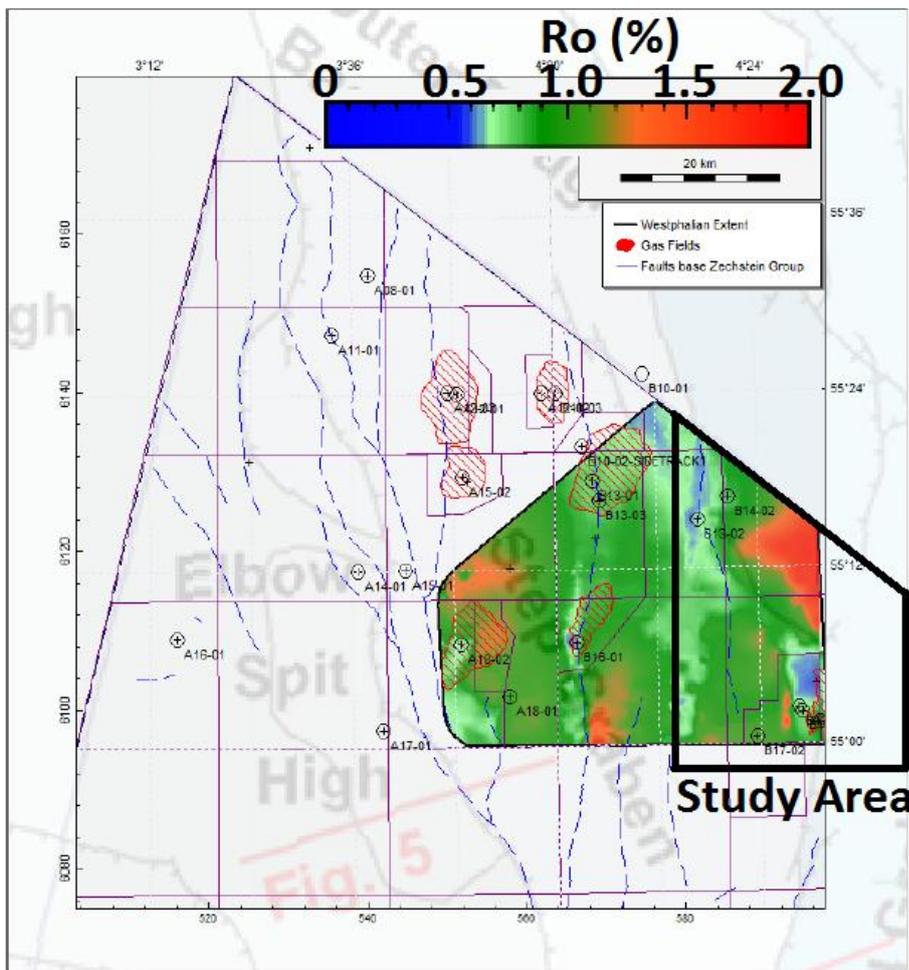


Figure 9; A map showing the distribution and modeled maturity of the Klaverbank and Maurits Formations. In the Step Graben, the source rock is currently in the gas window. Source: Chevron source rock study, 2009

B17-04

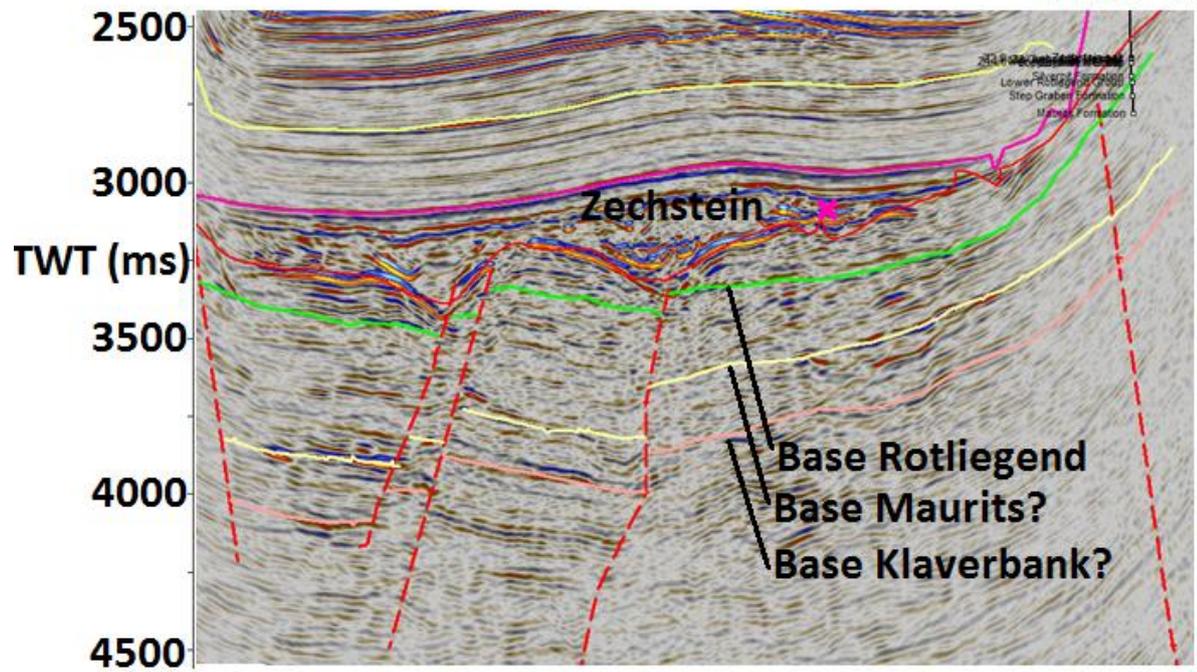


Figure 10; An E-W seismic section through the Step Graben and the B17-04 well. The base of the Zechstein, Upper Rotliegend, Maurits and Klaverbank Formations have been interpreted.

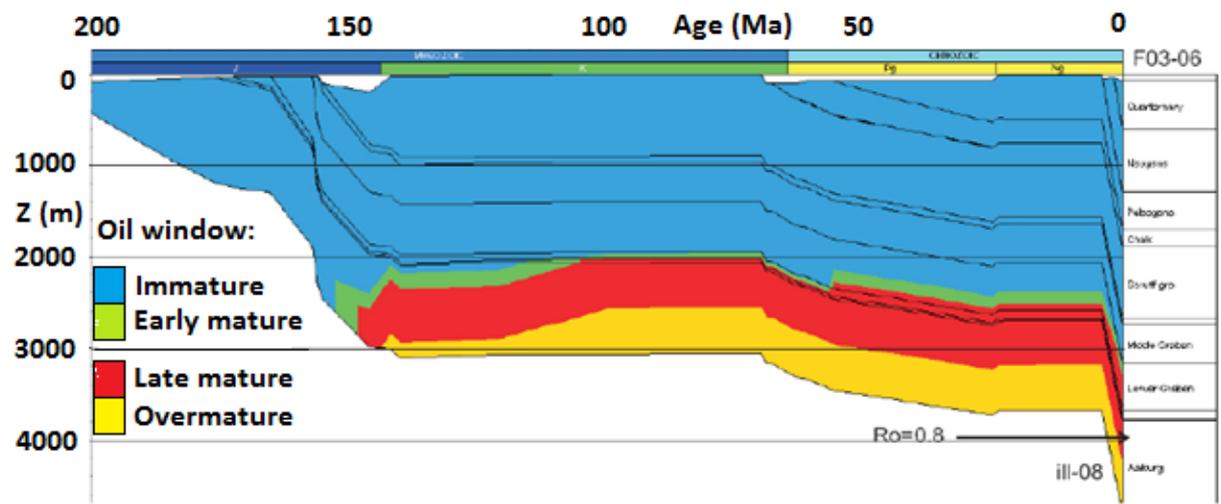


Figure 11; A burial graph showing the maturity of the Posidonia Shale Formation. The Posidonia seems to have a pulse of oil generation since the Plio-Pleistocene boundary. The basin modeling leading to this graph was done for an artificial pseudo well on the western flank of the Dutch Central Graben in the F quadrant. Modified from Panerra: Remaining hydrocarbon prospectivity of the Dutch Central Graben (2010)

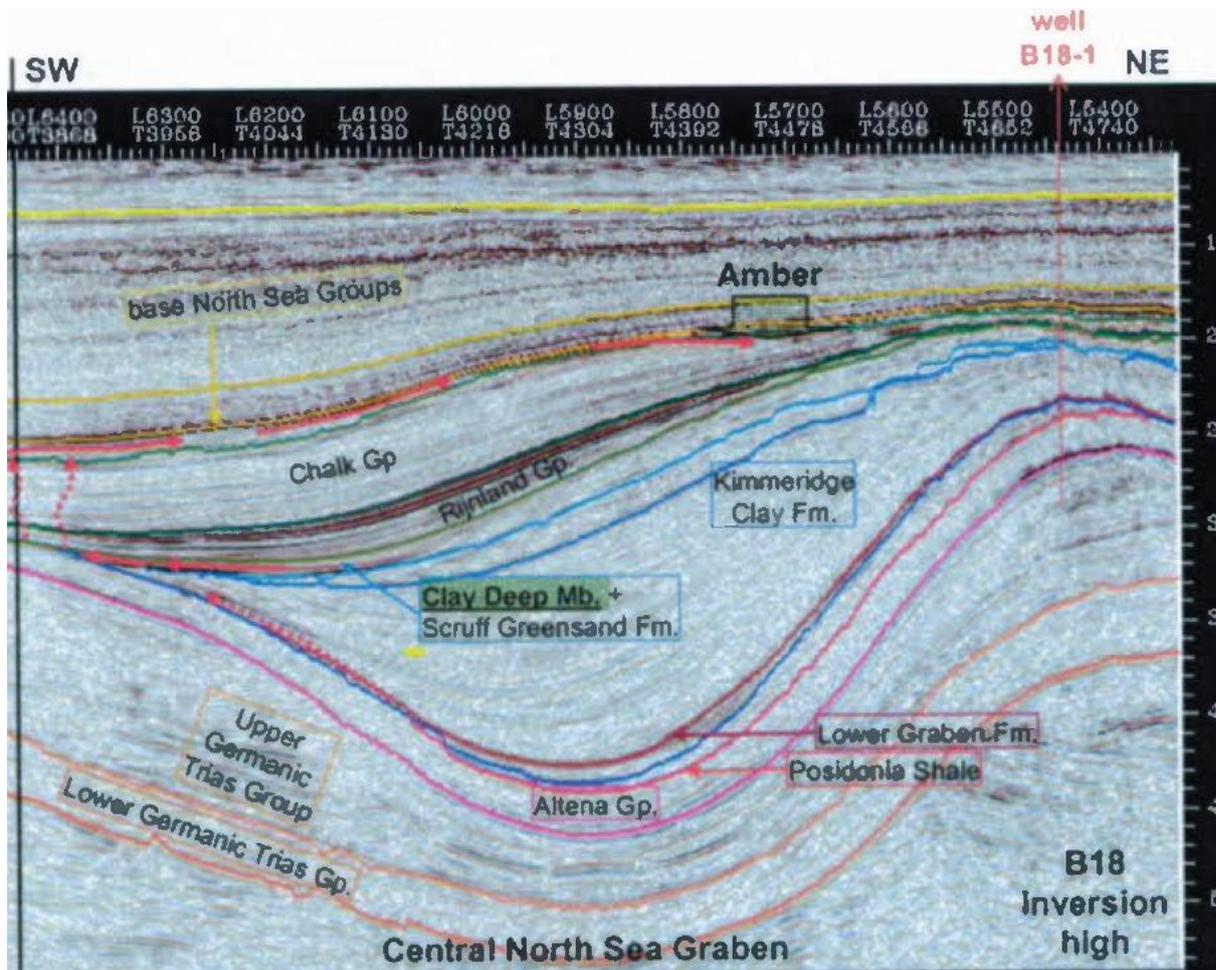


Figure 12; A seismic section connecting well B18-01 just over the German border to the Dutch part of the B quadrant. The Posidonia Shale, which has not been encountered in any wells in the study area, is present in this well. Source: Amber prospect review by GDF Suez (2004)

Well	Depth [m]	VRr [% refl.]
F03-01	500	0.3
	590	0.37
	680	0.3
	770	0.28
	860	0.32
	1040	0.33
	1130	0.29
	1220	0.33
	1750	0.49
	2634	0.57
	2714	0.57
	2806	0.62
	2850	0.62
	3019	0.68
	3062	0.57
	3122	0.67
	3188	0.67

Table 3; From the F03-01 well, samples from various depths have been analyzed for their Vitrinite reflectance content. Based on this, the top of the oil window seems to be at ~2000 m depth. Source: Panterra: Remaining hydrocarbon prospectivity of the Dutch Central Graben (2010)

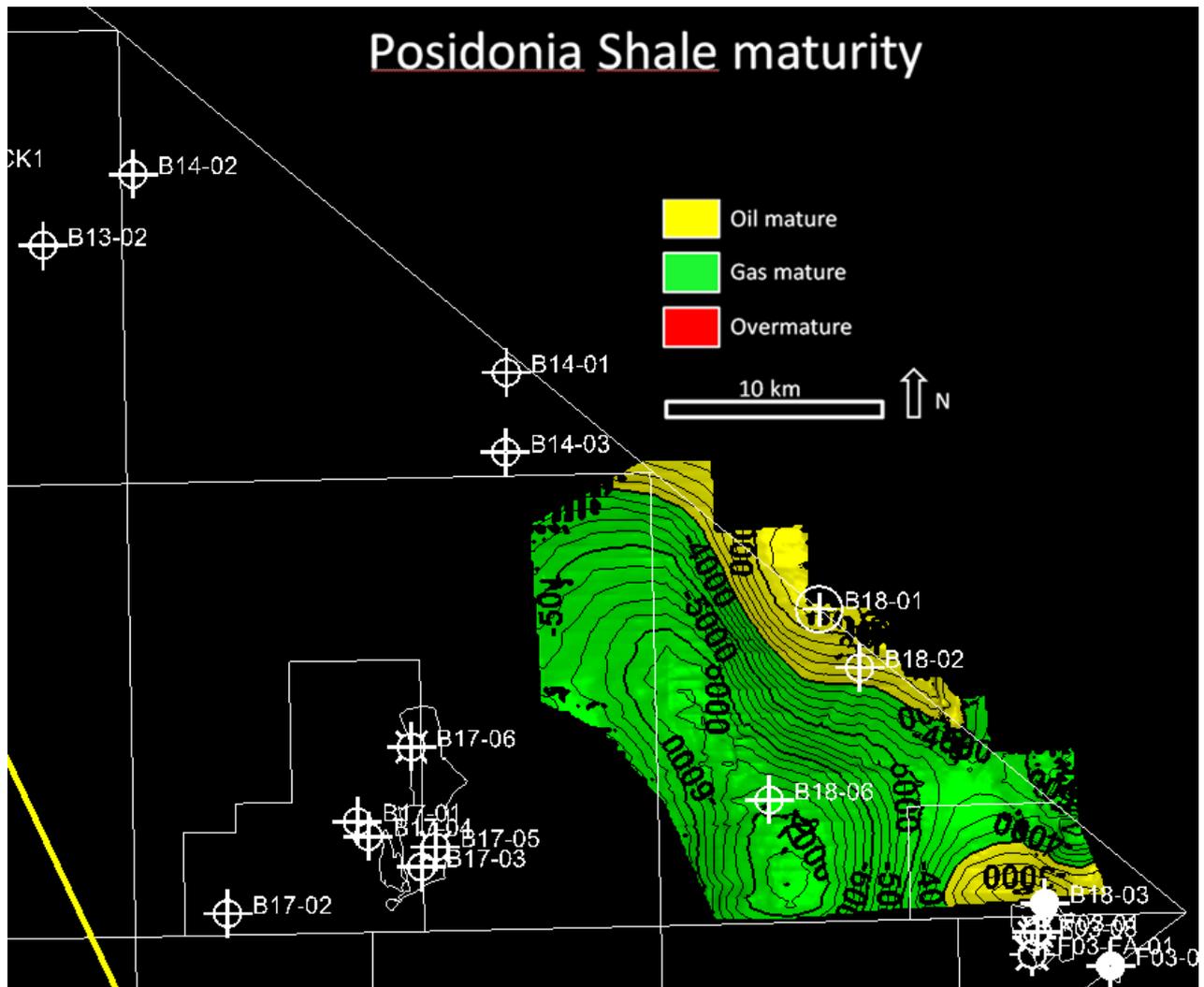


Figure 13; A map showing the depth and estimated maturity of the Posidonia Shale Formation in the study area. On the fringes of the Central Graben, the source rock is oil mature while deeper it is gas mature. However, since the Posidonia Shale is a type II source rock it has limited gas potential

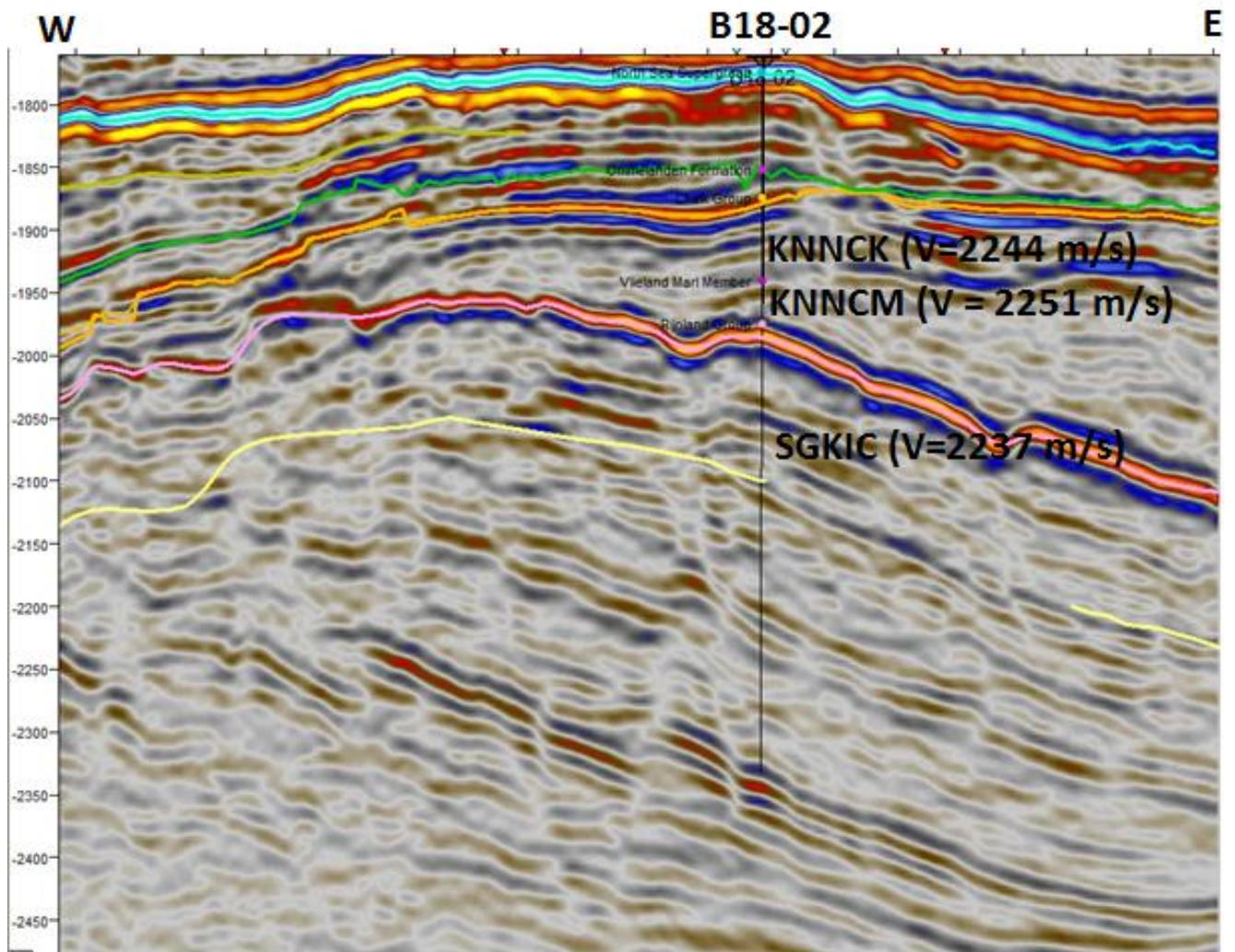


Figure 14; An E-W seismic section through well B18-02, showing the pick of the Clay Deep Member.

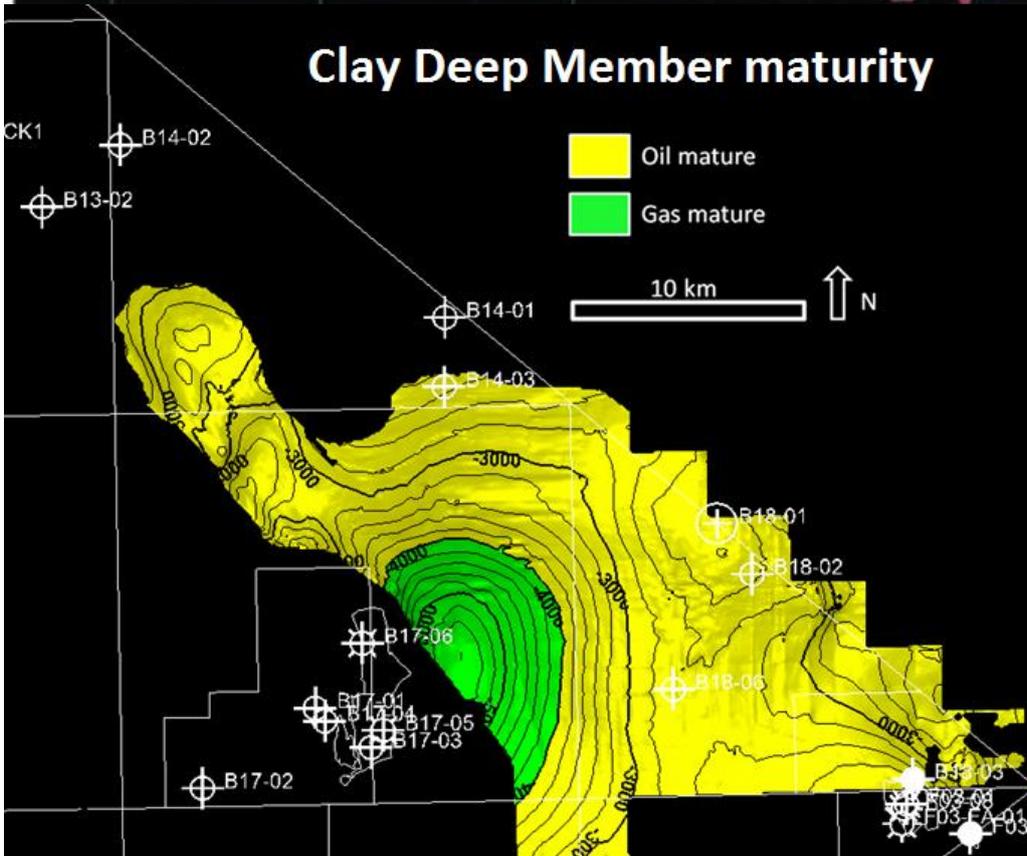
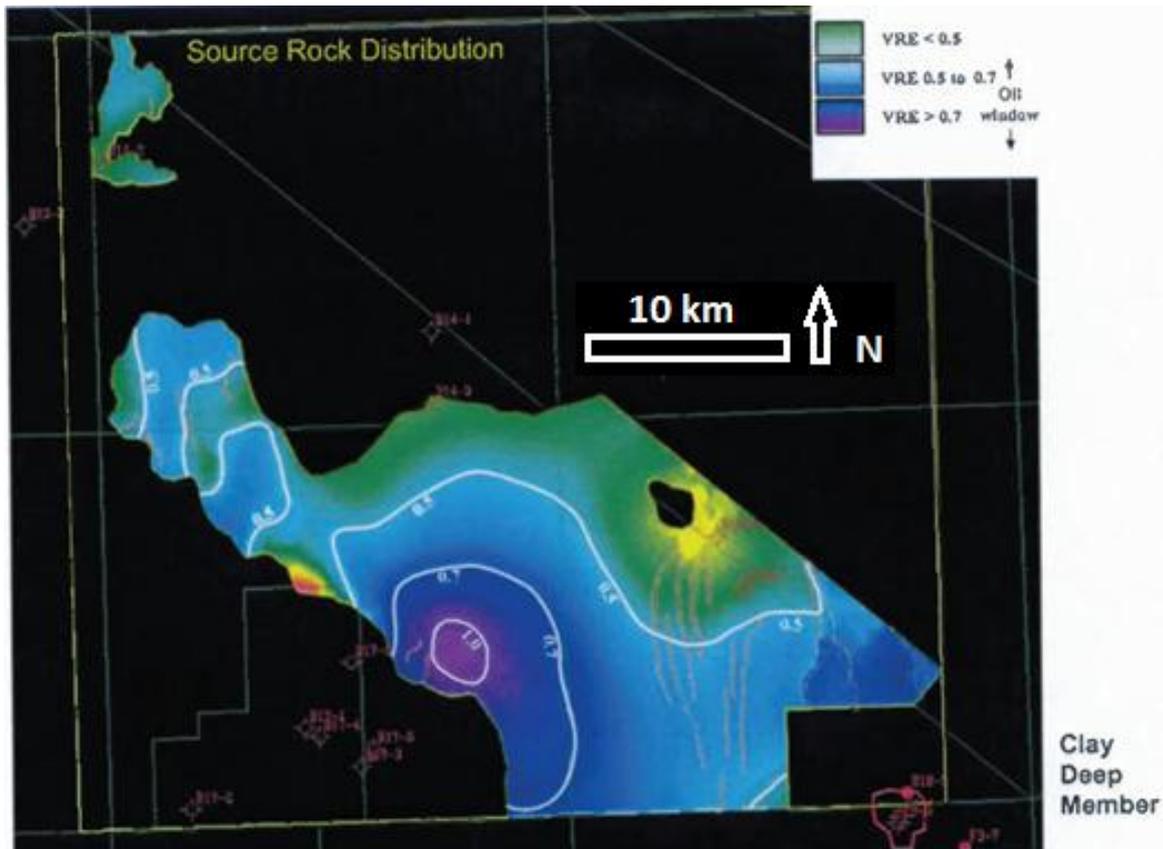


Figure 14;

Above: a map showing the modeled maturity of the Clay Deep Member by GDF Suez (2004). Below: A map showing the estimated maturity of the Clay Deep Member based on the depth model from this study. Overall, the Clay Deep Member seems to be more mature than in the GDF Suez model

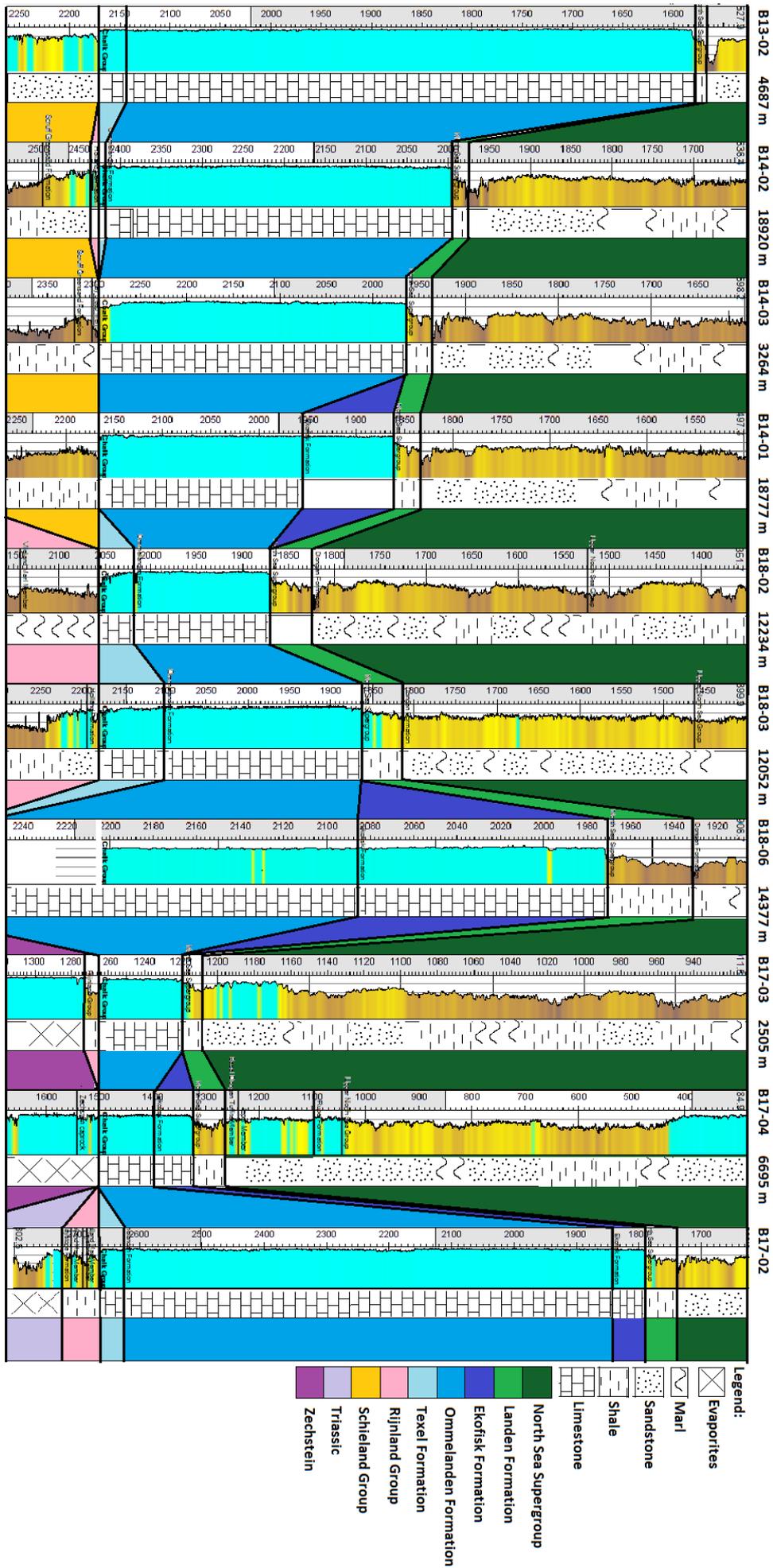


Figure 15; A well correlation flattened on the base of the Chalk Group. The sealing Landen Formation is present everywhere in the study area.

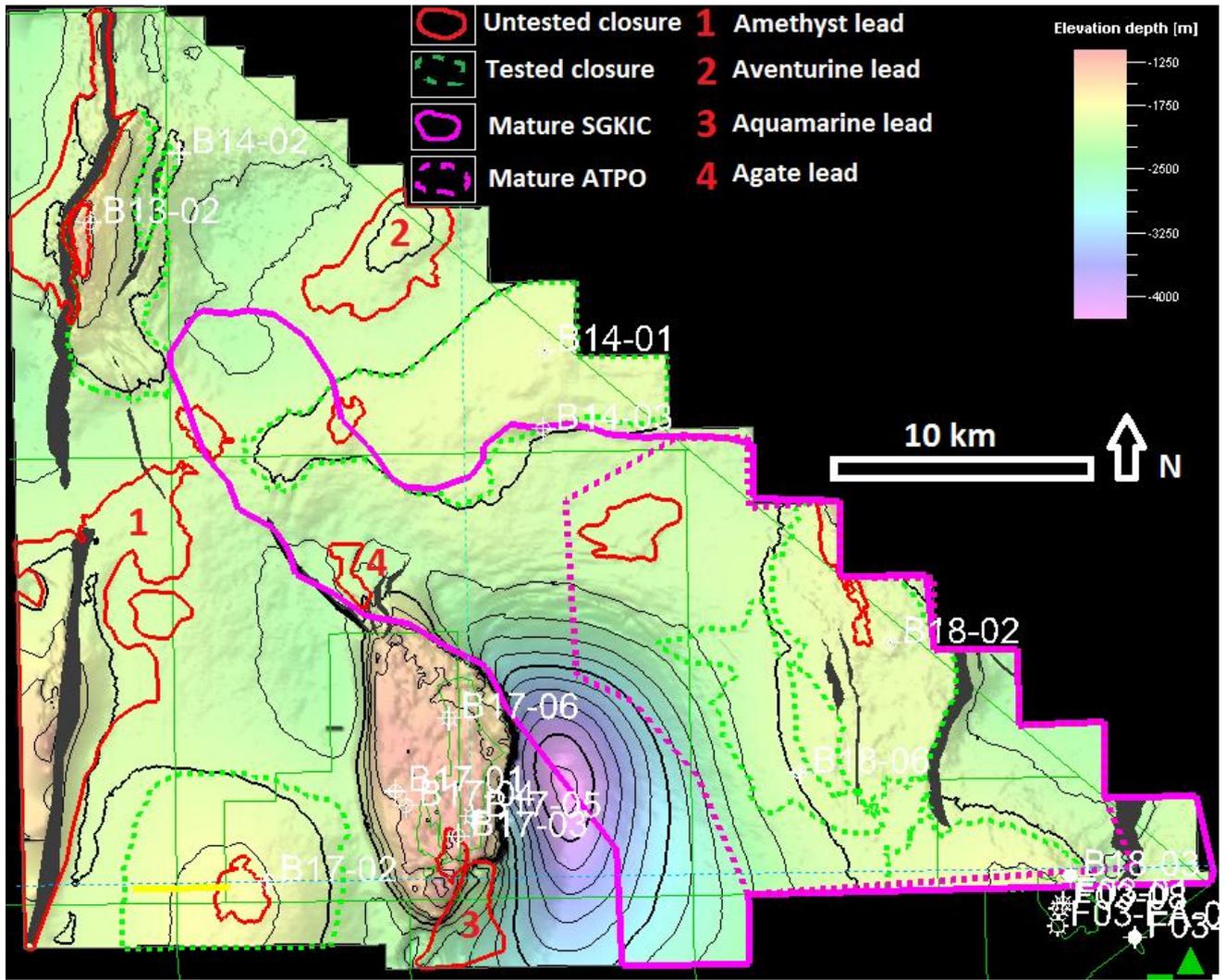
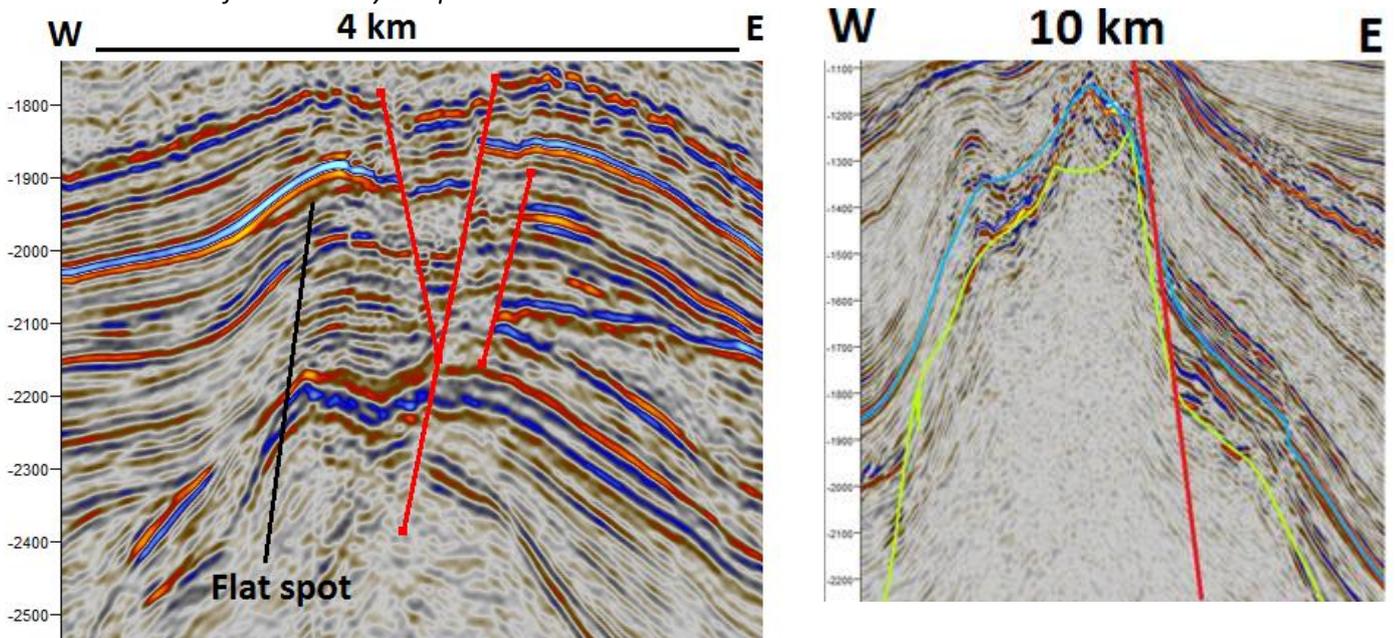


Figure 16; A play map of the Chalk Group, showing all play elements: the depth of the top Chalk, the distribution of mature Clay Deep Member and Posidonia Shale Formation. Also shown are tested



(green) and untested (red) structures. Four leads have been identified, numbered 1-4

Figure 17; left) an E-W seismic section showing the flat and bright spots in the Agate lead. Right) The truncation of the top Chalk (blue horizon) by the North Sea Supergroup on the very steep bounding fault of the Central Graben in the Aquamarine lead.

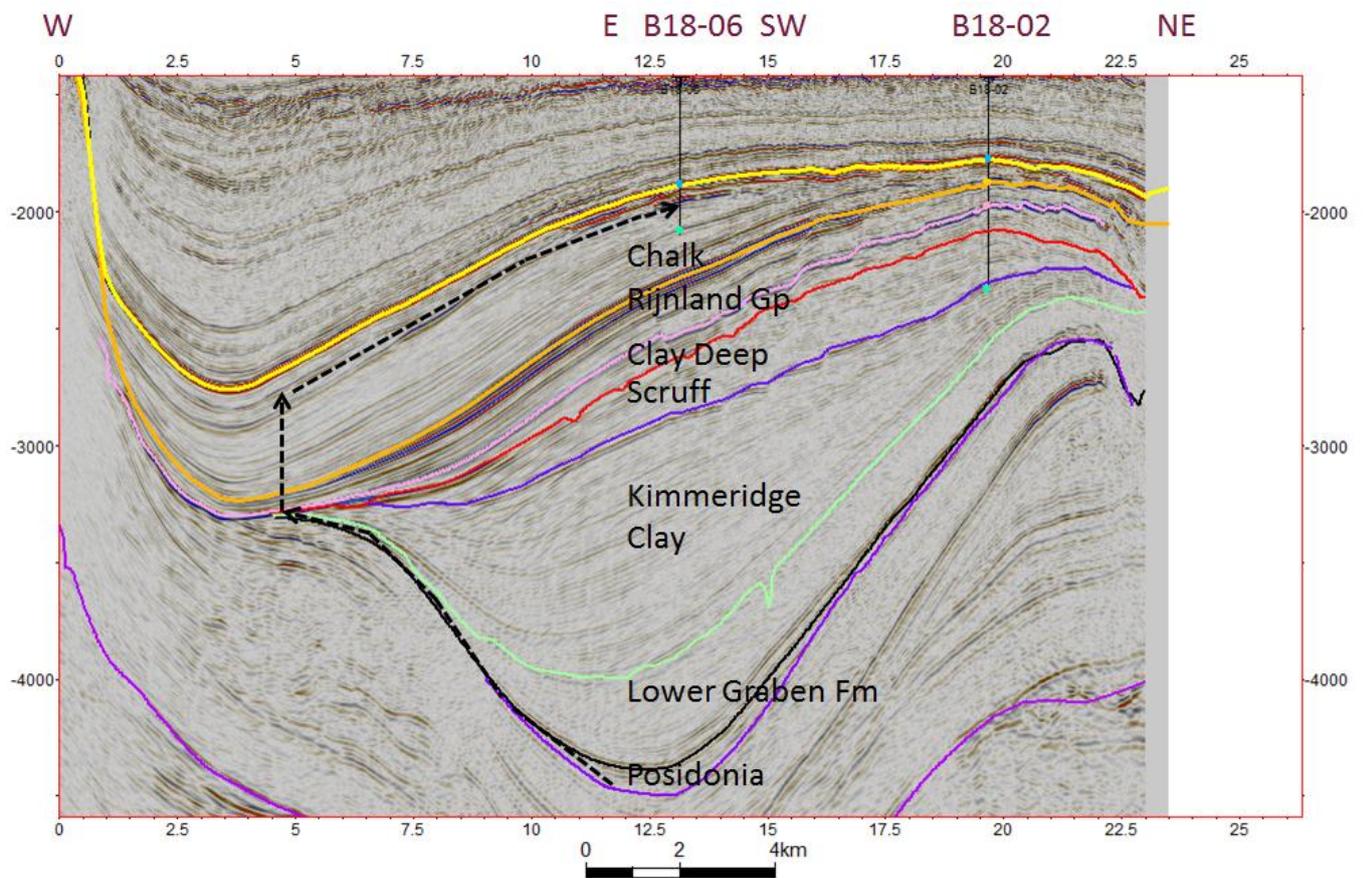


Figure 18 (previous page); the Amber prospect in the Chalk. Note the bright reflector underneath the base of the Tertiary (yellow) near well B18-06. The proposed migration route of gas charged from the Posidonia in the Central Graben is denoted by arrows. Probably, hydrocarbons proved unable to migrate through the thick chalk section in the rim syncline towards the west

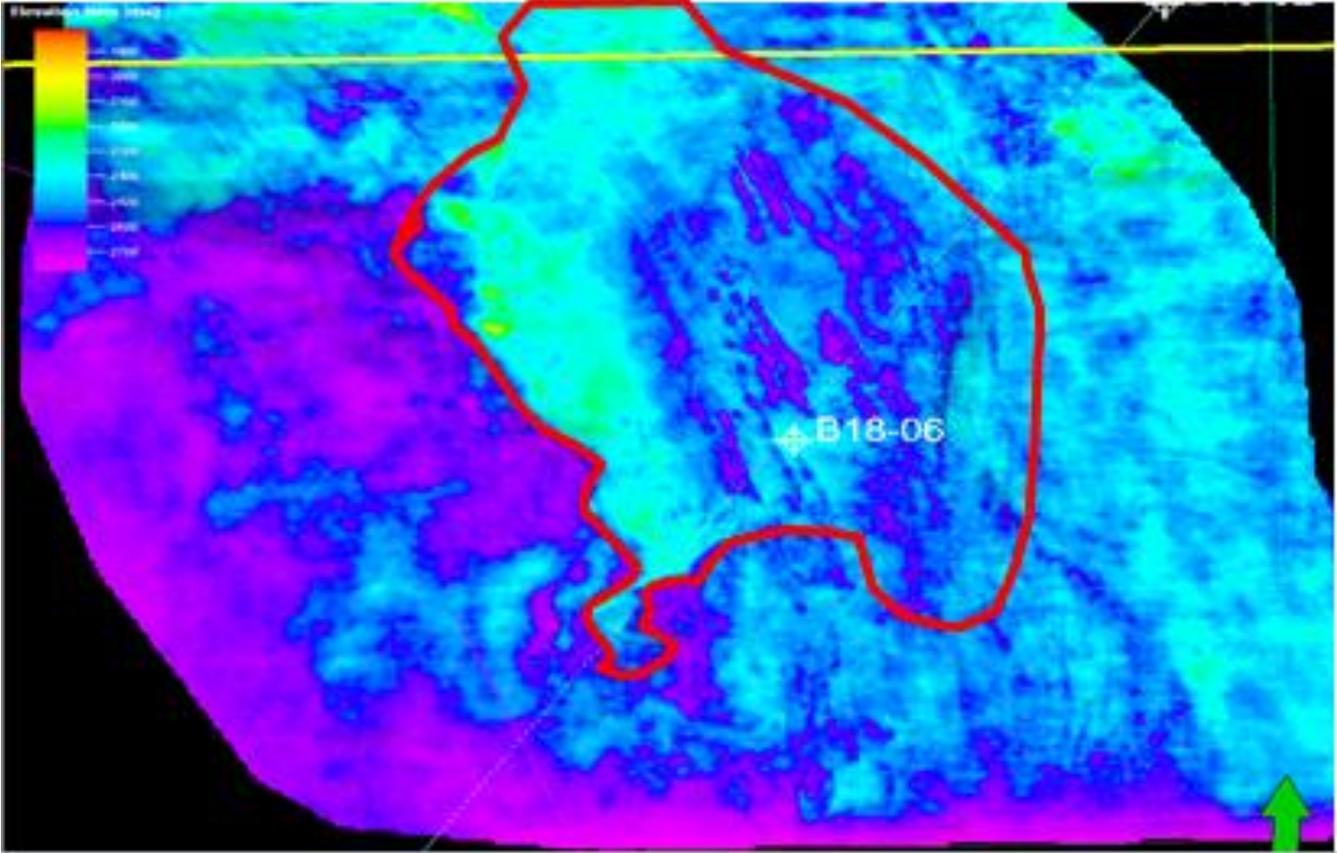


Figure 19; an RMS amplitude extraction below the base Ekofisk horizon. Blue-green colours represent higher amplitudes. The high amplitudes are correlated with locally enhanced porosities in the top of the Ommelanden Formation. In red, the Amber prospect is shown.

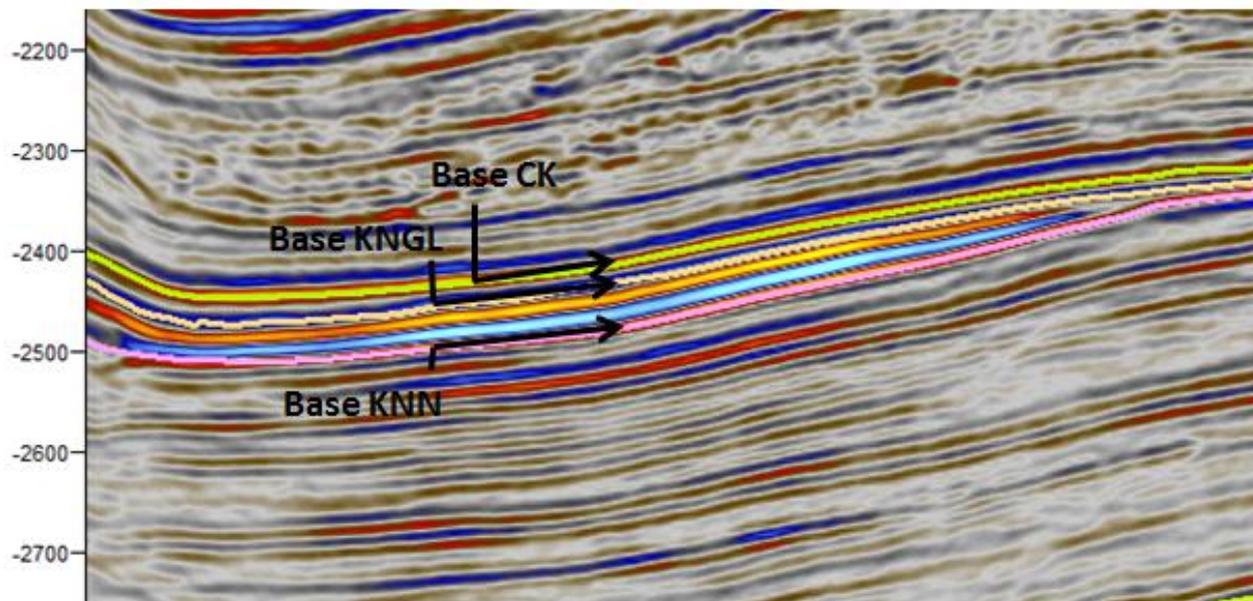


Figure 20; An E-W seismic section in the Step Graben showing the truncation of the Vlieland subgroup against the base of the Holland Formation.

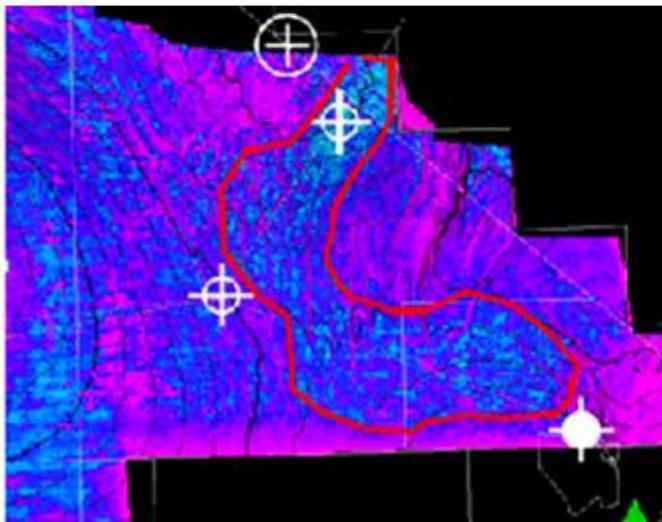
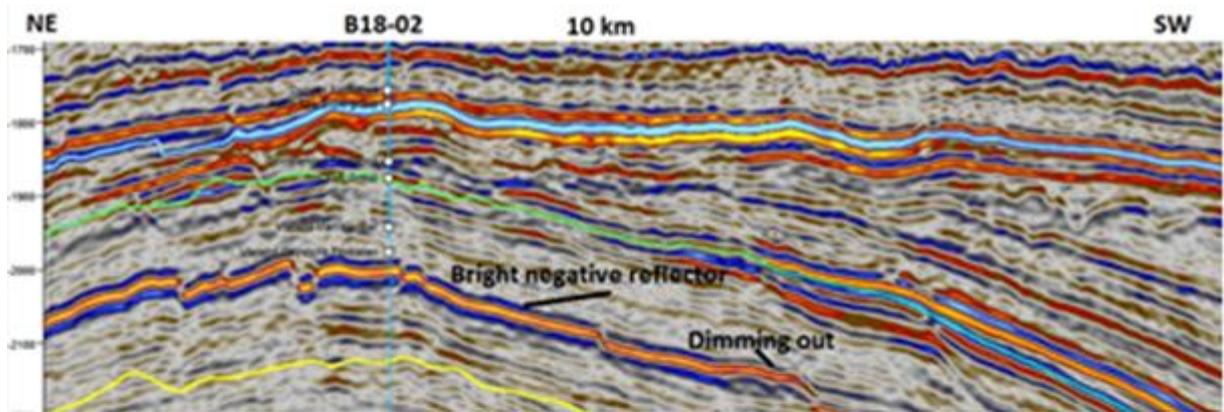
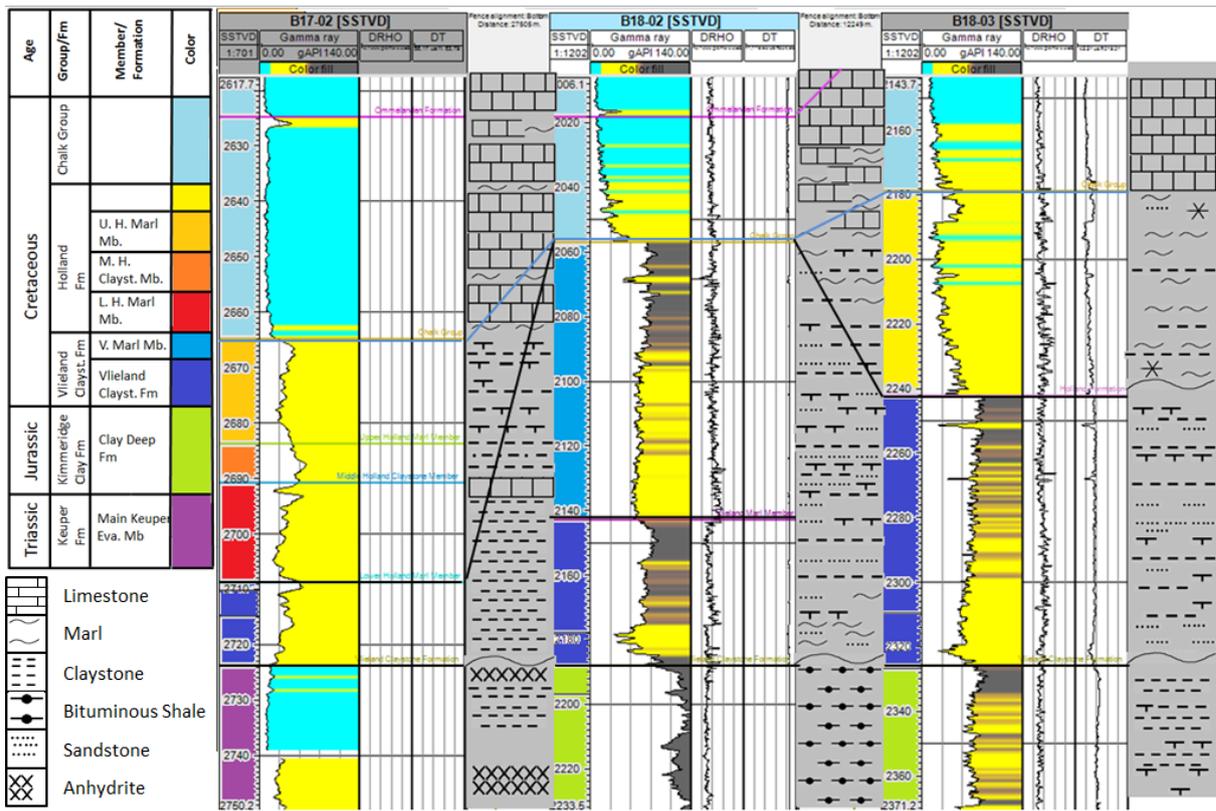


Figure 22; Above) A NE-SW seismic section through the B18-02 well, showing the dimming of the reflector which may represent the thin sandbody at the base of the Vlieland Claystone Formation. Below) the extent of the bright reflector

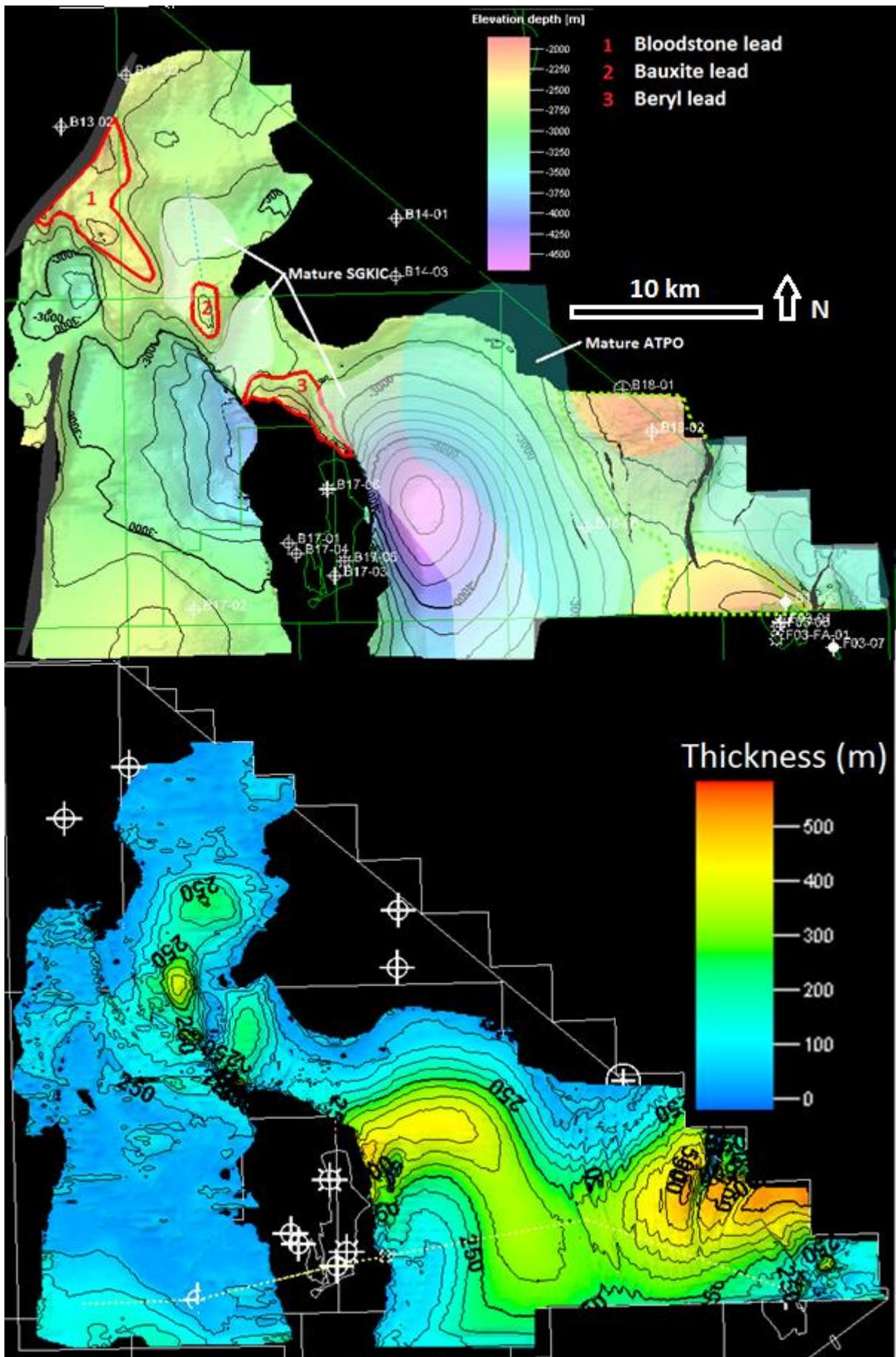


Figure 23 (previous page); Above) a play map of the Vlieland Sandstone play. The depth of the reservoir is shown as well as the distribution of mature Clay Deep Member and Posidonia Shale Formation. Based on the depositional model, three leads numbered 1-3 have been identified. Below) a thickness map of the Vlieland Claystone Formation

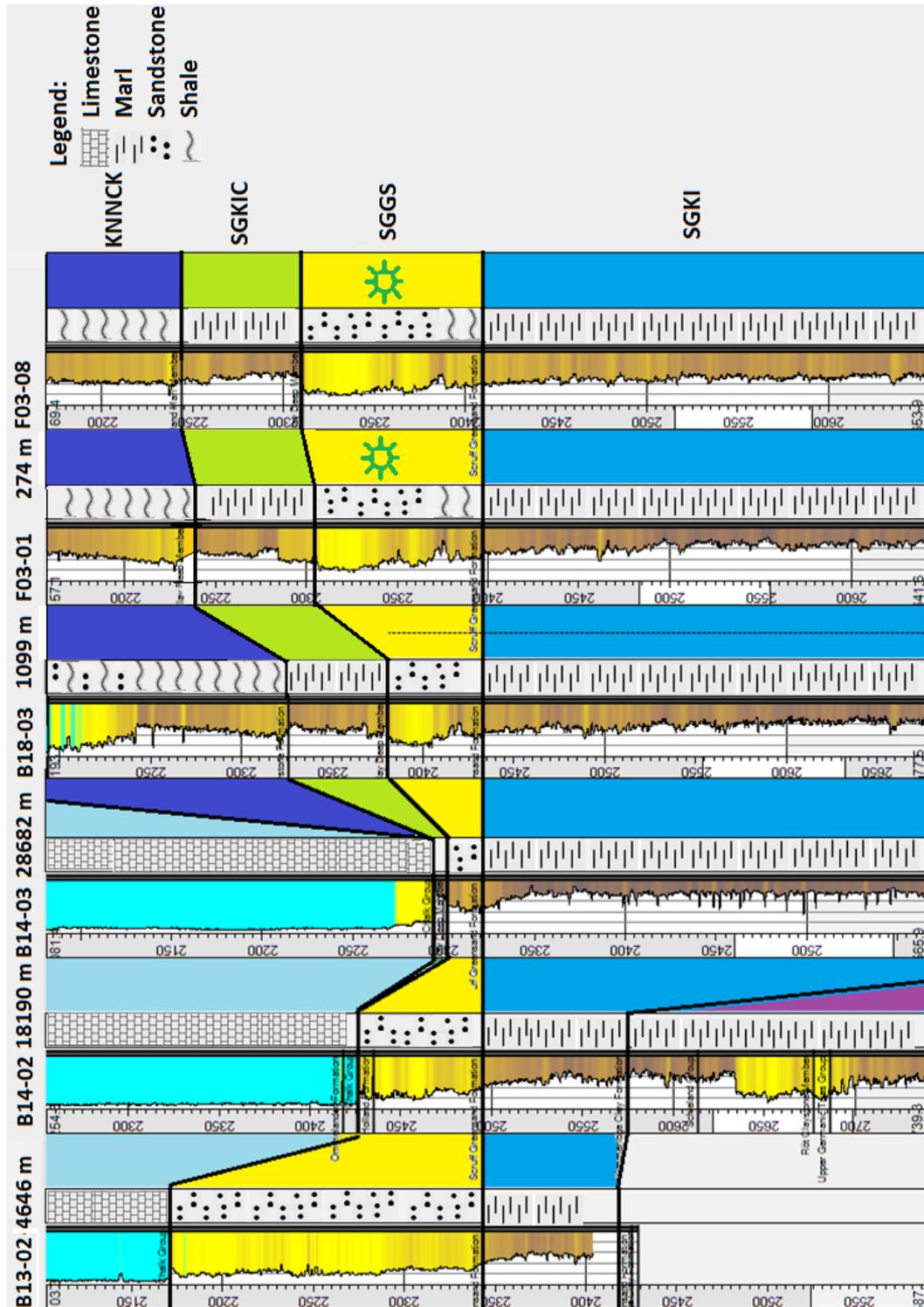
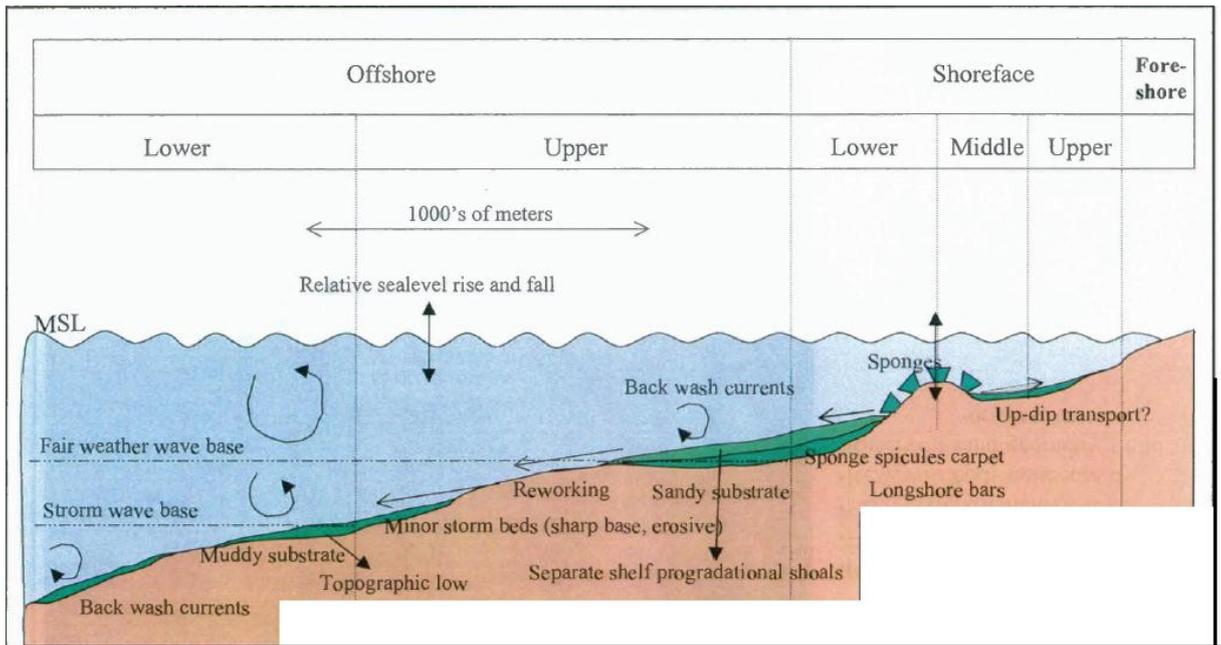


Figure 24; a well correlation flattened on the base of the Scuff Greensand Formation. Towards the north-west, the overlying Clay Deep Member thins out and the reservoir is directly overlain by the Late Cretaceous Chalk Group



Figur 25; A schematic overview of the depositional environment of the Scruff Greensands. Sponges grow near the shoreline in clear water; spicules from these sponges are transported a short distance basinwards where they form high-porosity spiculite sandstones.

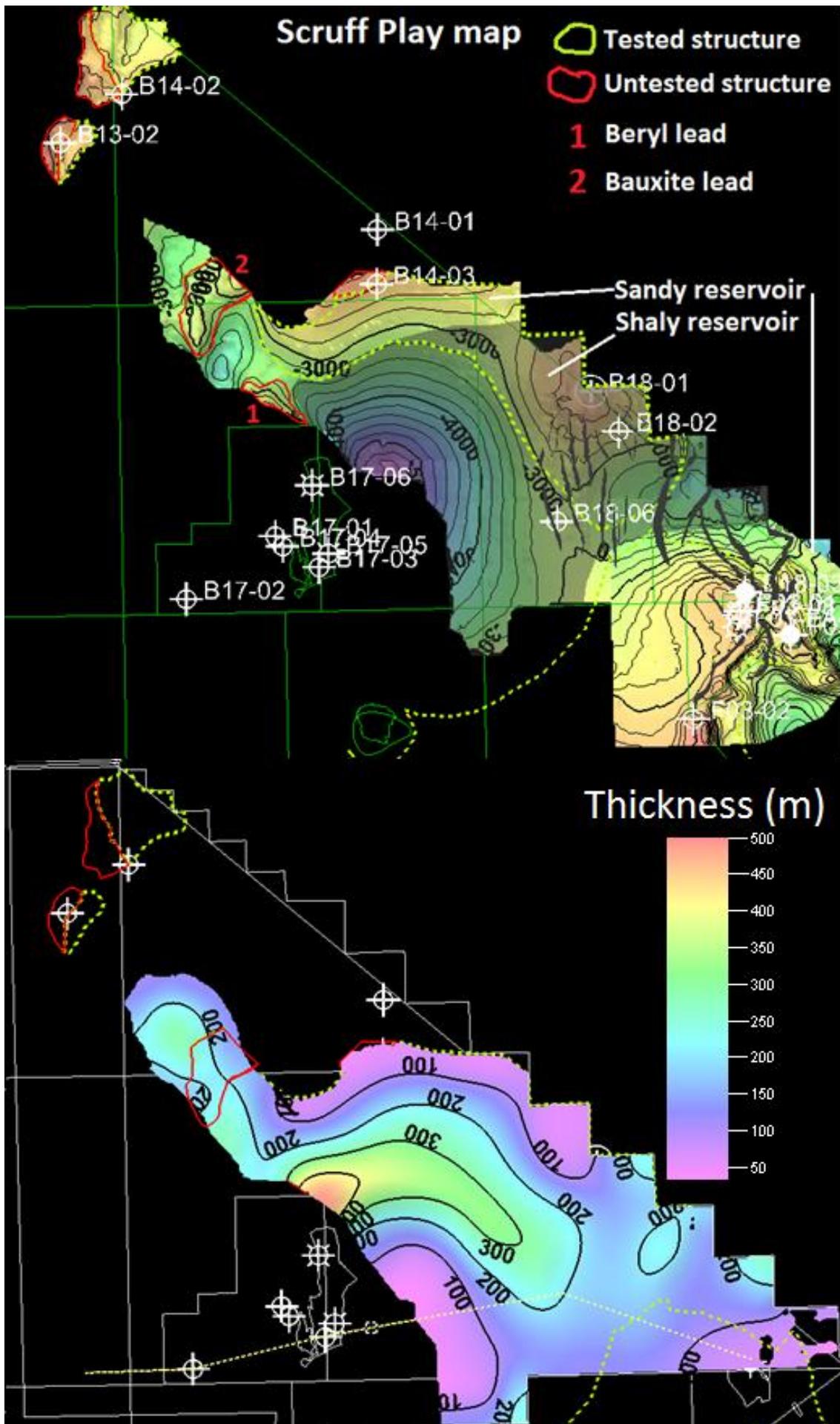
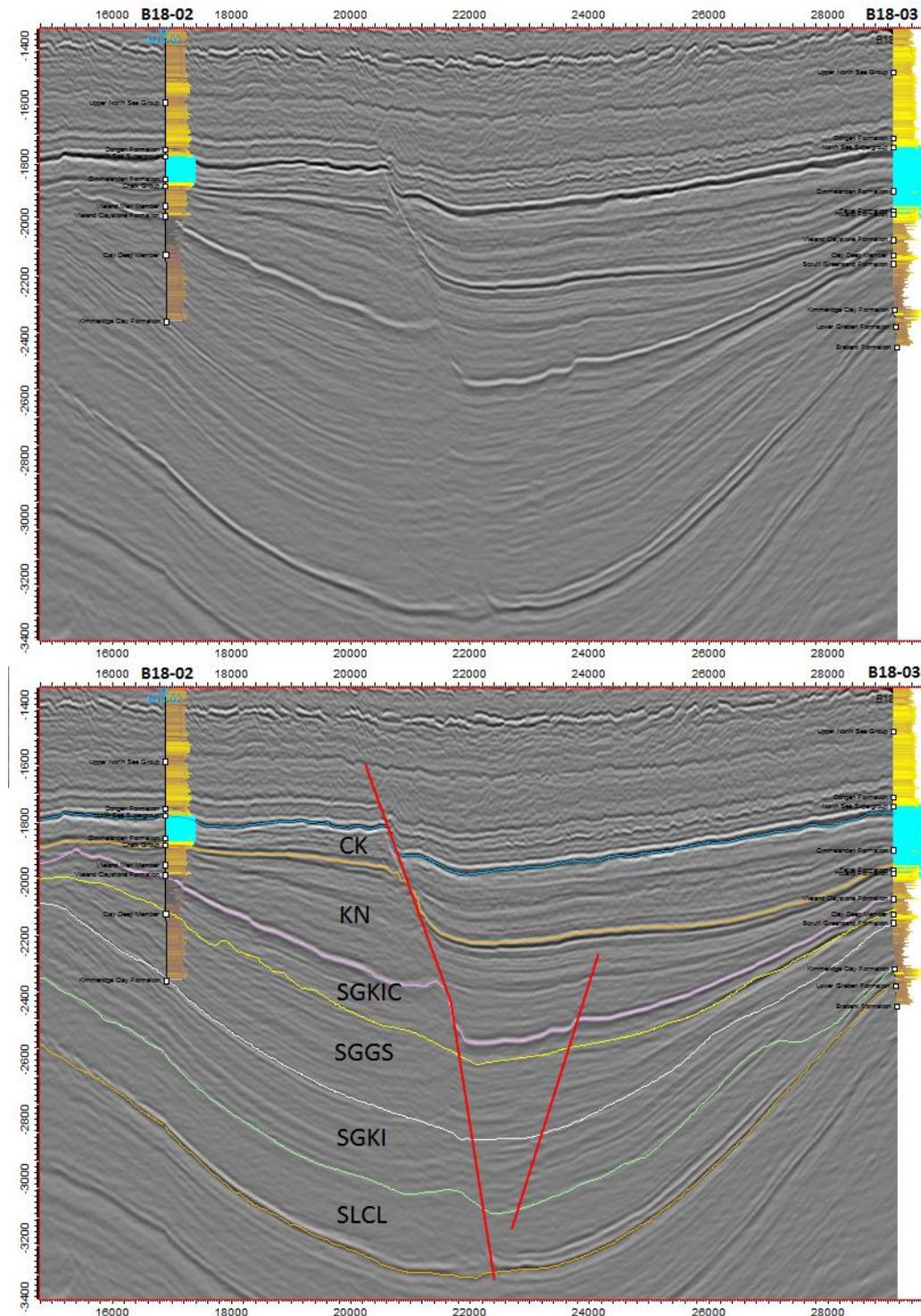


Figure 26 (previous page); A play map of the Scruff Greensand play. Top) Depth of the Scruff Greensand Formation with tested (green) and untested (red) structures. Also shown are fault polygons and the area where the Scruff is likely to be shaly (dark shaded). Bottom) Thickness of the Clay Deep Member which is the top seal for the Scruff Play

Figure 27; a seismic section connecting the B18-02 and B18-03 wells. The Scruff Greensand Formation should be present as a thick (~200 ms) section in the B18-02 well; however, only Kimmeridge Clay is encountered here below the Clay Deep Member. Somewhere in this section, the sandstones of the Scruff Greensand shale out into the claystones of the Kimmeridge Clay Formation.



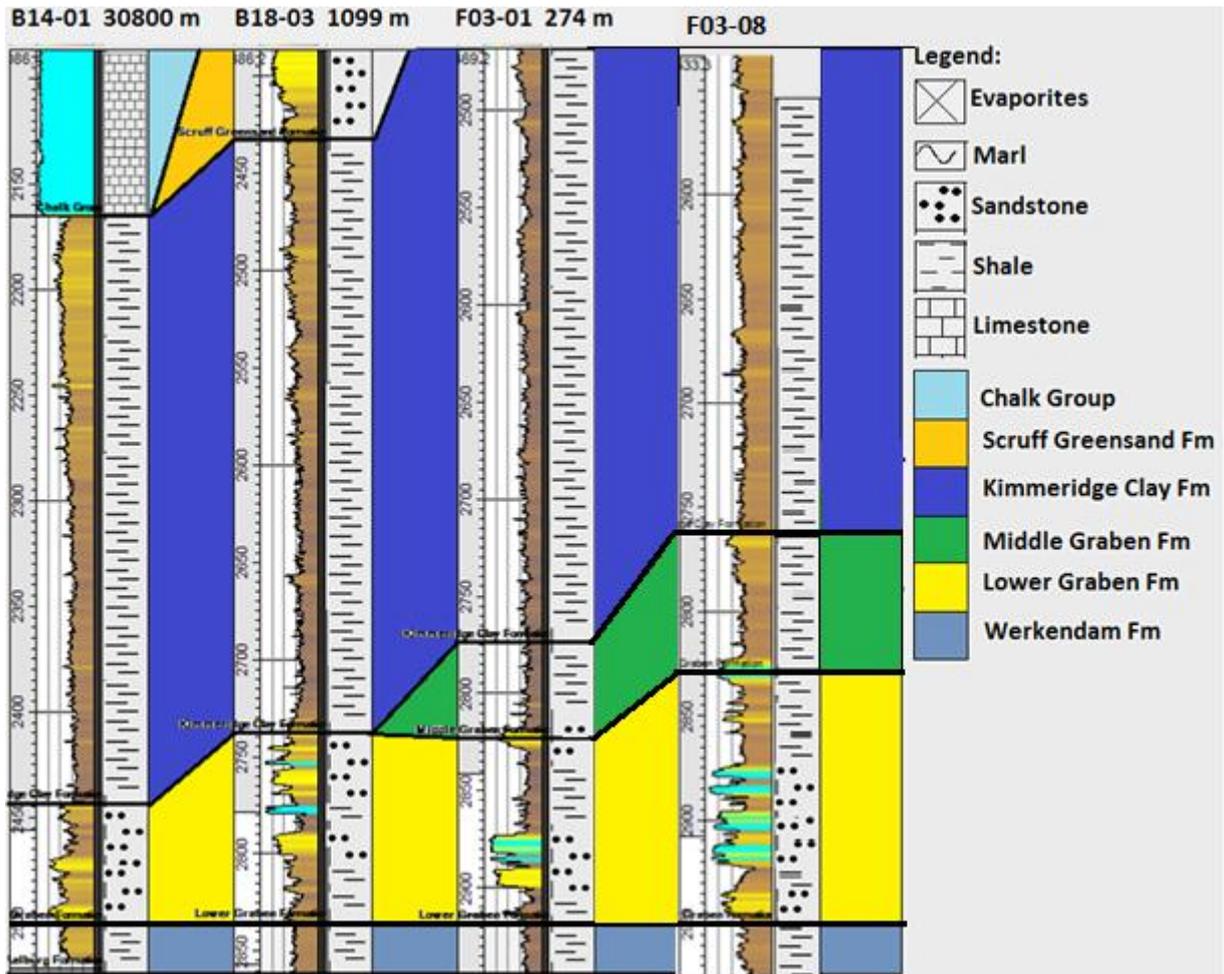


Figure 28; A well correlation of the Lower Graben Formation. Several stacked sandbodies make up the reservoir formation; in the F3-FA field it is overlain by the Middle Graben Formation while in the study area this is absent

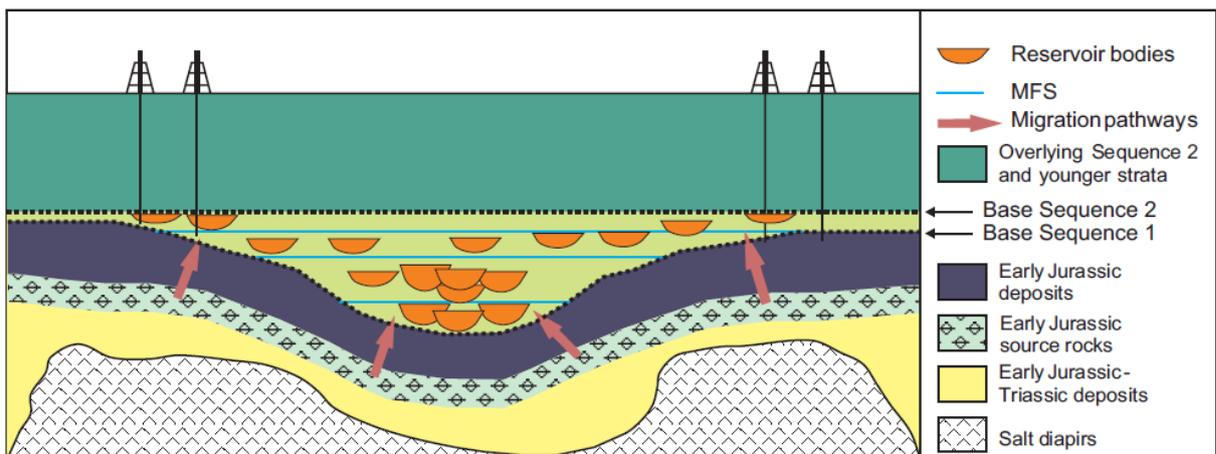


Figure 29; A conceptual play overview, showing the Posidonia Shale Formation from which oil charges through the Werkendam Formation into the isolated channel infills of the Lower Graben Formation. N/G ratios are probably higher in the center of the basin where the fluvial axis was located

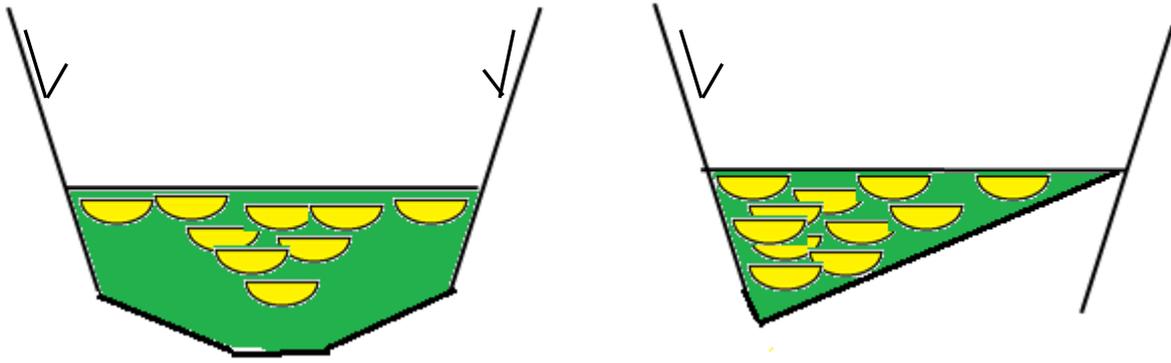


Figure 30; A conceptual figure showing the distribution of sandbodies in a fault-bounded graben. If faults on both sides of the graben are active, subsidence is highest in the center of the graben. If the graben is asymmetrical, more channels will be located on the active side

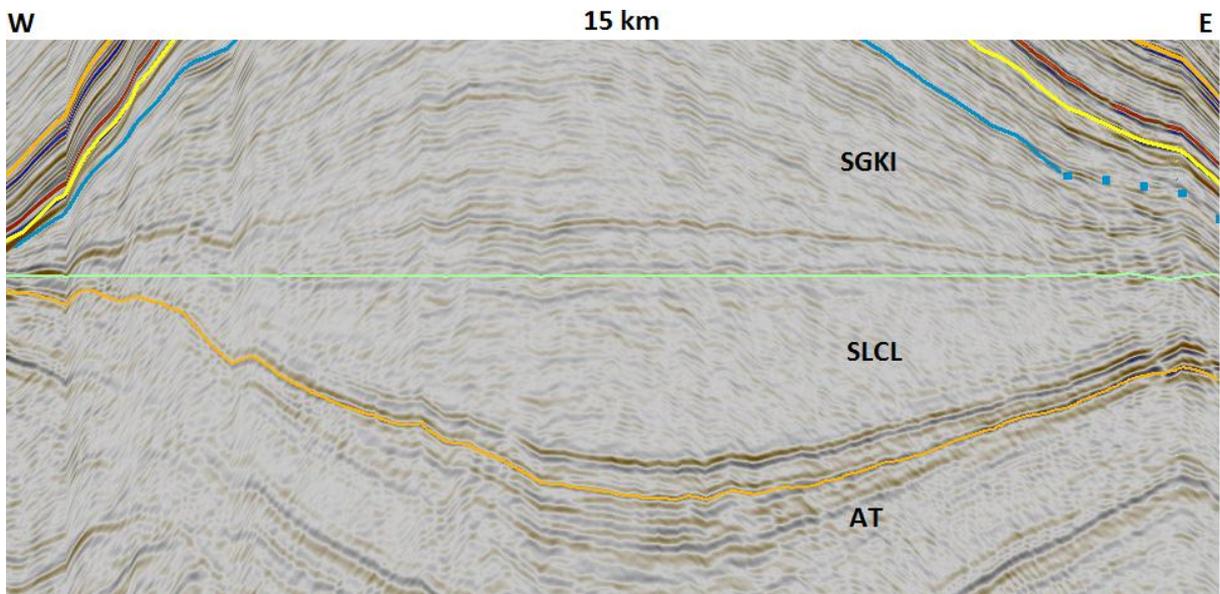


Figure 31; An E-W seismic section through the Central Graben flattened on the top of the Lower Graben Formation. The formation is thickest in the center of the graben so probably, the highest channel density will be here. The seismic character of the Lower Graben Formation is different from the over- or underlying sediments. The discontinuous, transparent reflectors are probably channel deposits. The bright reflector at the base of the formation may be a coal seam.

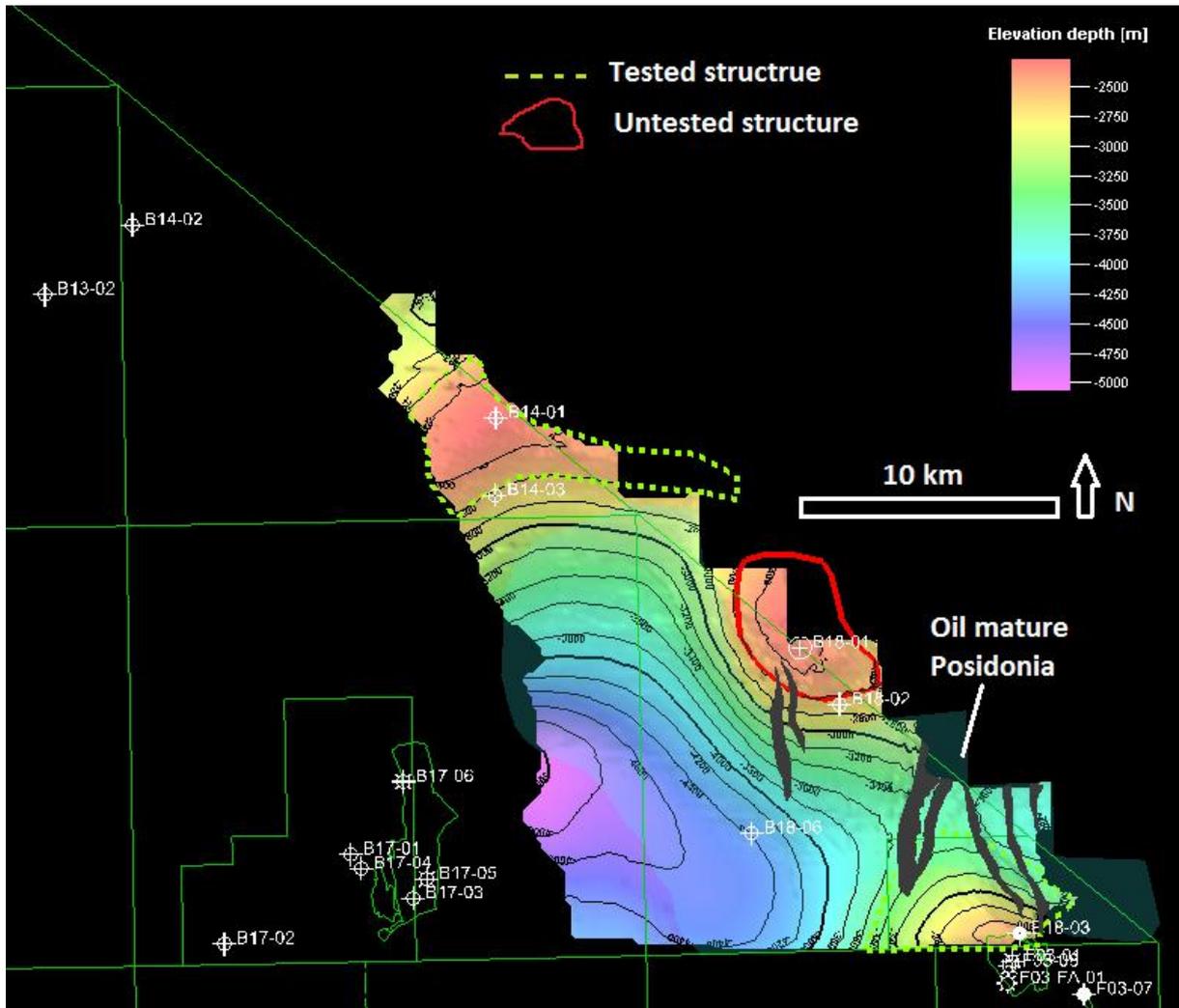


Figure 32; A play map of the Lower Graben Play. Also shown here is the distribution of mature Posidonia Shale Formation (blue shaded). Only one structural closure has not been drilled yet. However, just over the German border, the B18-01 well probably penetrates the Lower Graben Formation. No information about the well results is available, though.

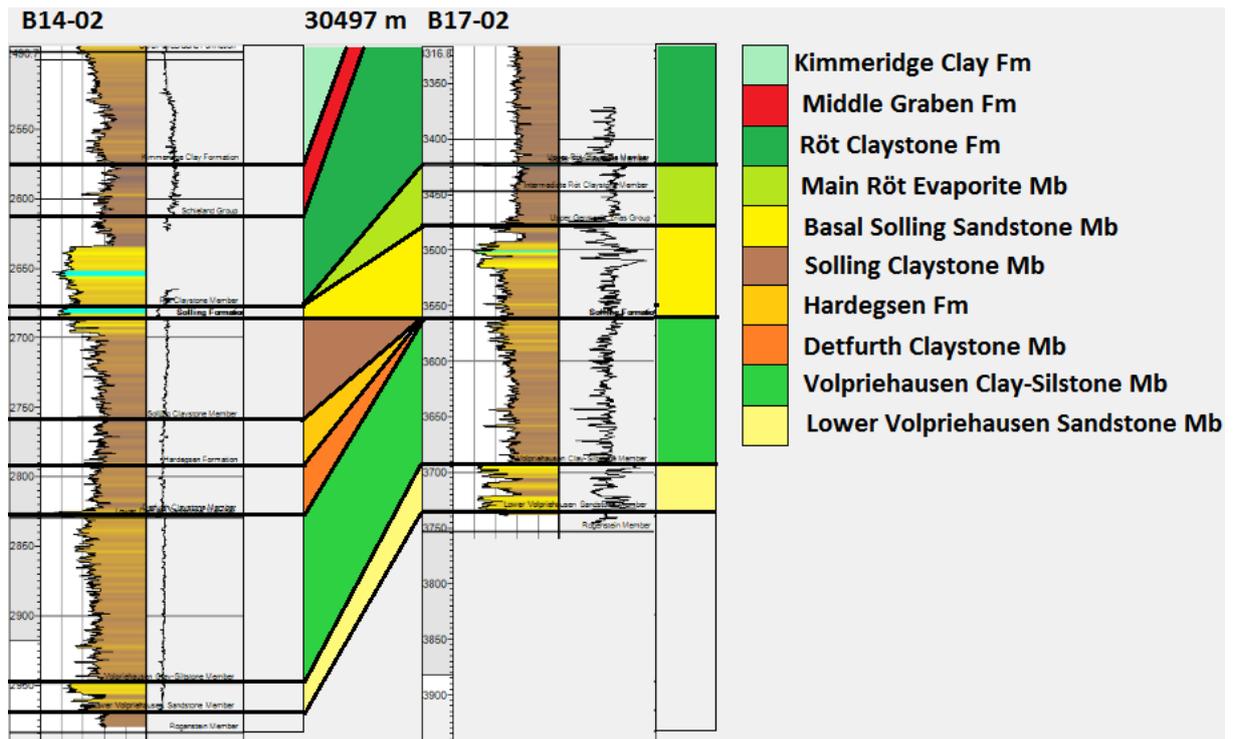


Figure 33; A well correlation of the Lower Buntsandstein, flattened on the base of the Solling Formation. In well B14-02, several lithostratigraphic units are present which are absent in well B17-02. In both wells, the Detfurth sandstone is absent and the third Lower Buntsandstein reservoir, the Lower Volpriehausen Sandstone Member, is present as a tens of meters thick sequence of stacked sandbodies

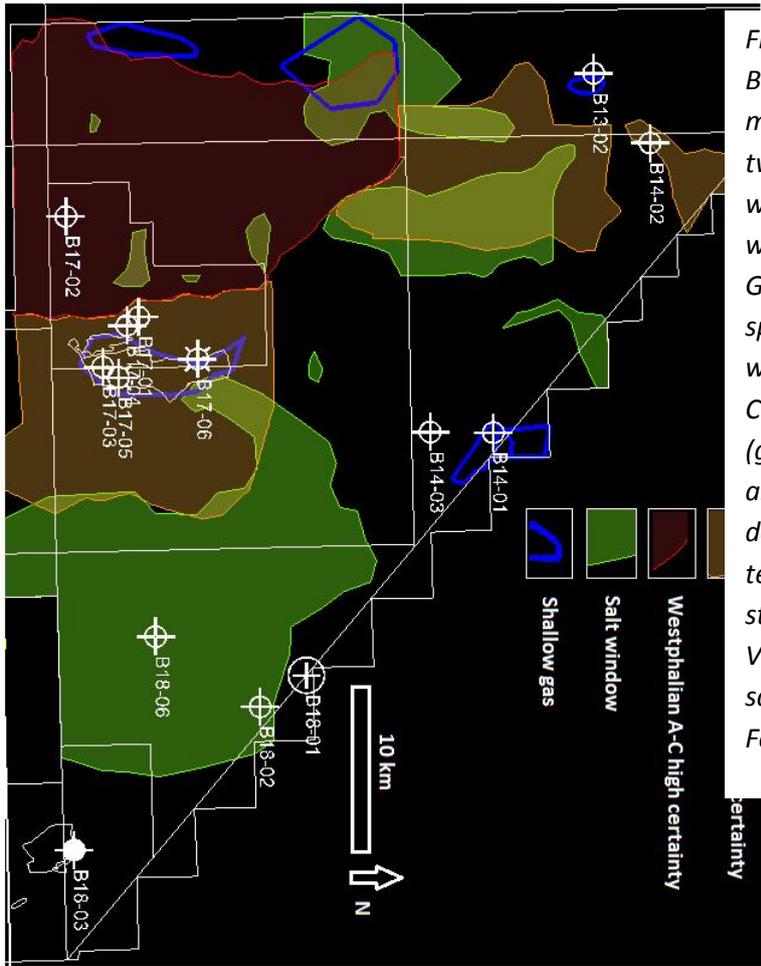
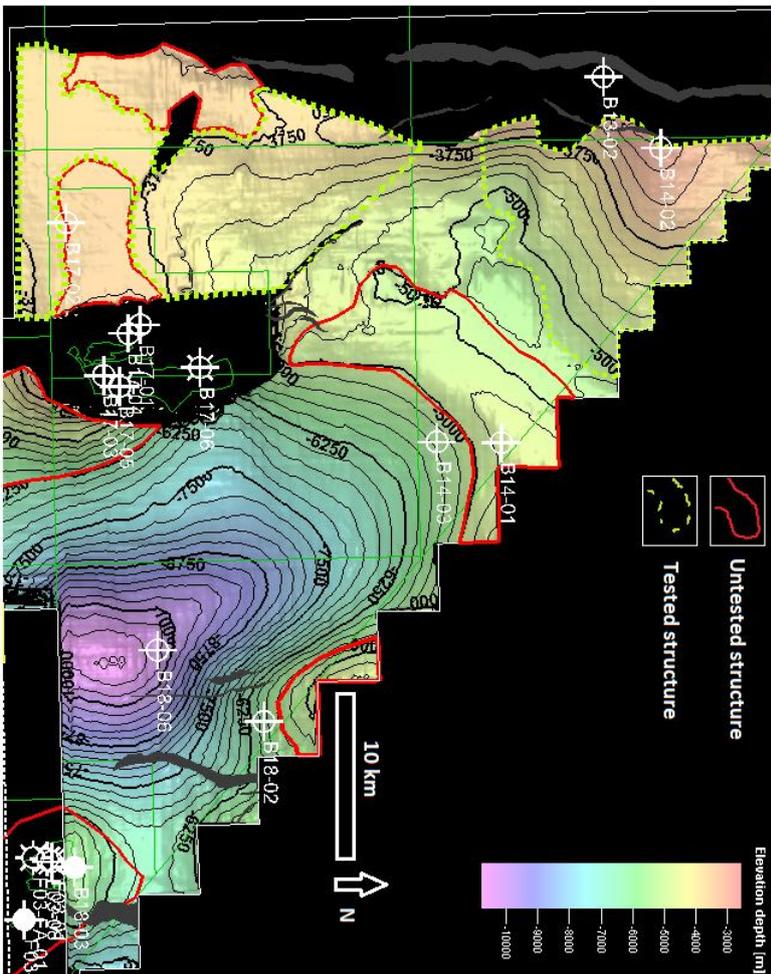


Figure 34; A play map of the Lower Buntsandstein play. Left) the mapped Westphalian is divided into two domains: the Step Graben, where it could easily be traced from well B17-04, and outside the Step Graben, where its presence is more speculative. Also shown are salt windows through which Carboniferous gas may migrate (green) and locations with amplitude anomaly outlines (blue). Right) The depth of the Solling Formation, with tested (green) and untested (red) structures shown. The Detfurth and Volpriehausen reservoirs have the same structure as the Solling Formation



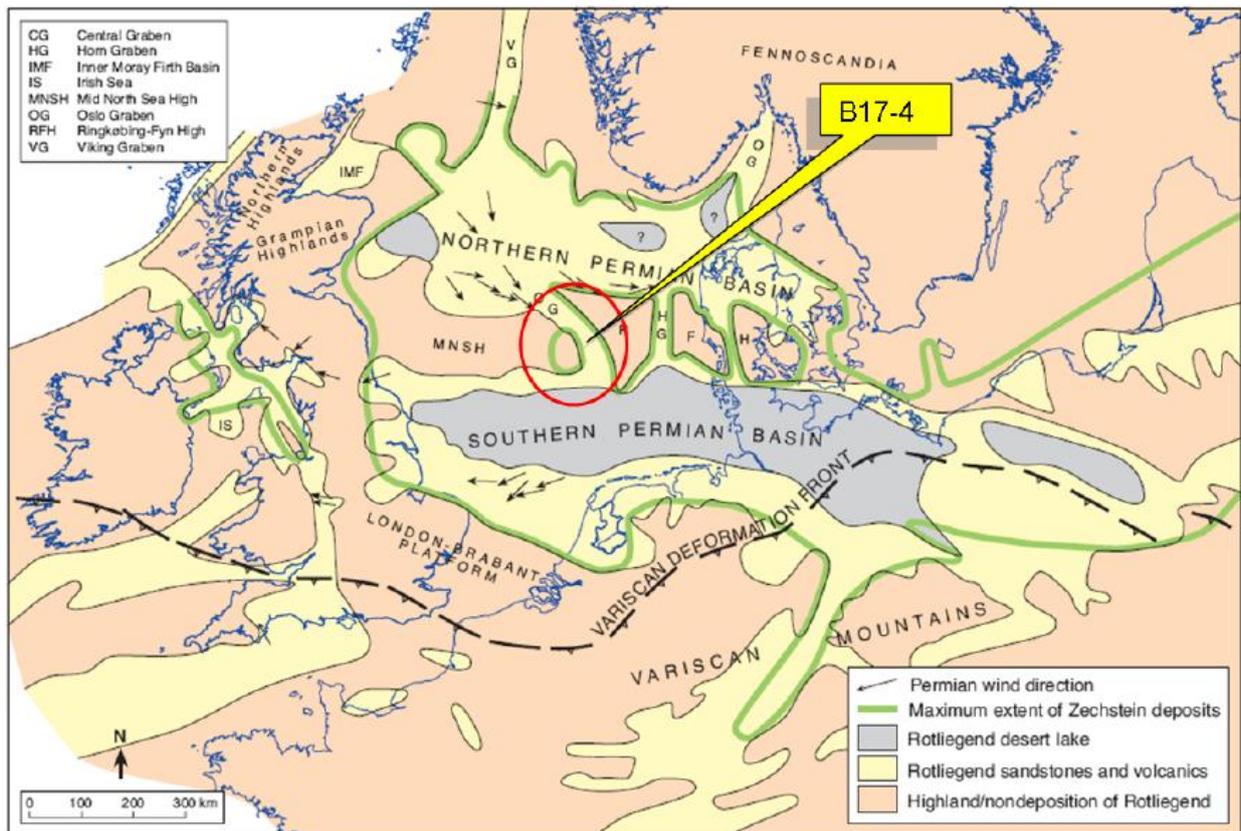


Figure 35; A map of Permian basins, showing the Northern and Southern Permian basin, which were connected by a series of large channels. One of these channels ran just east of the B17-04 well and may indicate that the western bounding fault of the Central Graben was already active during Permian times. Source: Glennie, 2002 in the Millennium Atlas

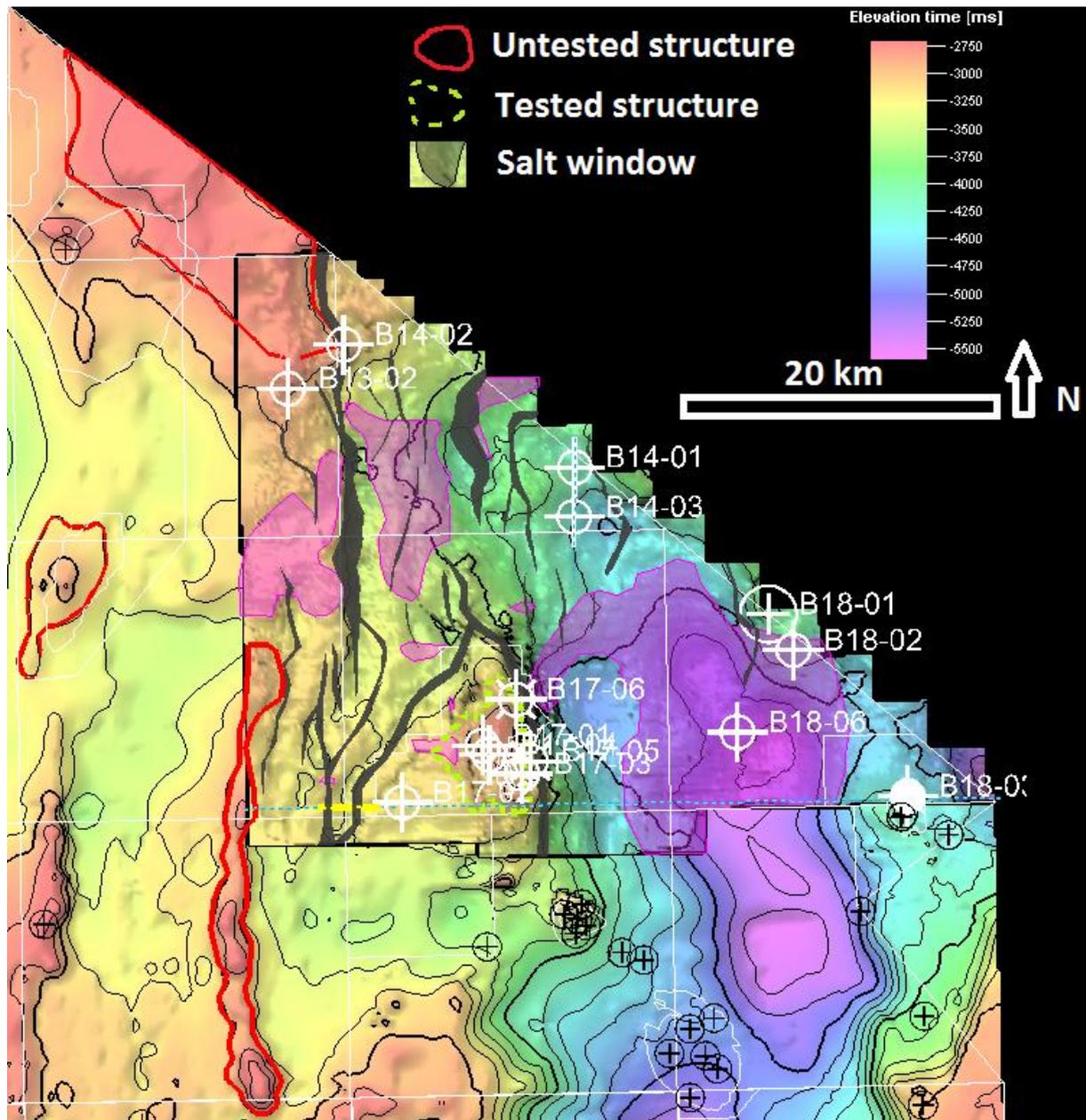


Figure 36; A play map of the Rotliegend Play. Shown are salt windows where the seal of the play may be absent (purple). There are three structures which have not yet been drilled

Figure 37; A seismic Z-section at ~100 ms. A large, N-S trending channel can clearly be seen on seismic; several smaller, meandering channels are connected to the glacial channel. Note that the channel in the B17 block coincides with the position of the western bounding fault of the Central Graben. This may indicate that the fault continues to be active

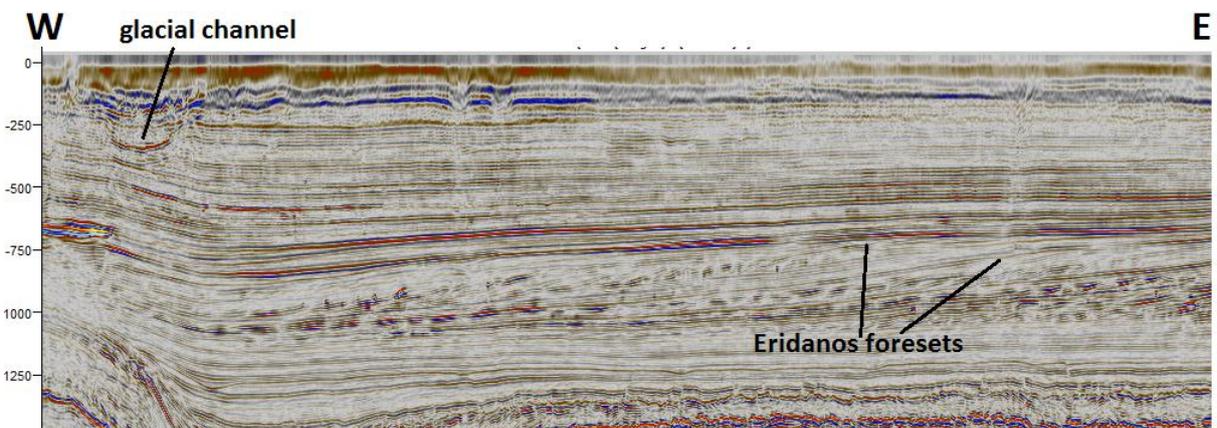
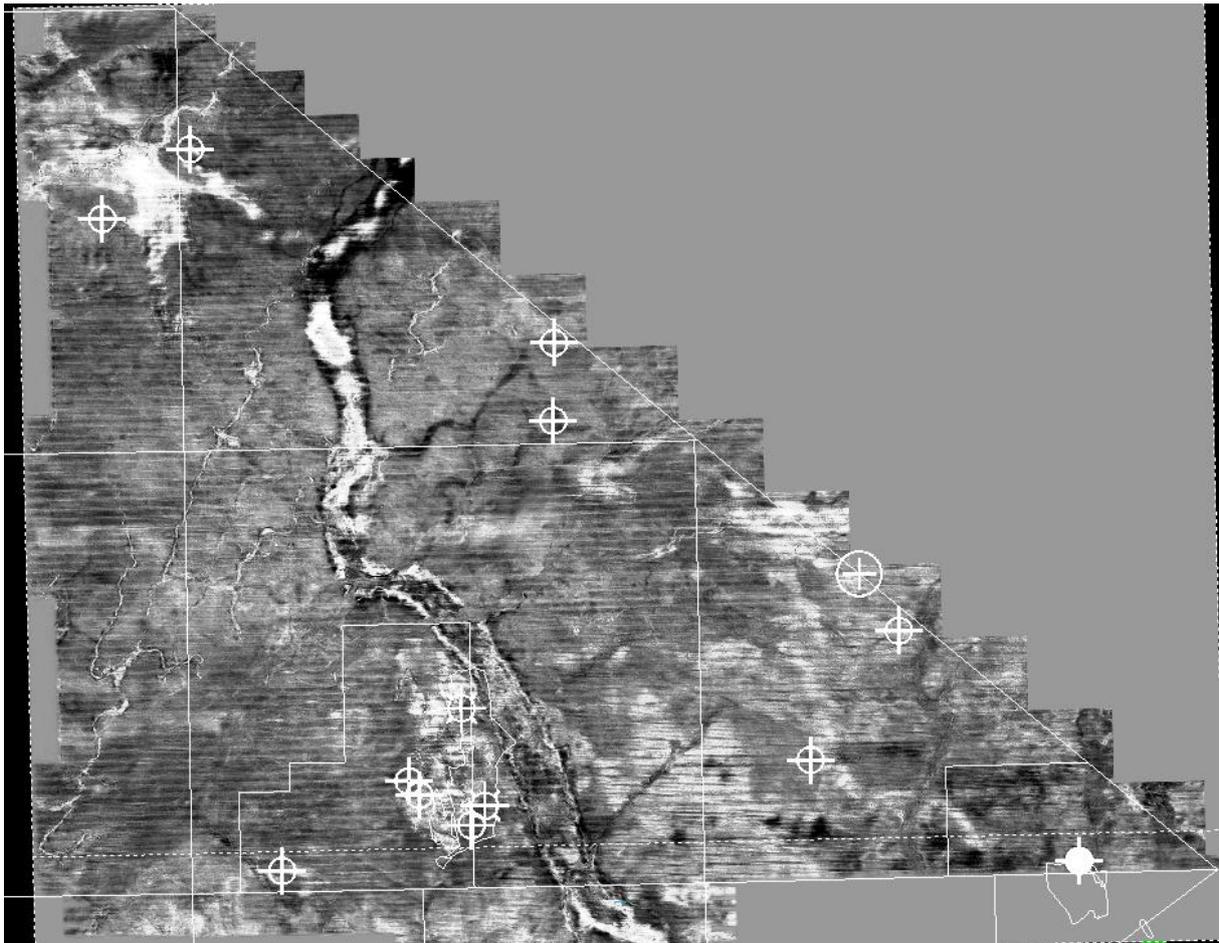


Figure 38; an E-W seismic section showing the Upper North Sea Group. The glacial channel shown in figure 37 can be seen on this cross-section. Deeper down, large foresets from the Eridanos delta can

be observed

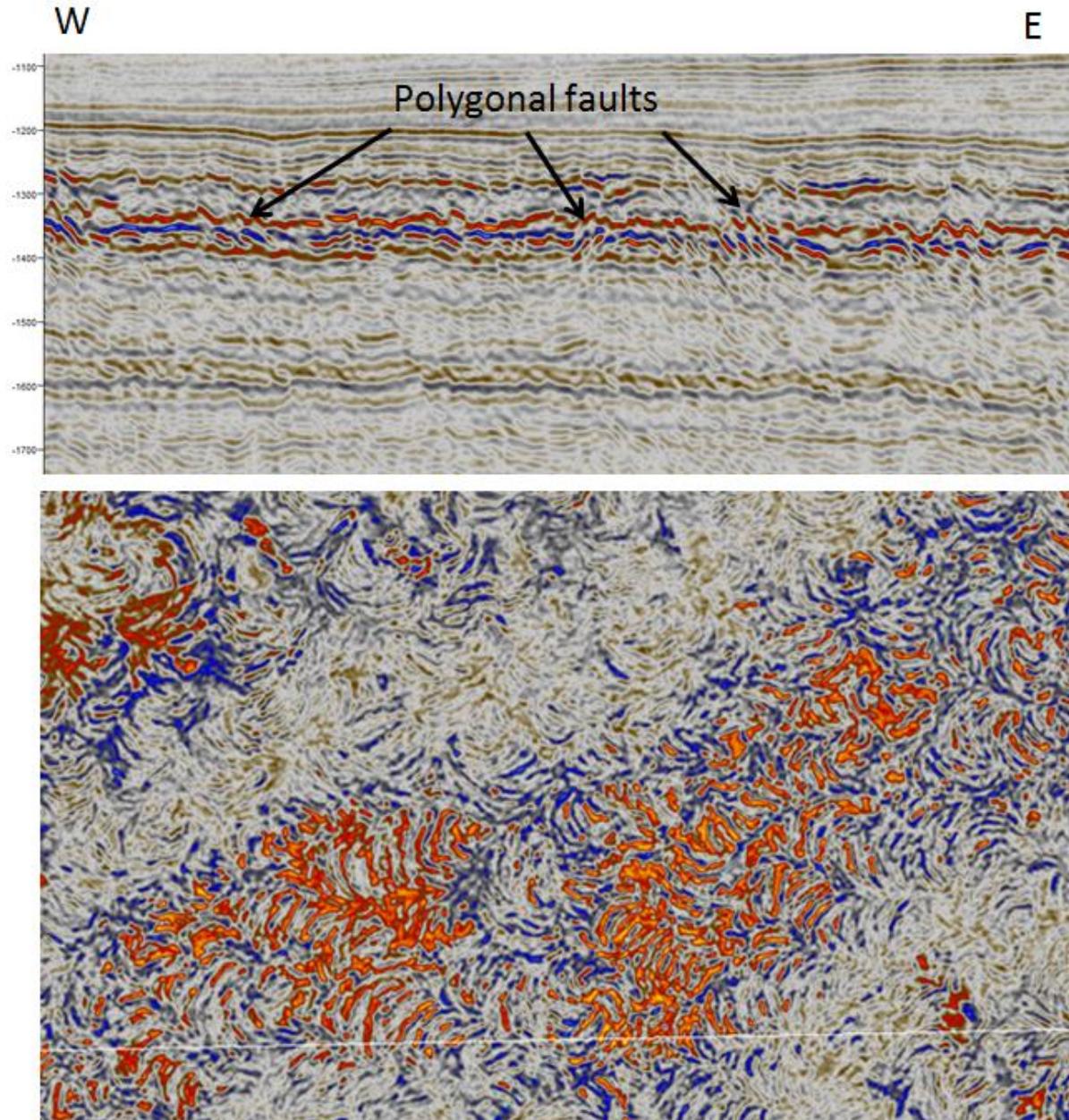


Figure 39; The Mid Miocene Unconformity shows up on seismic as a bright reflector which is broken up by faults. Above) an E-W section, showing the Mid Miocene Unconformity. Below) A top-view of the Mid-Miocene Unconformity; the polygonal character of the faulting is clearly visible

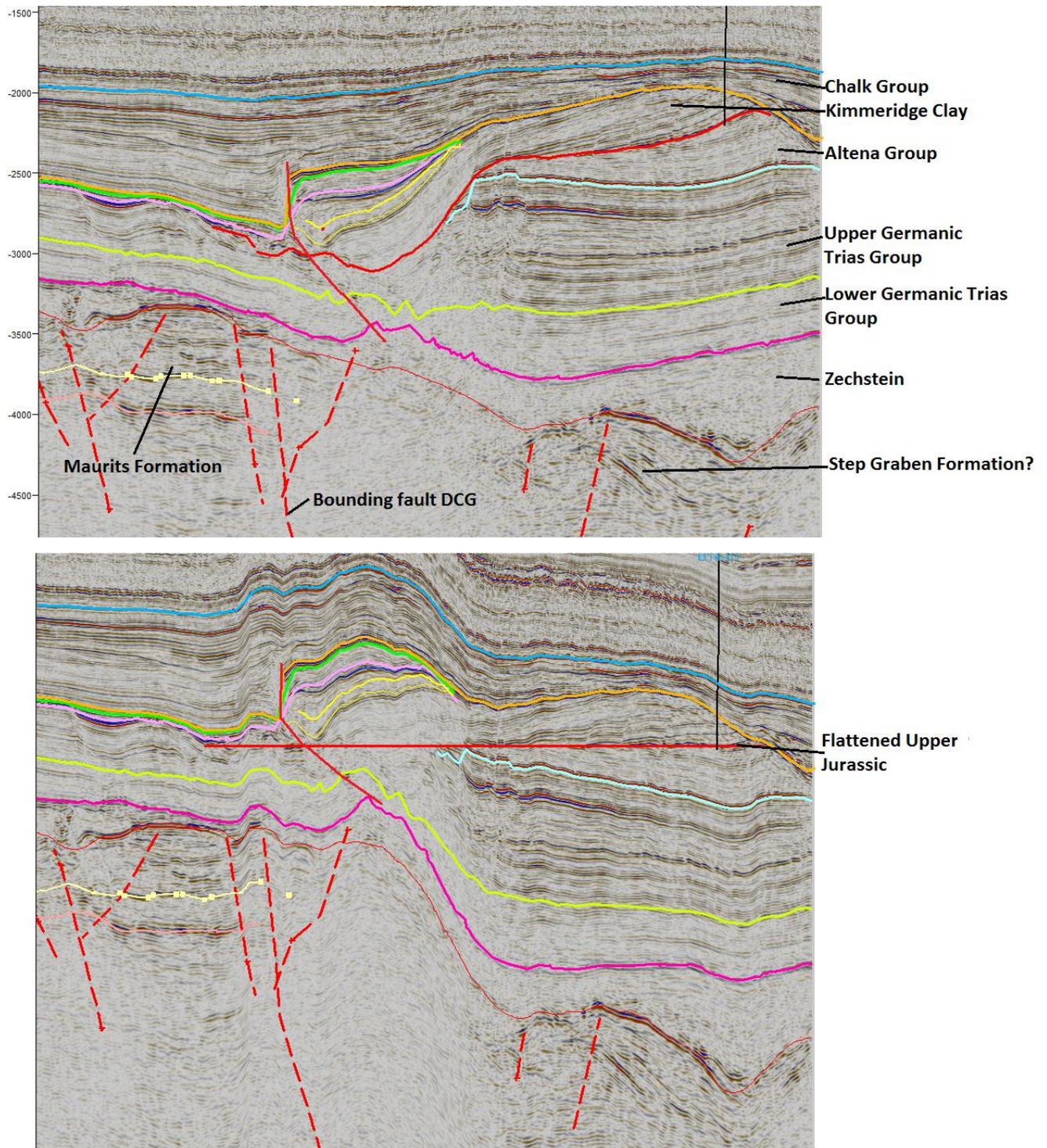


Figure 40; A NE-SW section through the Thor Transform Zone. Above) the Upper Jurassic wedge above the red reflector deeply truncates horizontal Triassic and Lower Jurassic sequences. Below) the same section, flattened on the Kimmerian Unconformity. The Triassic and Altena sediments were tilted towards the east during the Kimmerian tectonic phase and subsequently eroded. In this section it becomes apparent that the bounding fault of the Central Graben already was active during Permo-Carboniferous times. It must later have been reactivated, in the process of which the Triassic and Lower Jurassic layers were rotated back to their original position

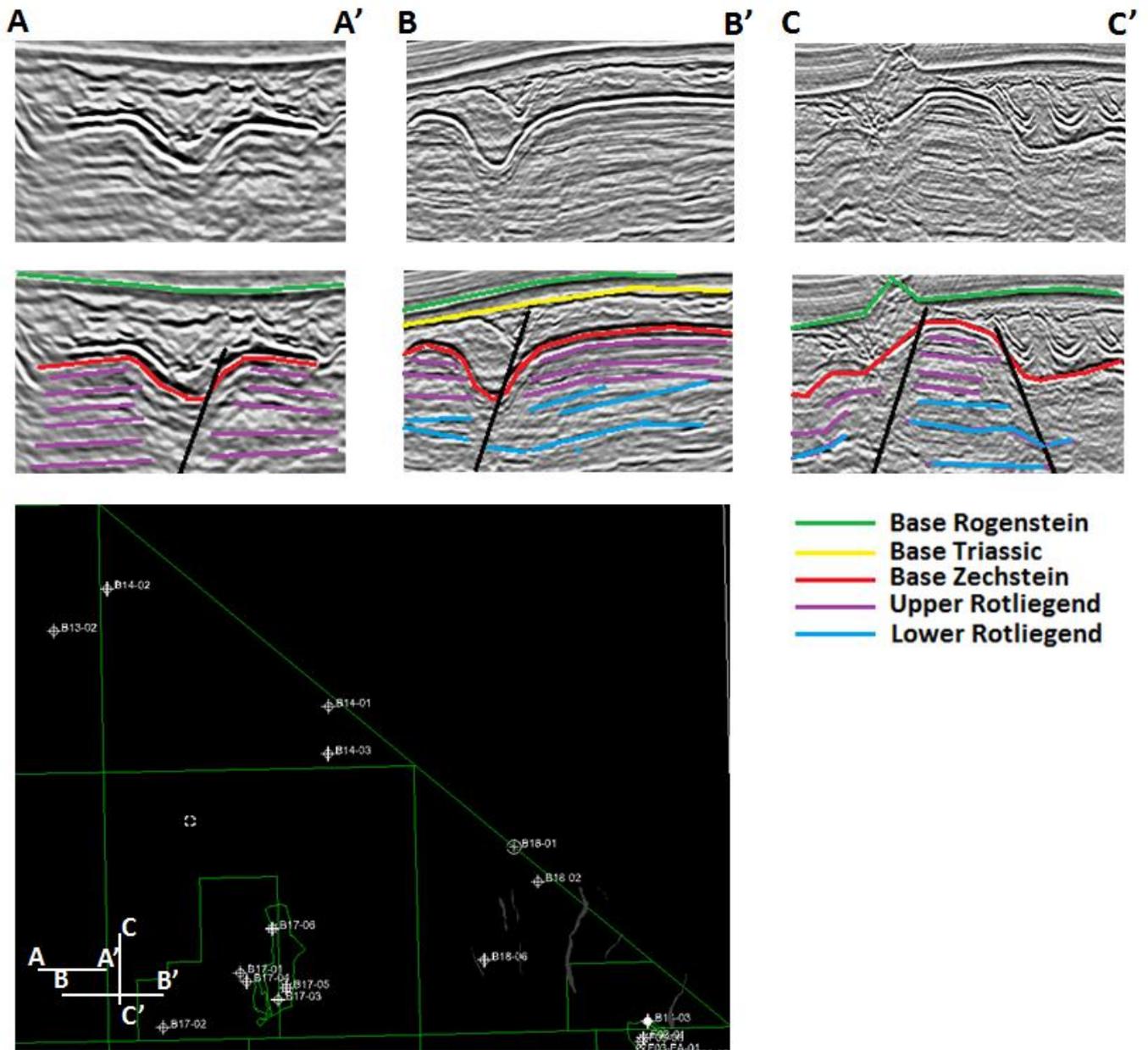


Figure 41; A composite figure showing the strange seismic character of the base Zechstein in the Step Graben. The base Zechstein is very clear, continuous reflector; the Zechstein appears to truncate in the Upper Rotliegend sediments which is strange since there should be no unconformity between these two groups. The strange seismic character of the base Zechstein may be an effect of the processing of the seismic

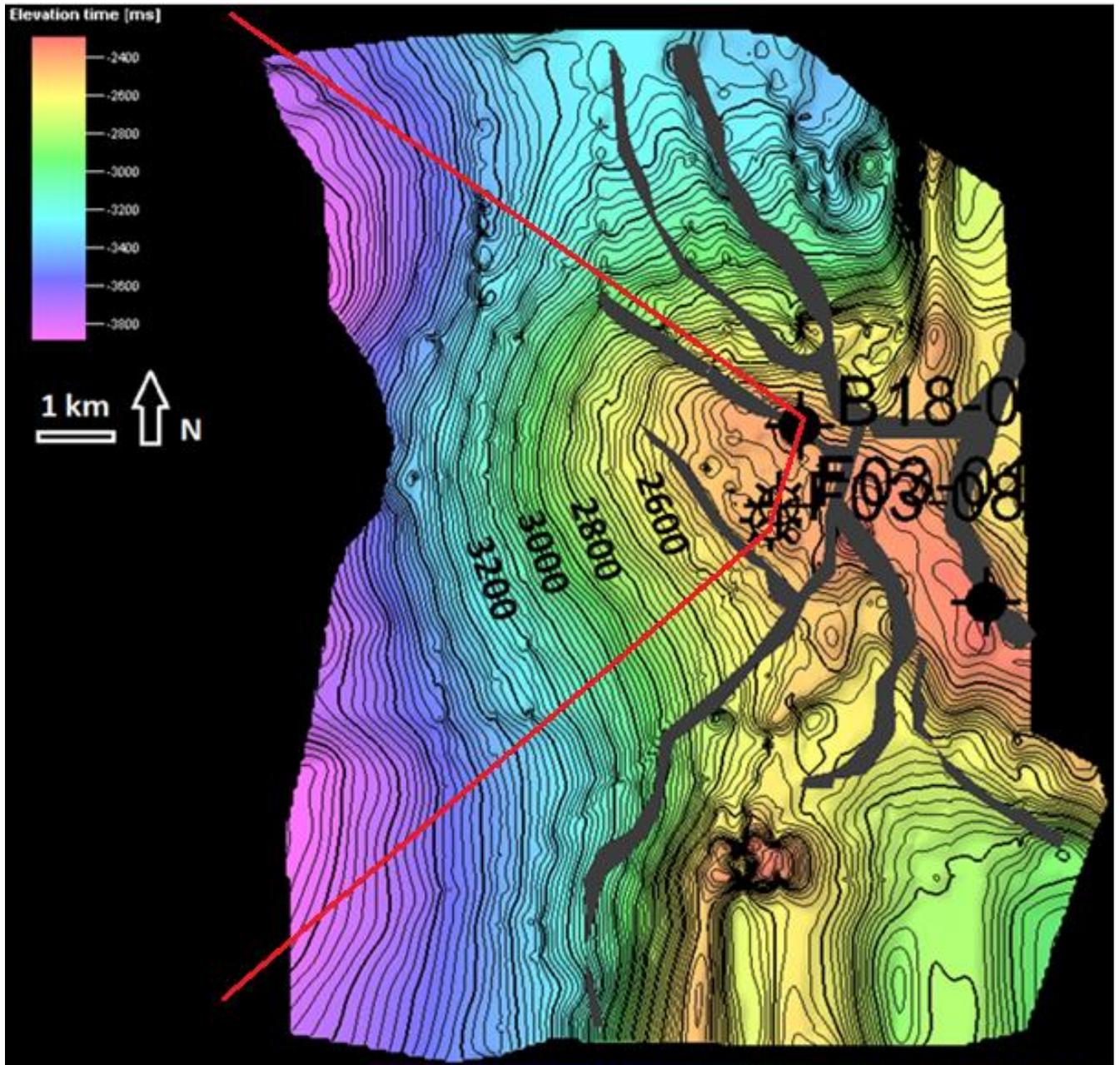


Figure A1-1; a TWT map of the top of the Lower Graben Formation. Well B18-03 contains oil in this reservoir. The red line shows the position of the seismic section in figure A3.

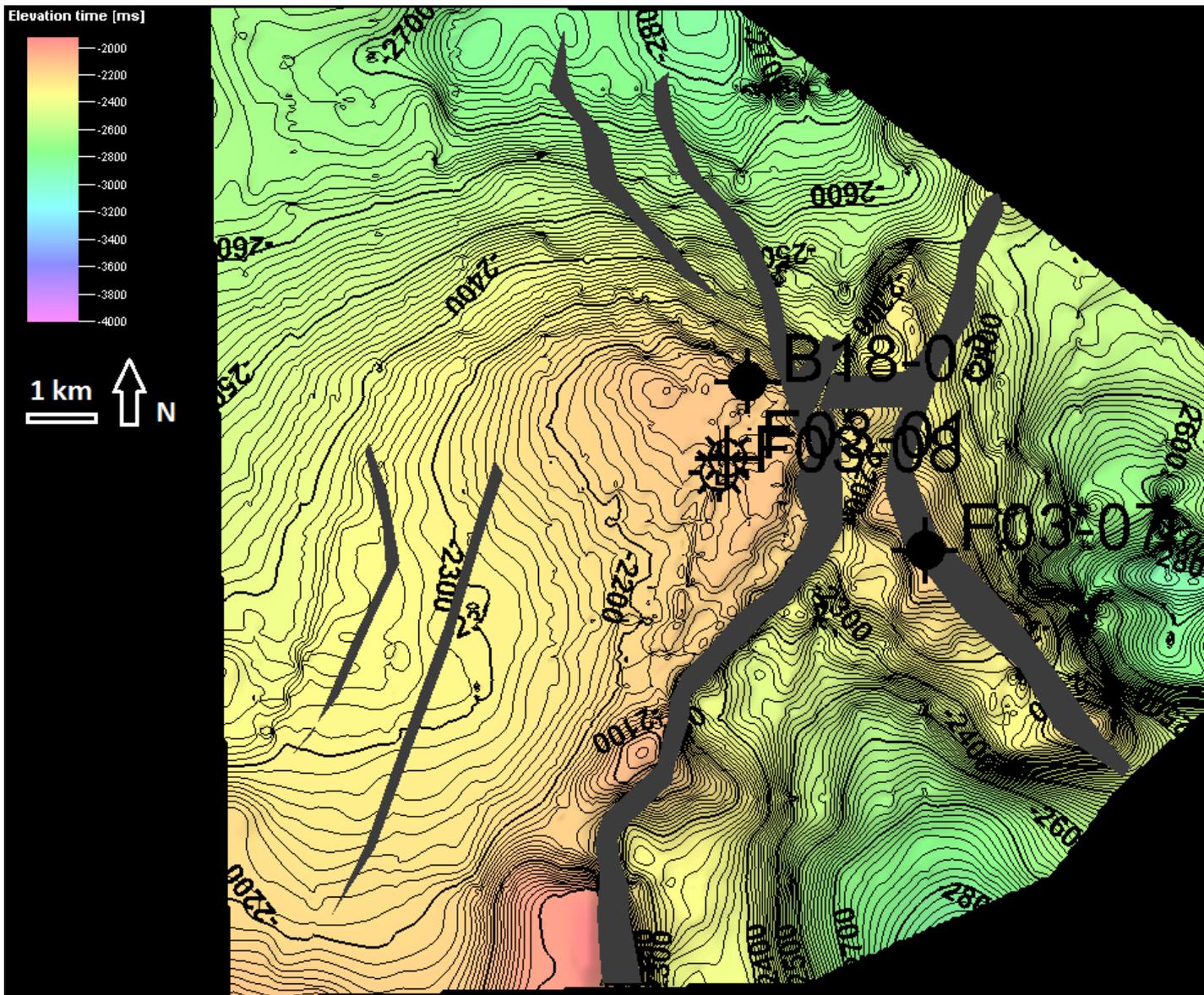


Figure A1-2; a depth map of the top of the Scruff Greensand Formation. Wells F03-01 and F03-08 contain gas in this reservoir. On the east side of the fault, well F03-07 has an oil-bearing Scruff interval

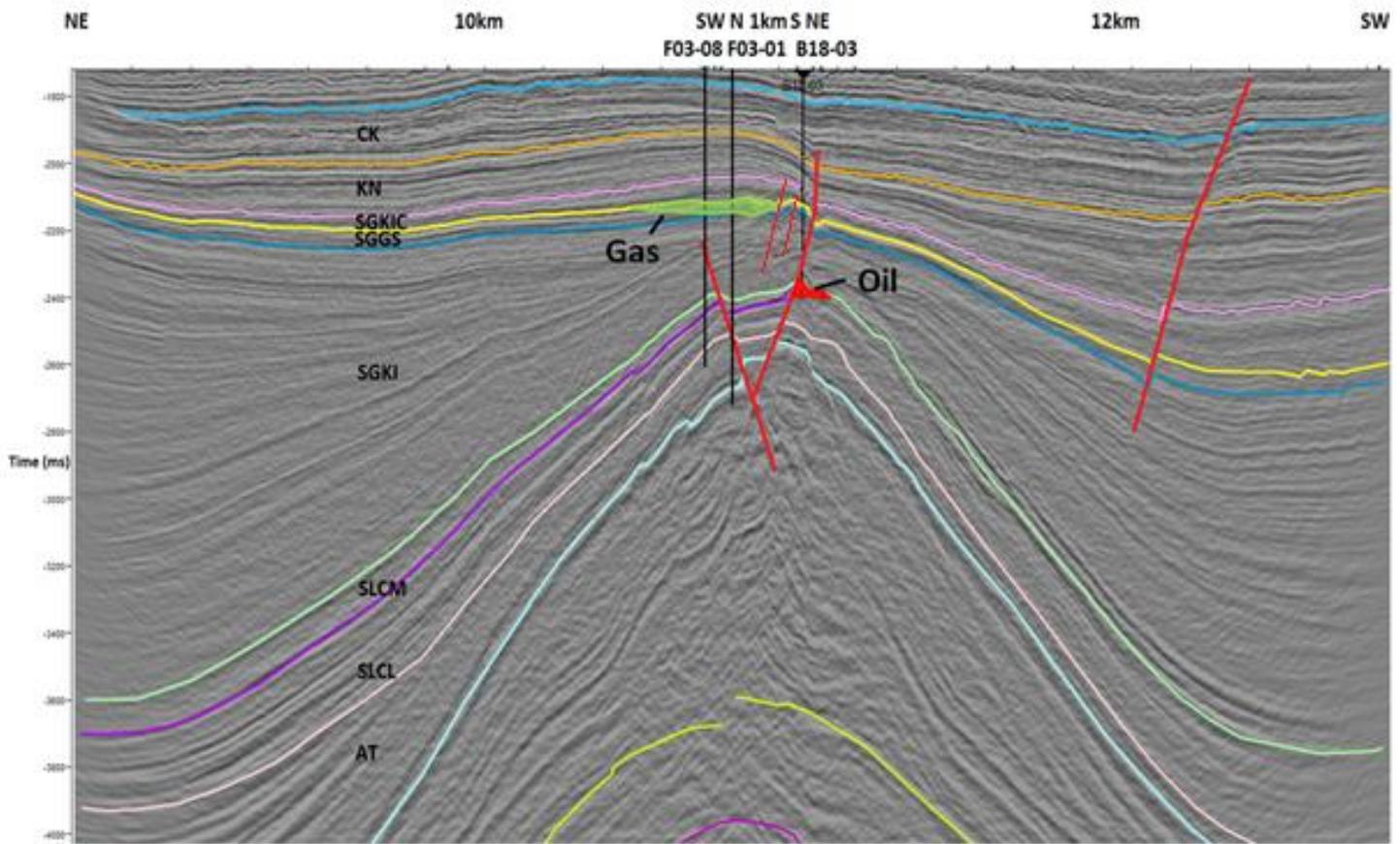


Figure A1-3; a seismic section through the F3-FA field, connecting the three wells in the western compartment of the structure. The thick Kimmeridge Clay Formation in the deeper parts of the basin indicates that the structure originated during the Kimmeridgian-Portlandian

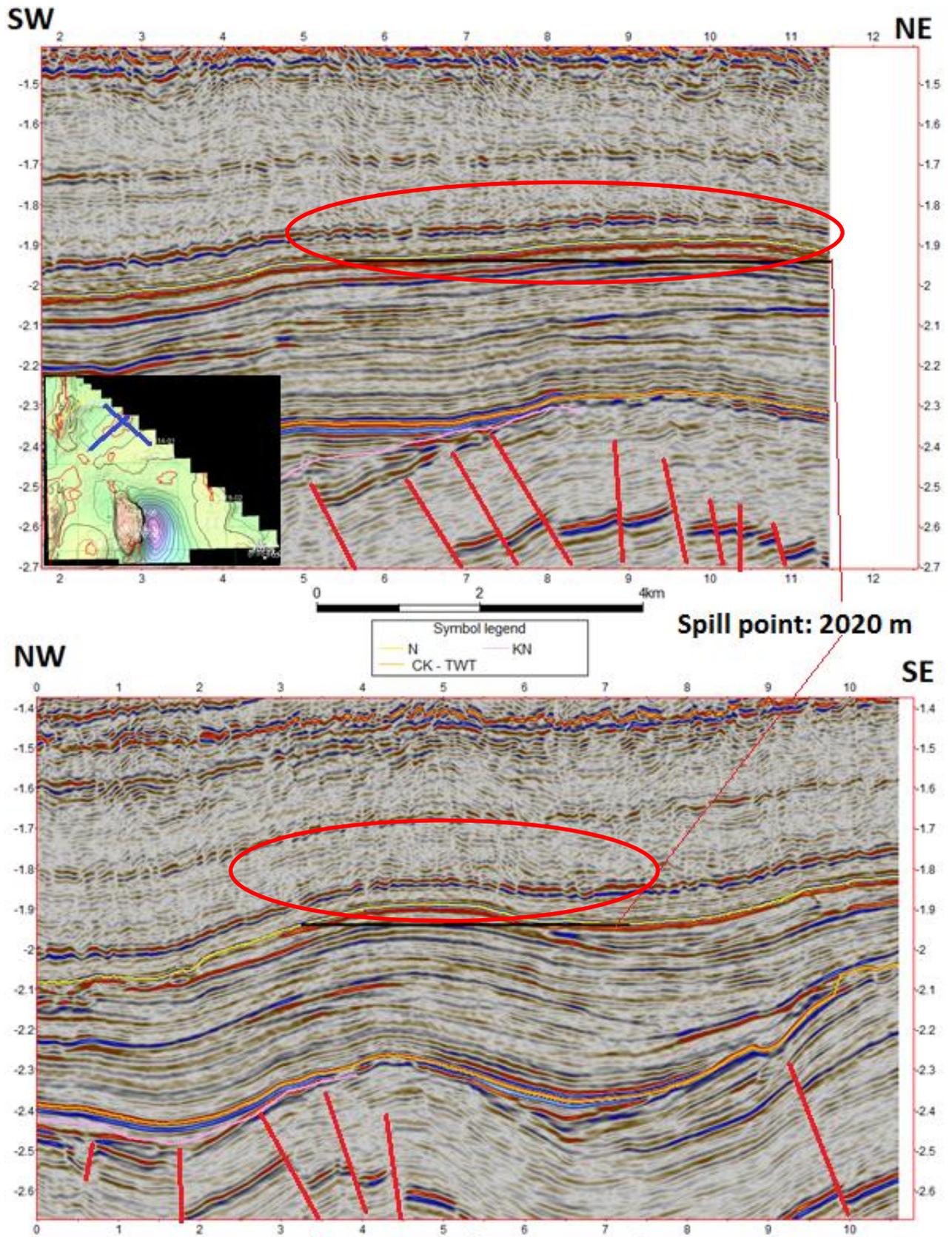


Figure A2-1; the Chalk Aventurine lead. Shown are the top Chalk (yellow), base Chalk (pink), base Rijnland Group (pink) and the spill point (black)

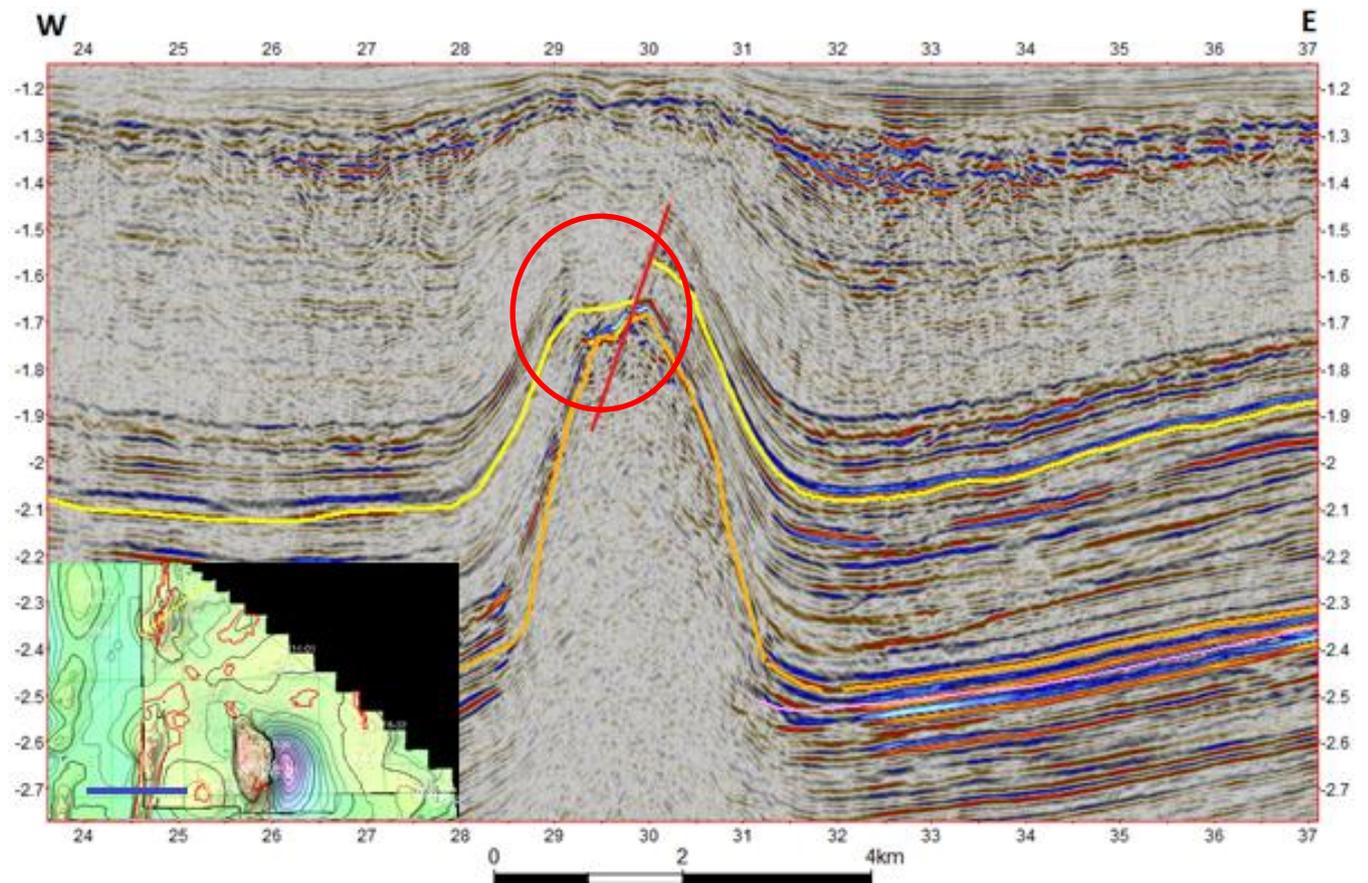


Figure A2-2; The Amethyst lead, located on top of the diapir west of the Step Graben. Shown are the top Chalk (yellow) and base Chalk (orange). Seismic data is sparse in this area, so no N-S section could

be shown

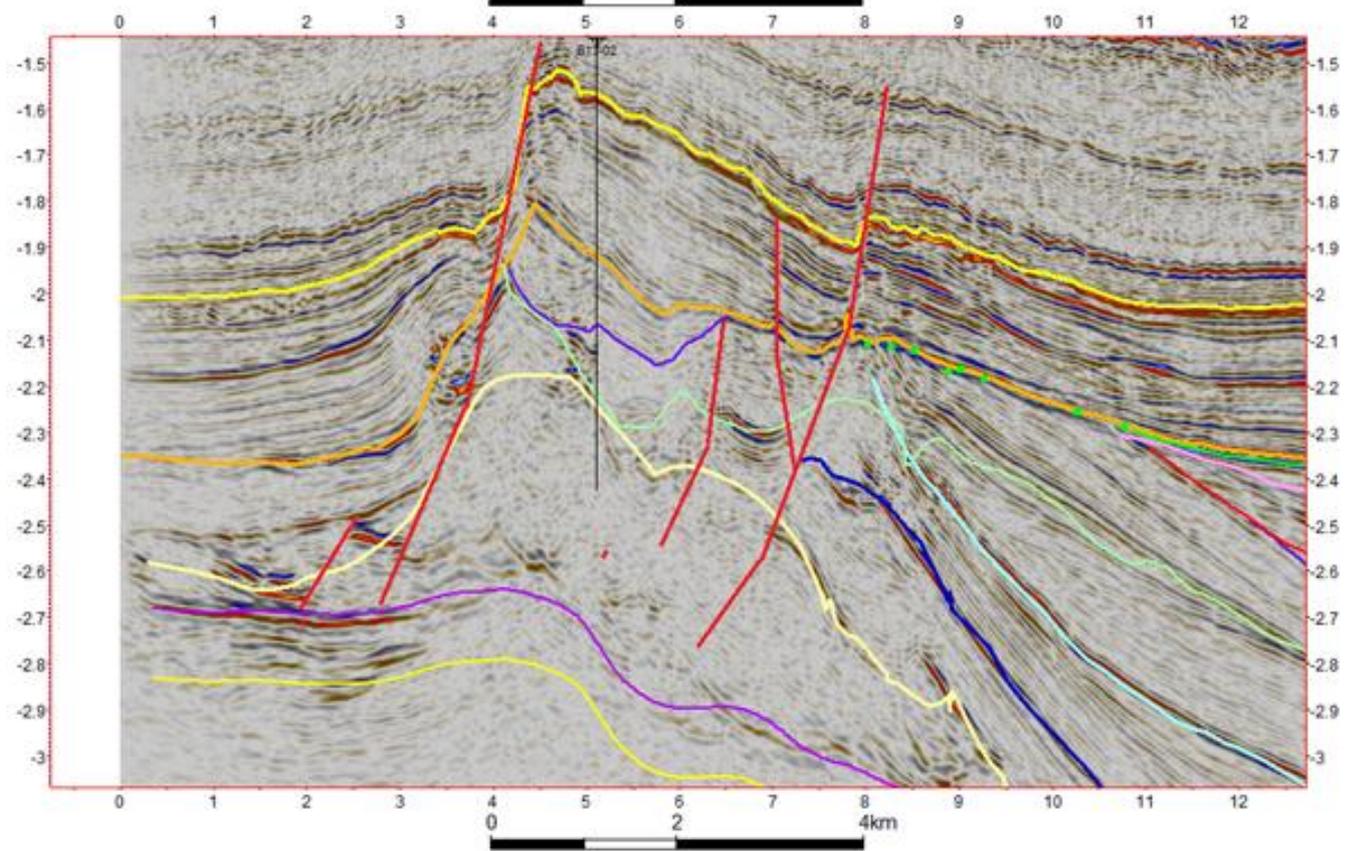
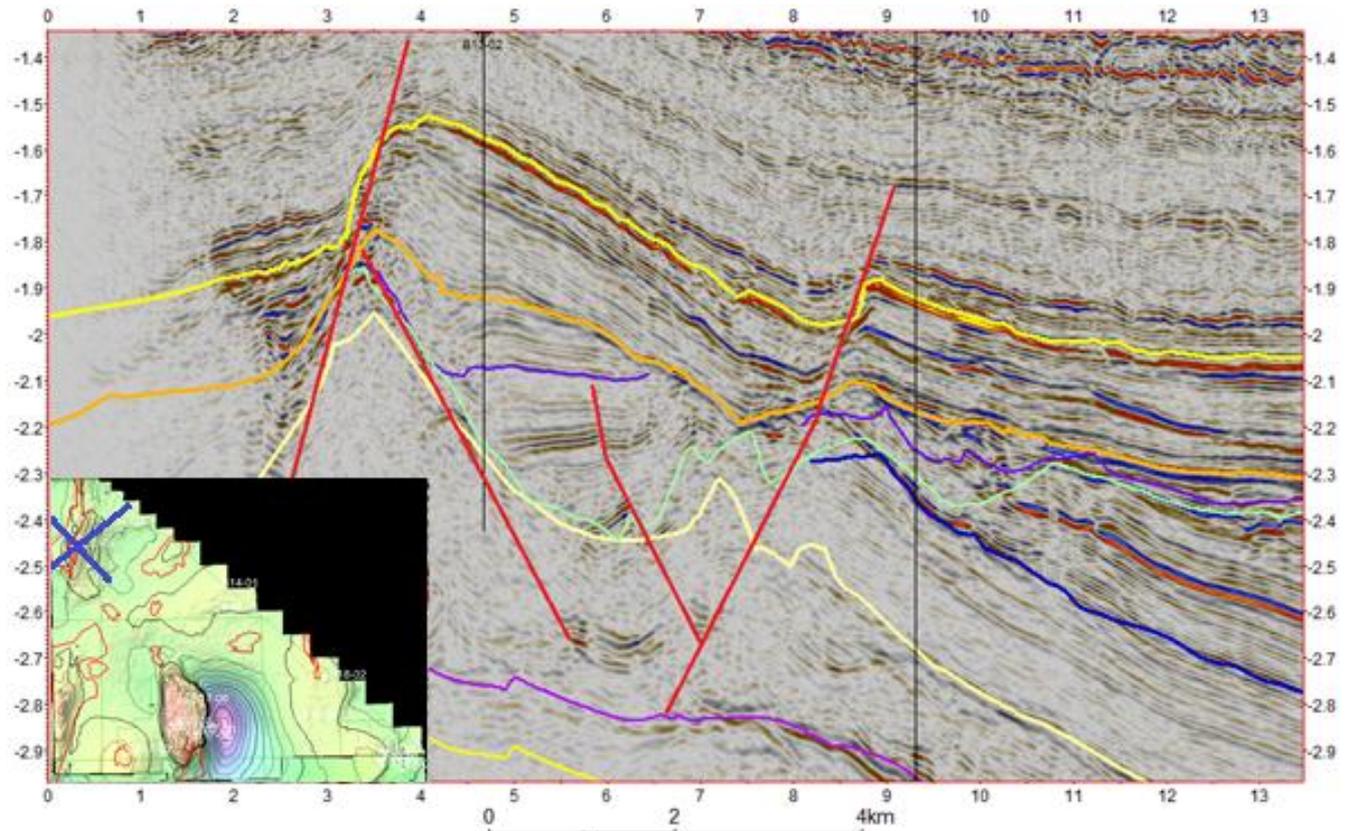


Figure A2-3; The rotated fault block through which the B13-02 well drilled. In the Chalk, there is some updip potential. A problem may be failure of the seal though, as shallow gas can be seen in the Tertiary section above the large normal fault

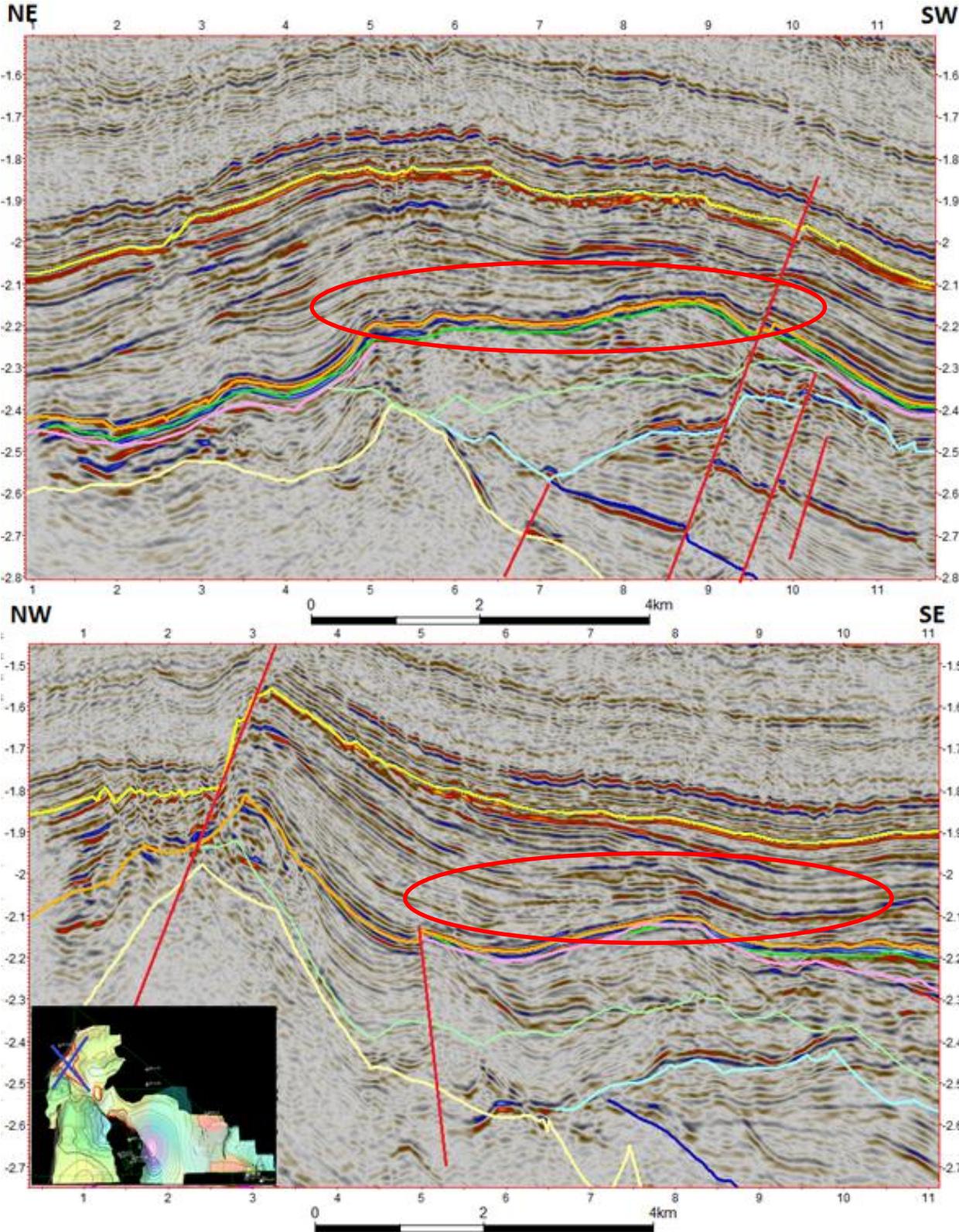


Figure A2-4; The Bloodstone lead in the Vlieland Sandstone. The base of the reservoir is the green line

underneath the base of the Chalk (orange).

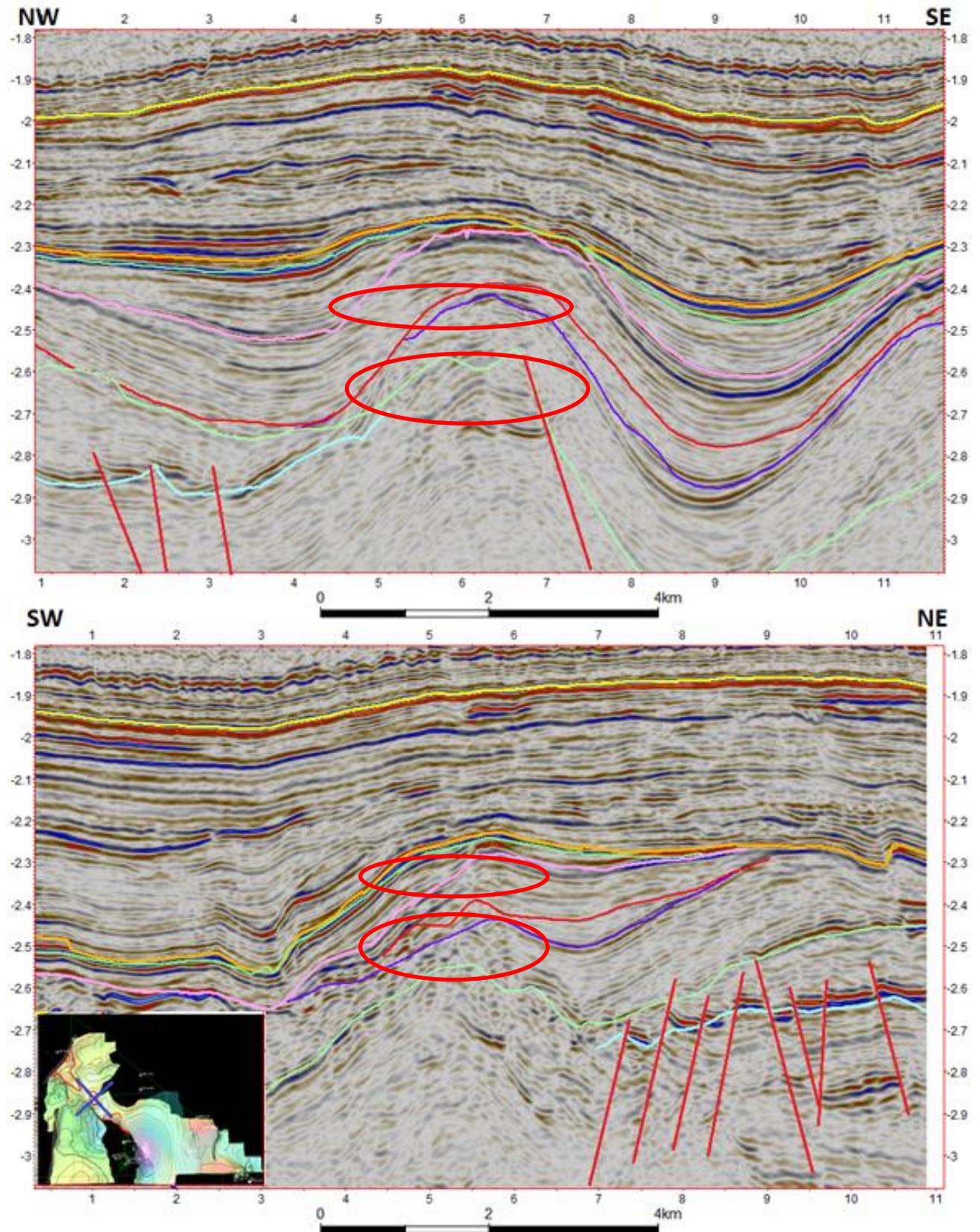
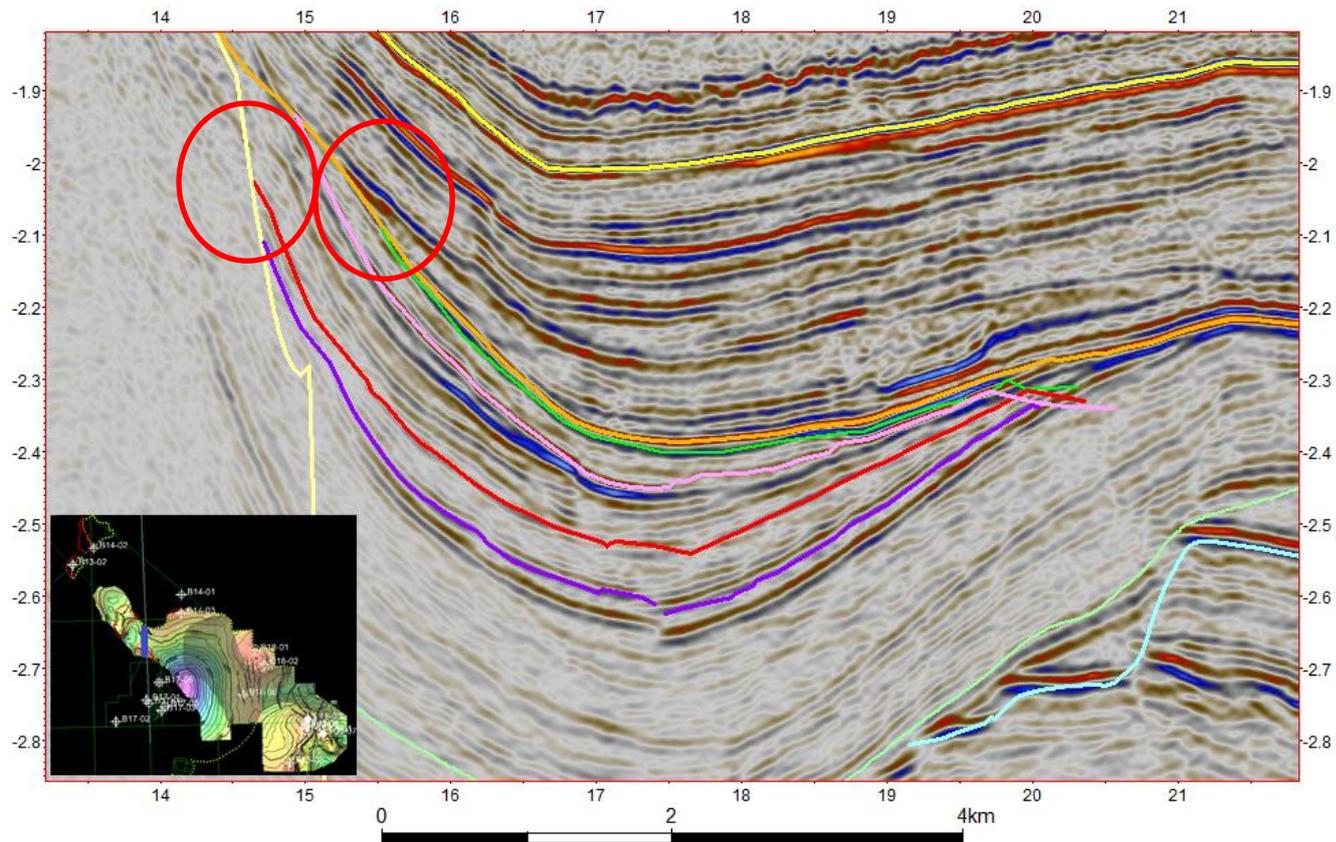


Figure A2-5; The Bauxite lead. This is a lead for both the Vlieland Sandstone (pink) and Scruff Greensand (purple) plays.

Figure A2-6; The Beryl lead for the Vlieland Sandstone (pink) and Scruff Greensand (purple) plays



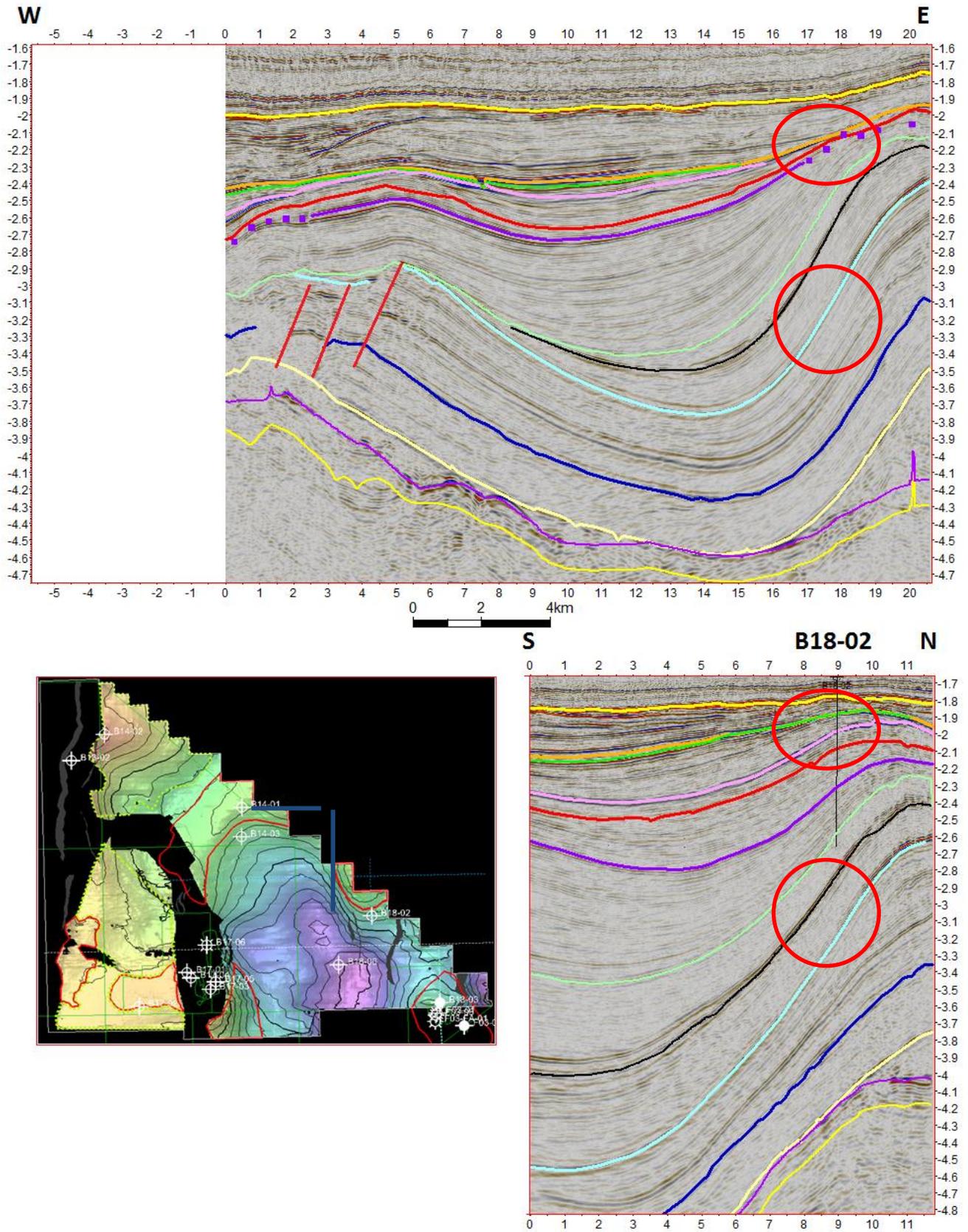


Figure A2-7; The Emerald lead at Lower Graben (black) and Lower Buntsandstein (blue) level. No seismic data is available from over the German border towards the north-east, so the structure cannot be fully imaged

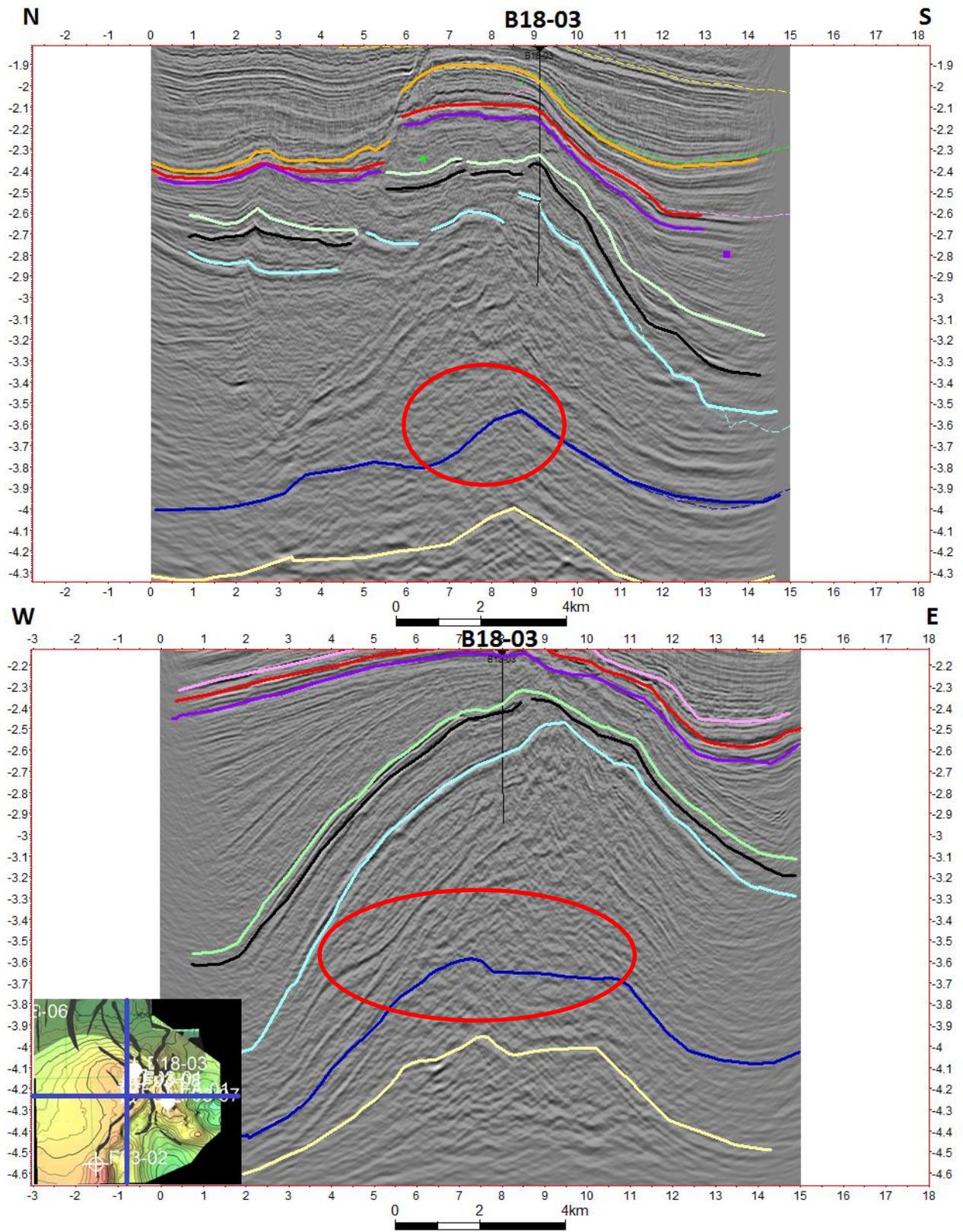


Figure A2-8; The F3-FA lead of the Lower Buntsandstein play (blue)

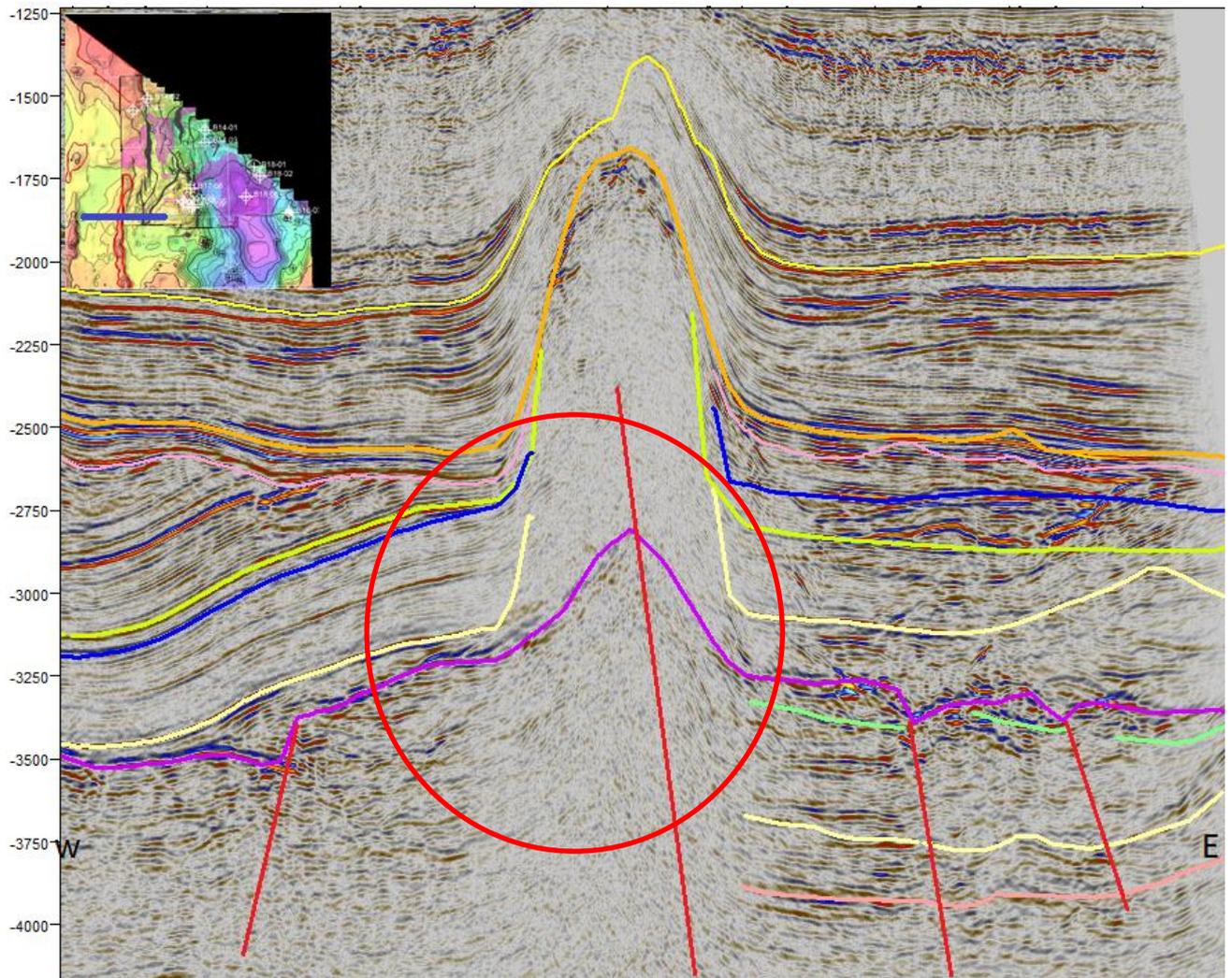


Figure A2-9; the B16 diapir lead of the Upper Rotliegend play. Only 2D seismic lines are available in this area; interpretations are from the NCP-1 project

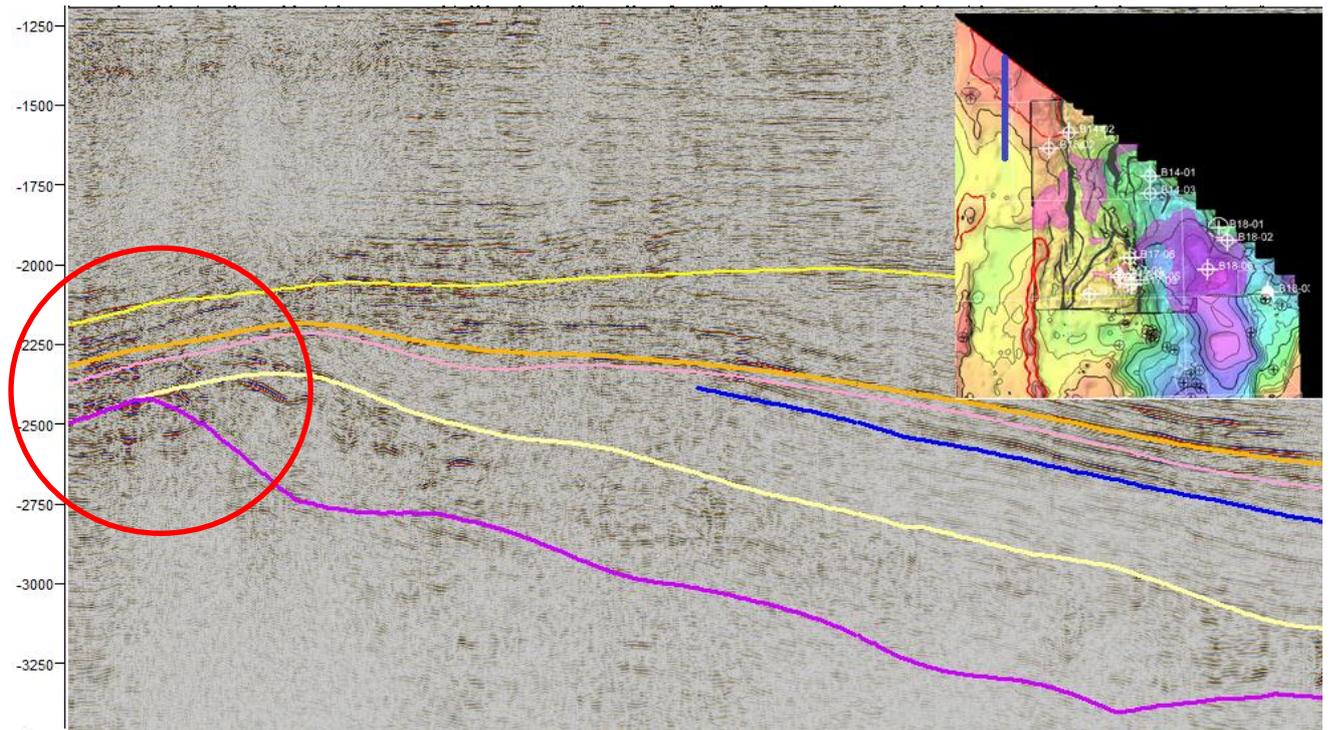


Figure A2-10; The B10 plateau lead of the Upper Rotliegend play. Only 2D seismic lines are available in this area; interpretations are from the NCP-1 project

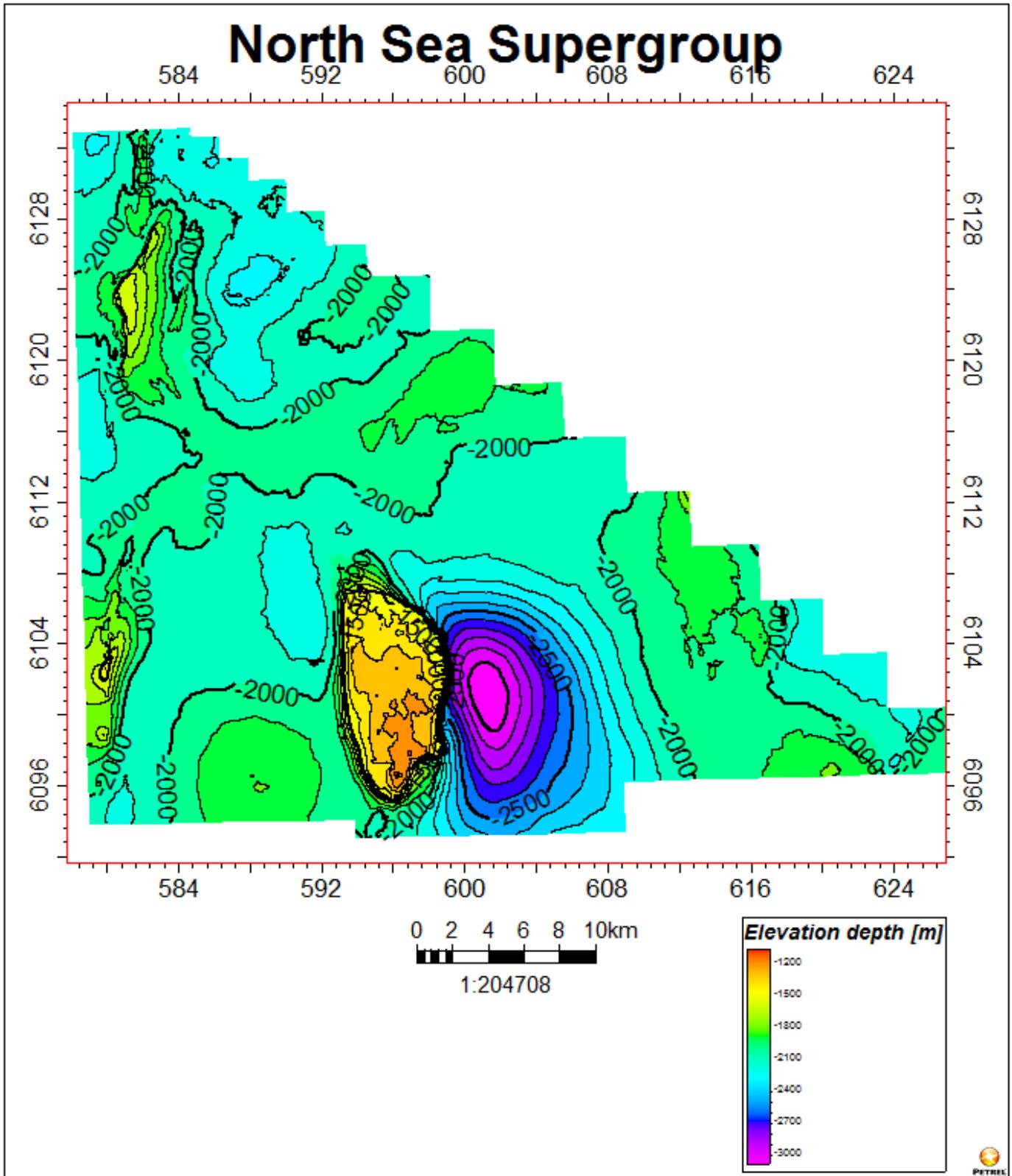


Figure A3-1: A depth map of the North Sea Supergroup. Contour intervals are 100 m.

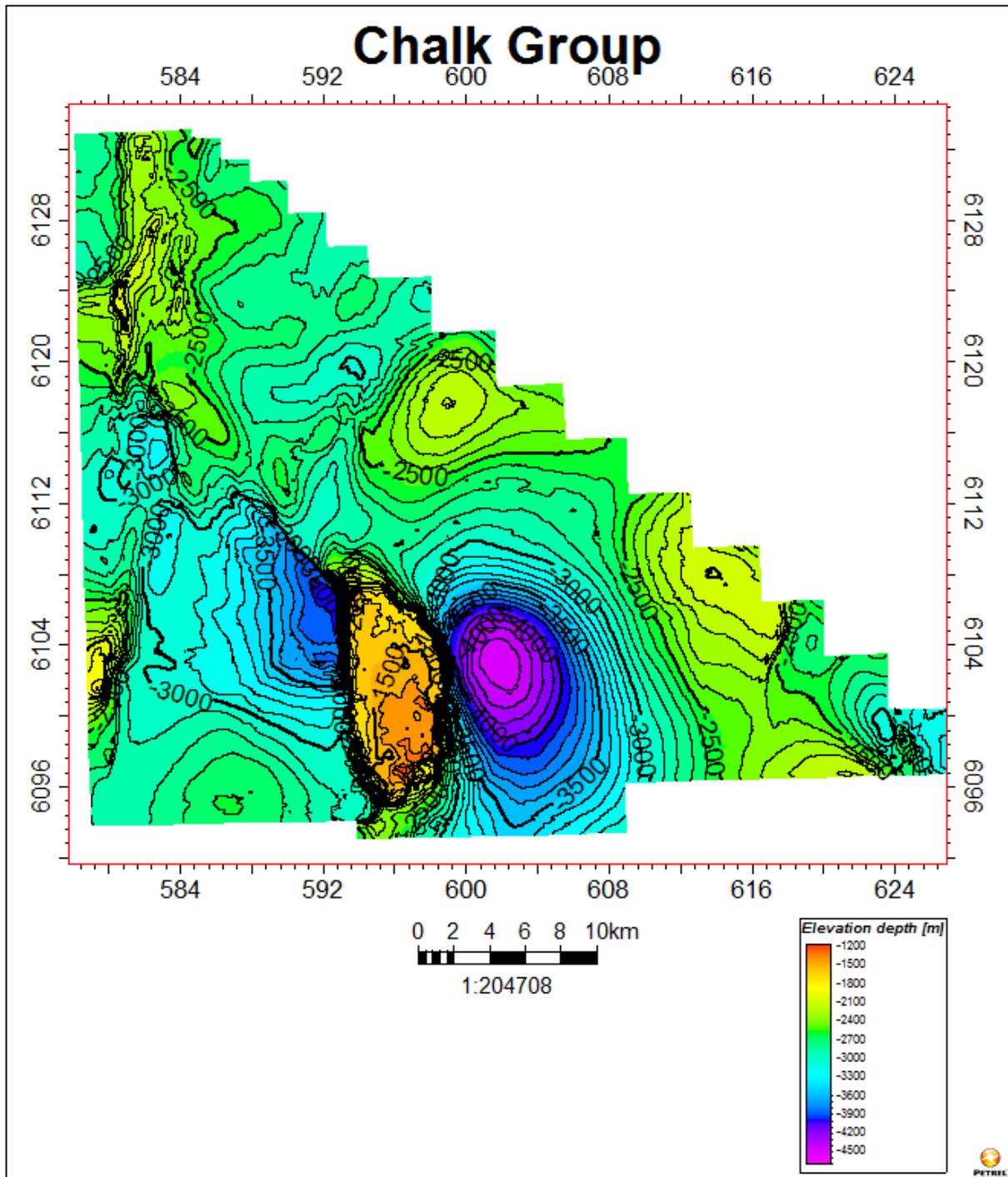


Figure A3-2; a depth map of the Chalk Group. Contour intervals are 100 m

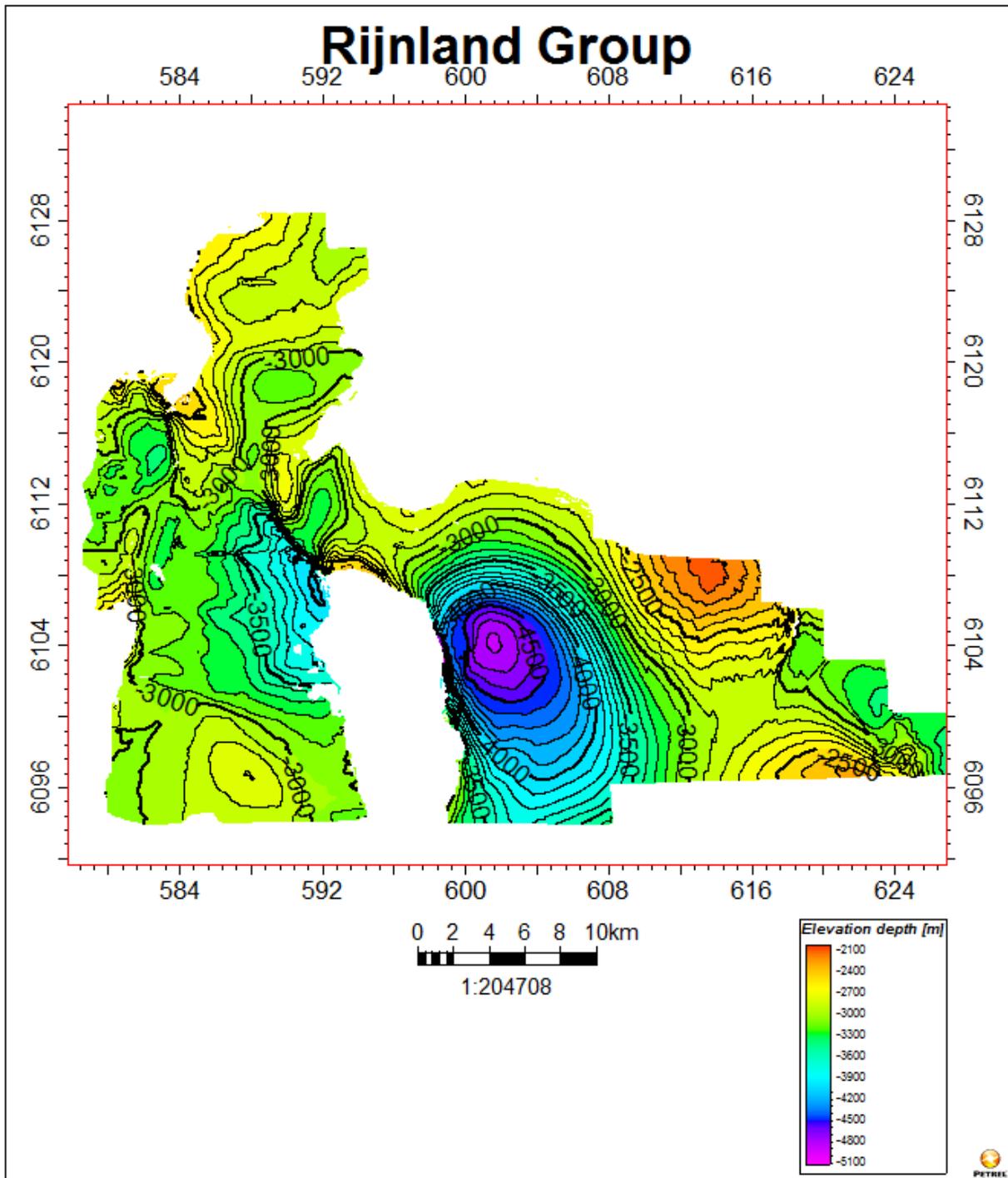


Figure A3-3; a depth map of the Rijnland Group; contour intervals are 100 m

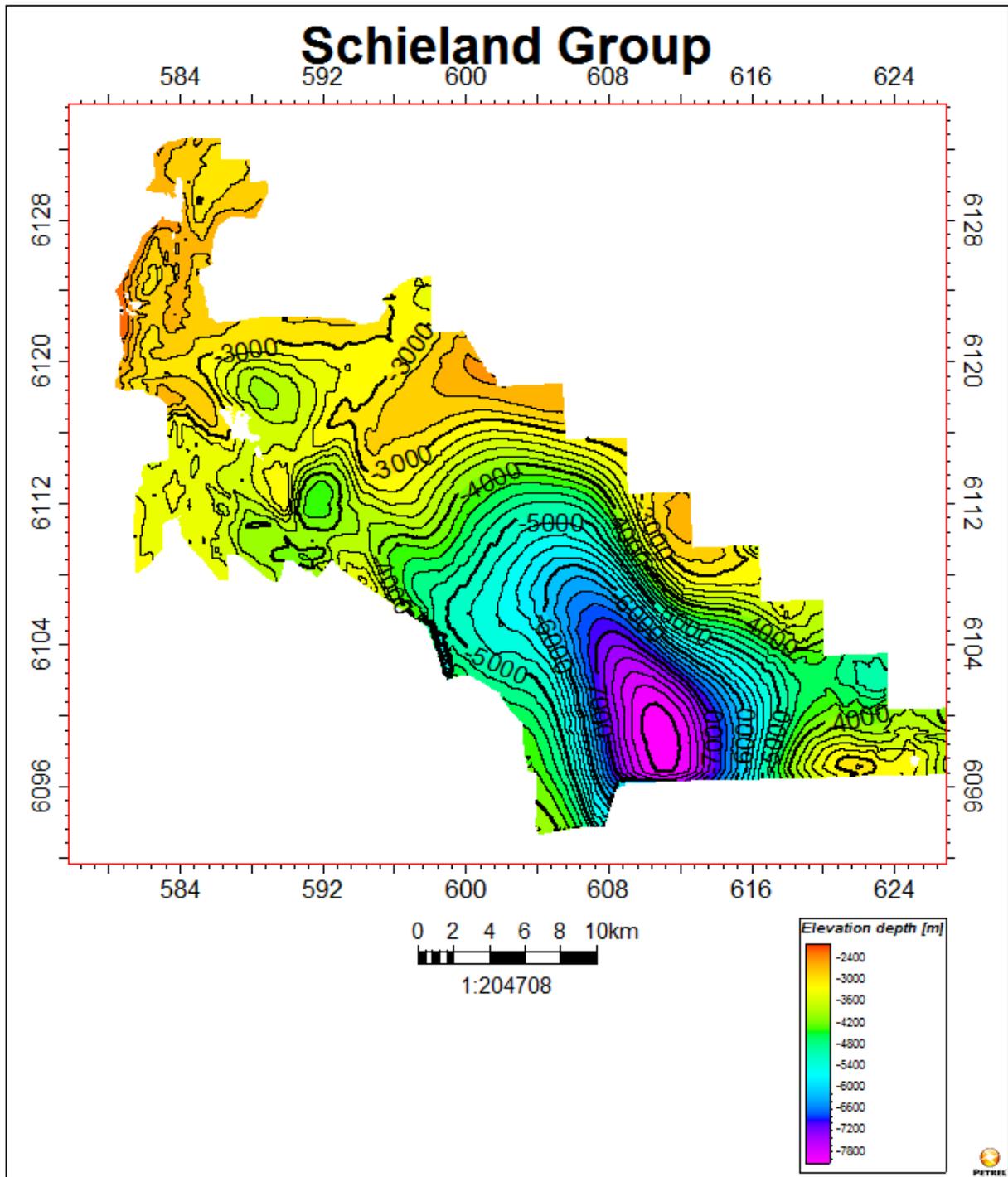


Figure A3-4; a depth map of the Schieland Group; contour intervals are 200 m

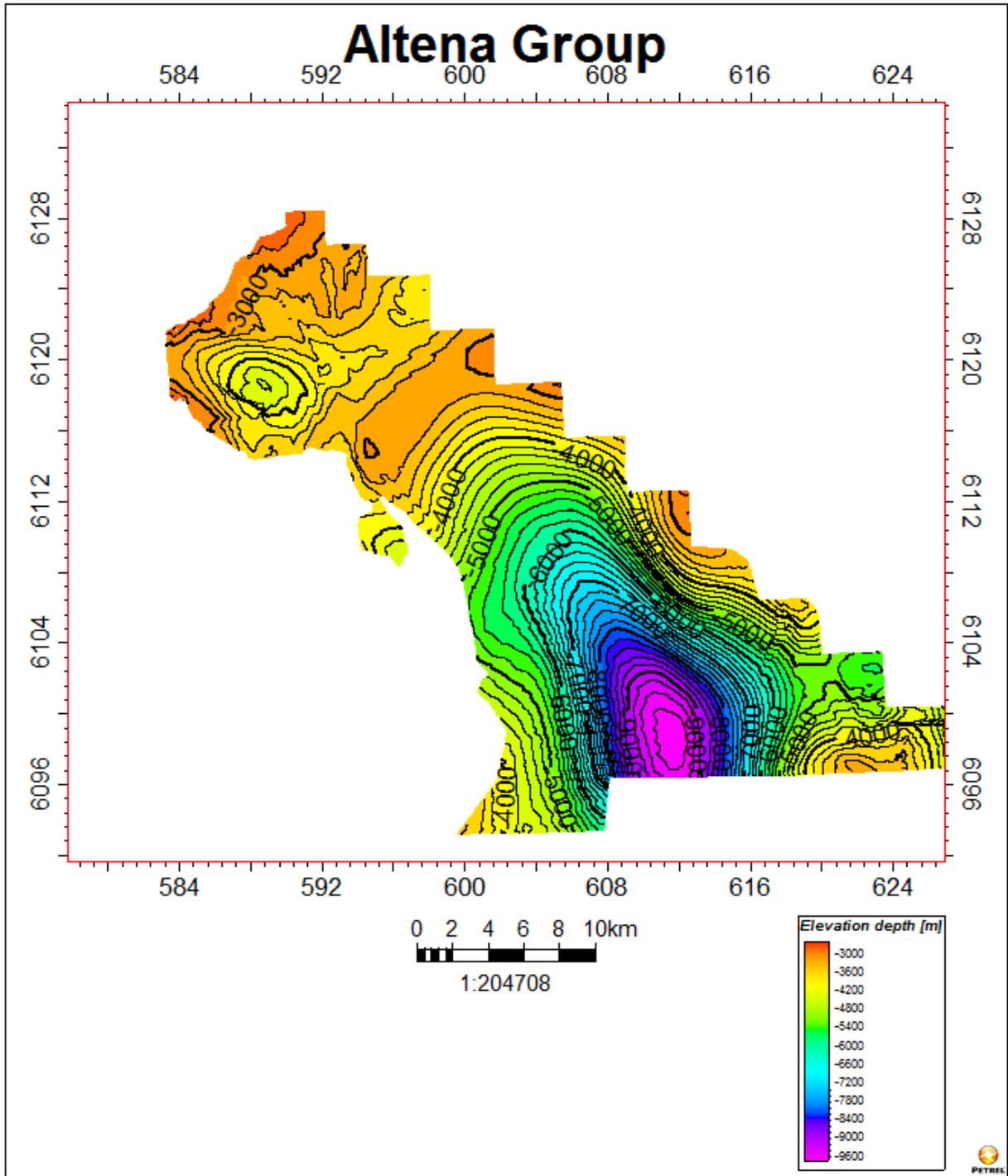


Figure A3-5; a depth map of the Altona Group; contour intervals are 200 m

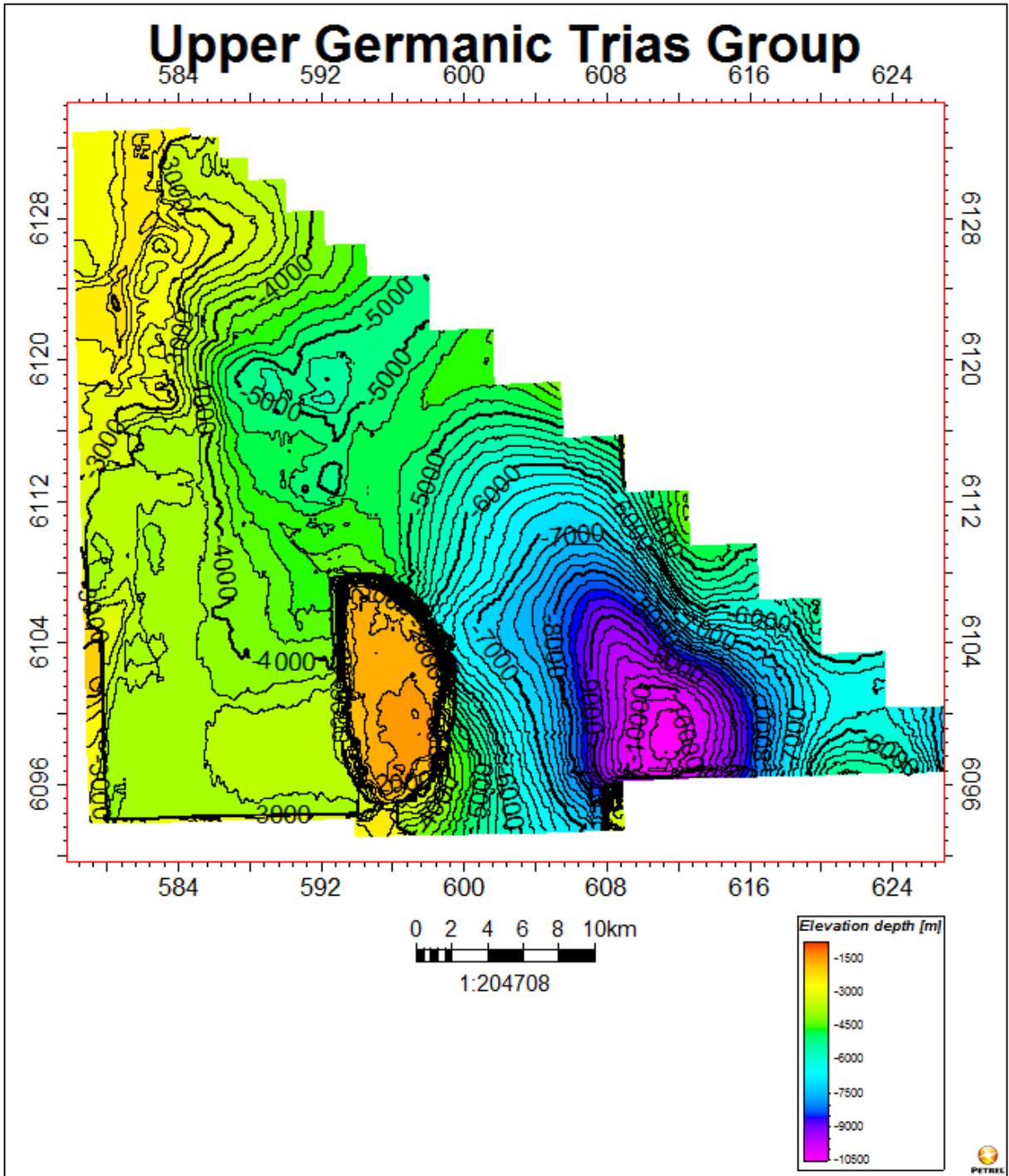


Figure A3-6; a depth map of the Upper Germanic Trias Group; contour intervals are 200 m

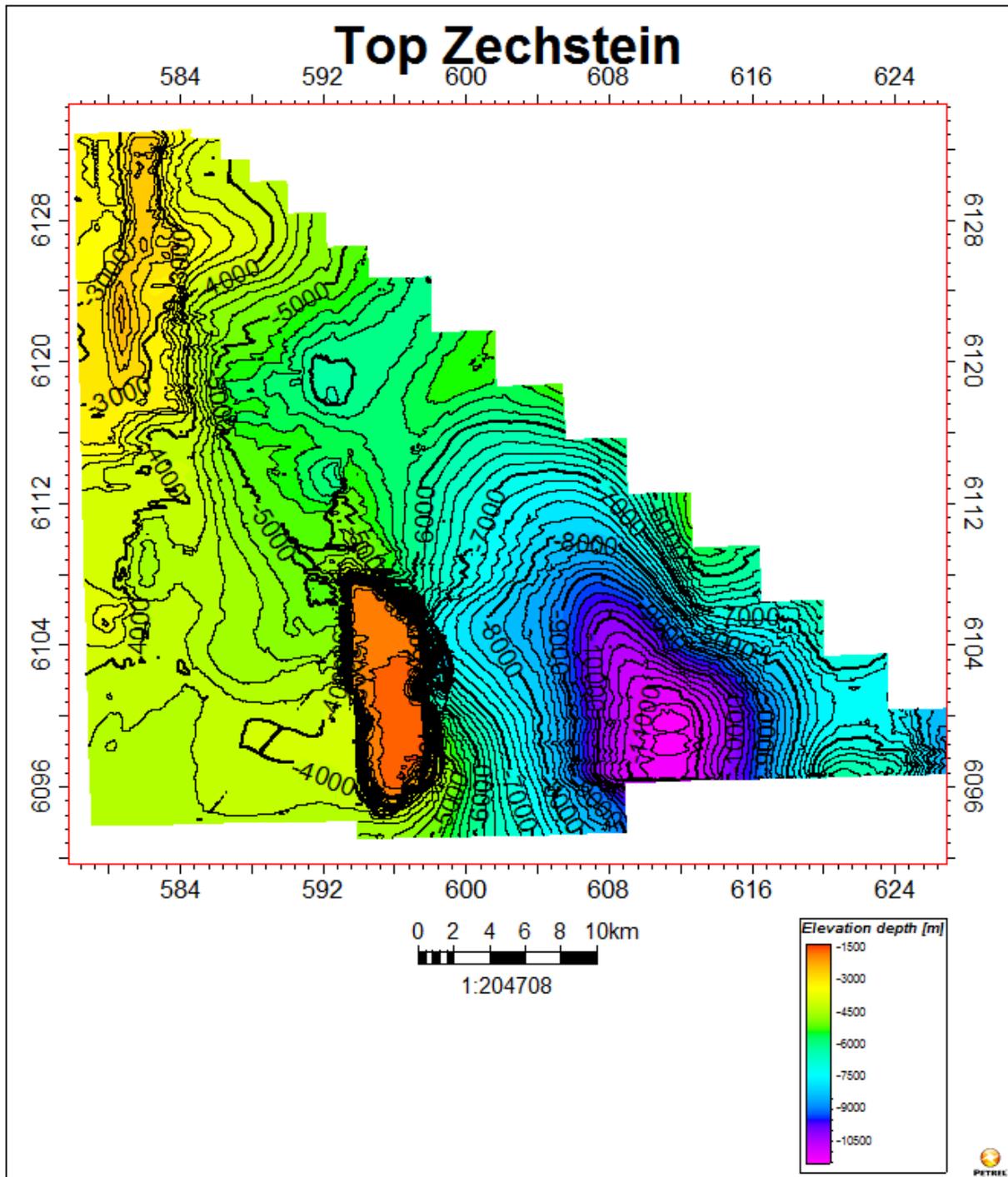


Figure A3-8; a depth map of the top Zechstein; contour intervals are 200 m

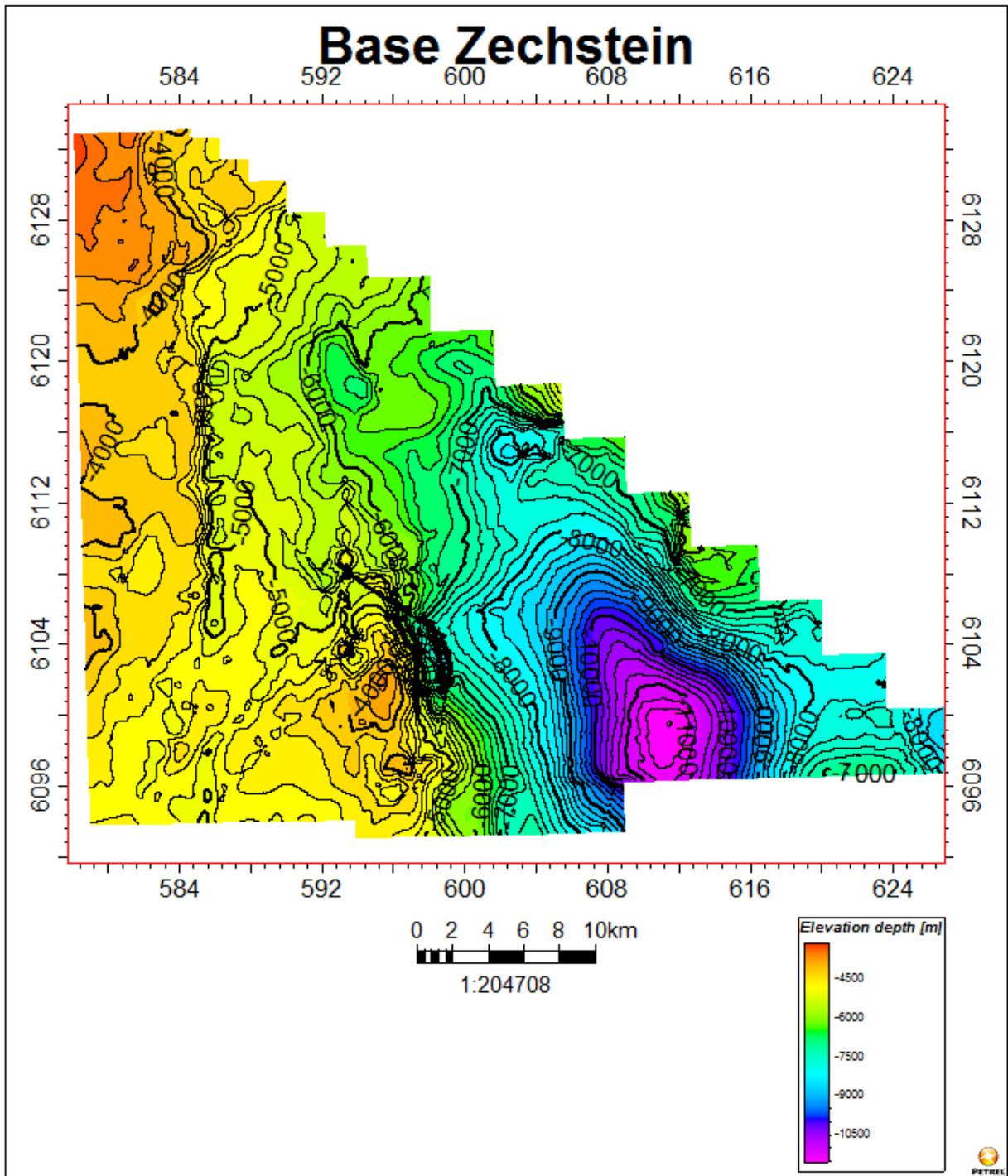


Figure A3-9; a depth map of the base Zechstein; contour interval is 200 m