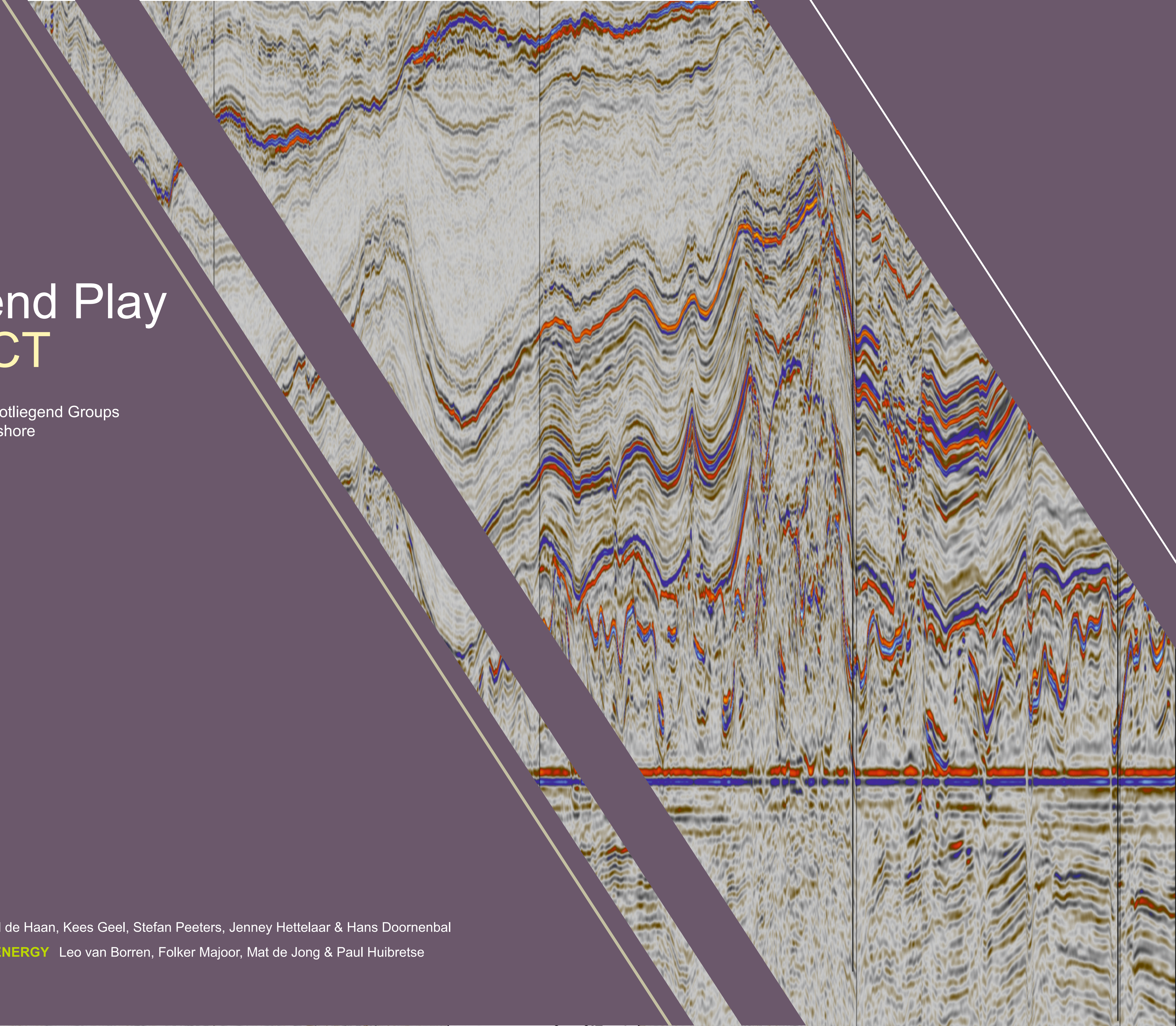
Rotliegend Play PROJECT

Characterisation of the Rotliegend Groups
in the Northern Dutch offshore



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In collaboration with **NEPTUNE ENERGY** Leo van Borren, Folker Majoor, Mat de Jong & Paul Huibretse

TNO Report: TNO 2020 R10861

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The Rotliend play Project is fully funded by financial contributions of Neptune Energy.
The research is conducted by TNO Geological Survey of the Netherlands, who acts as the project lead. The main goal of the project is to establish the exploration potential of the Rotliegend Group in the northern Dutch offshore.

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The main goal of this project is to better understand the distribution of Rotliegend reservoir sands in the Dutch northern offshore to increase prospectivity of this area. This project was executed as a close collaboration between the TNO Geological Characterisation Team (Geological Survey of the Netherlands) and Neptune Energy. The present document is an altlas-type report displaying the main research results and is complementary to the detailed power point document (master PPT presentation), which is also provided to Neptune Energy.

The main techniques deployed in this project are threefold:

- Detailed stratigraphic correlation combining knowledge from TNO and Neptune teams.
- 2D/3D seismic mapping using all data available, including the non-released DEF survey.
- Amplitude mapping using PaleoScan software package.

Dataset

150 wells assessed

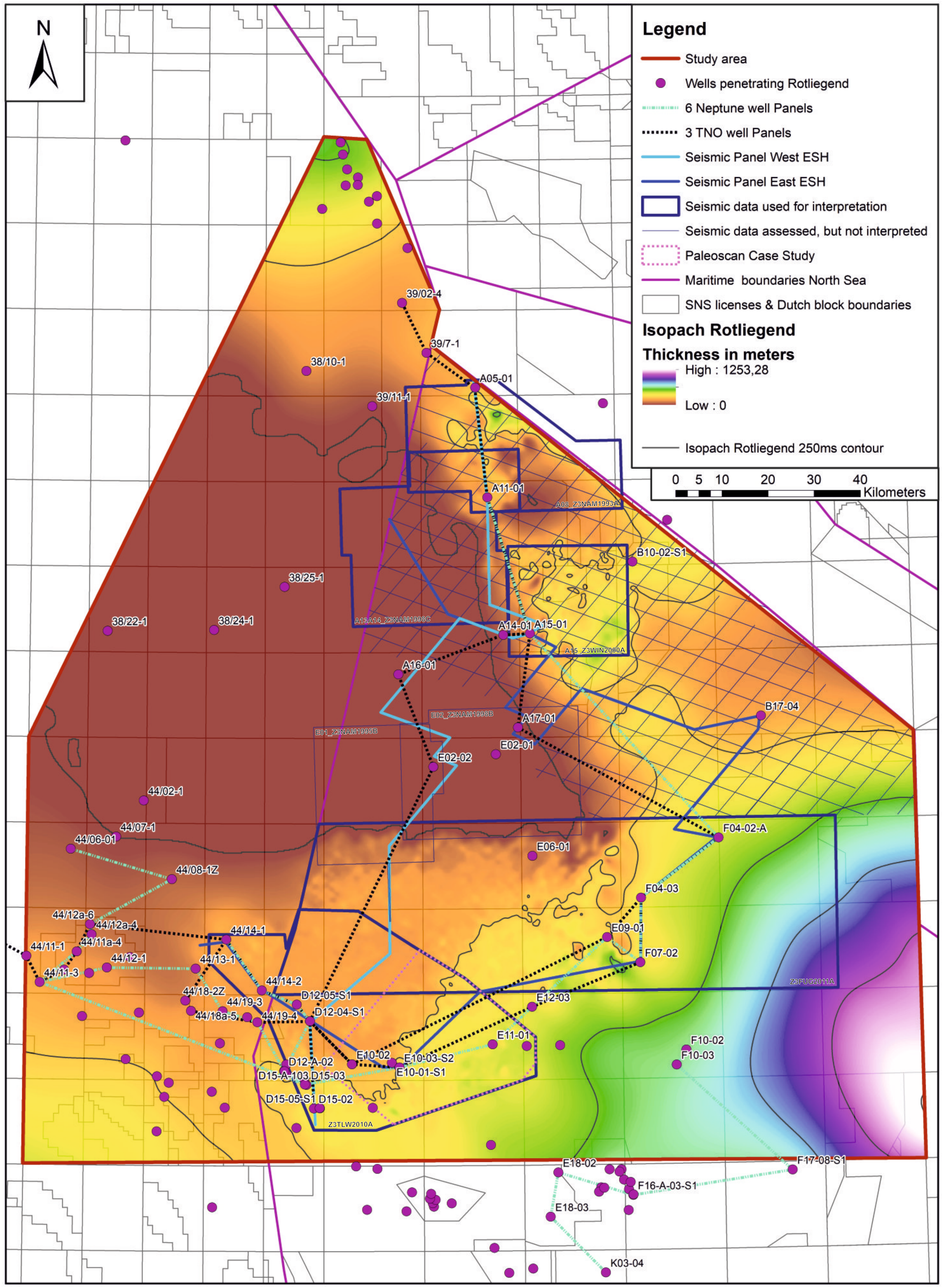
Core photos and sedimentarry logs (see master PPT presentation)

Main interpreted seismic surveys:

- A08_Z3NAM1993A
- A13A14_Z3NAM1998C
- A15_Z3WIN2000A
- Z3FUG2011A (“DEF-survey”)
- Z3TLW2010A (“Tullow-survey”)

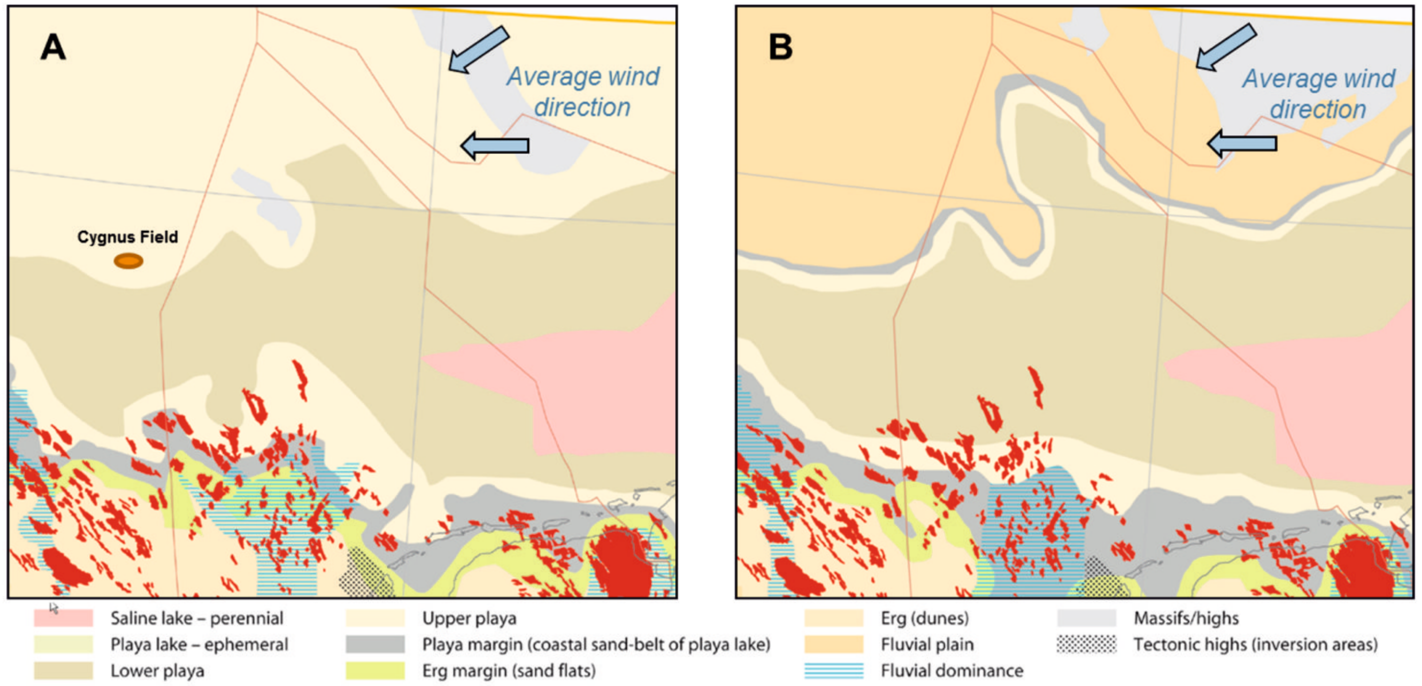
Other assessed surveys without systematic interpretation

- E02_Z3NAM1998B
- E01_Z3NAM1995B
- 2D NSR-lines north and east of the MNSH

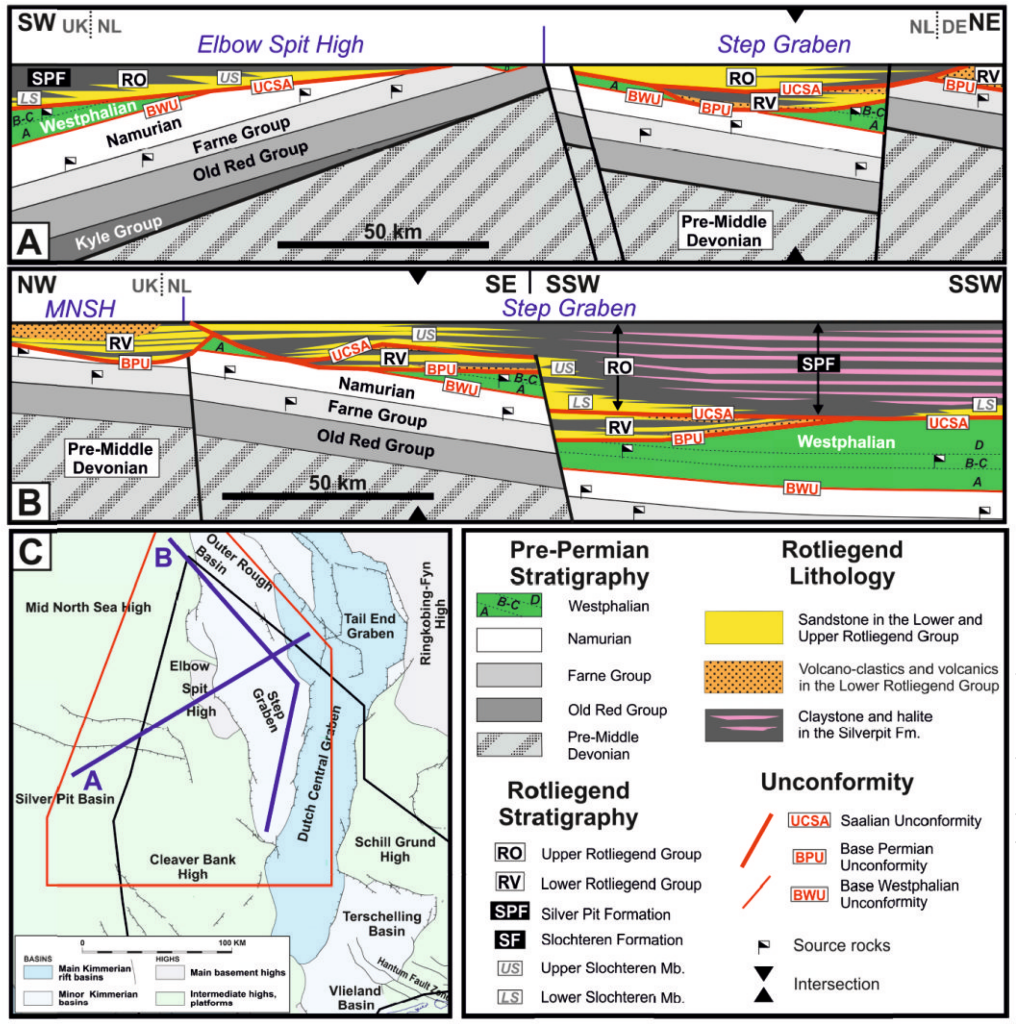


Right: Rotligend thickness map (m) showing the project’s study area (red polygon), key wells used (purple dots) and seismic survey used (dark blue polygons)

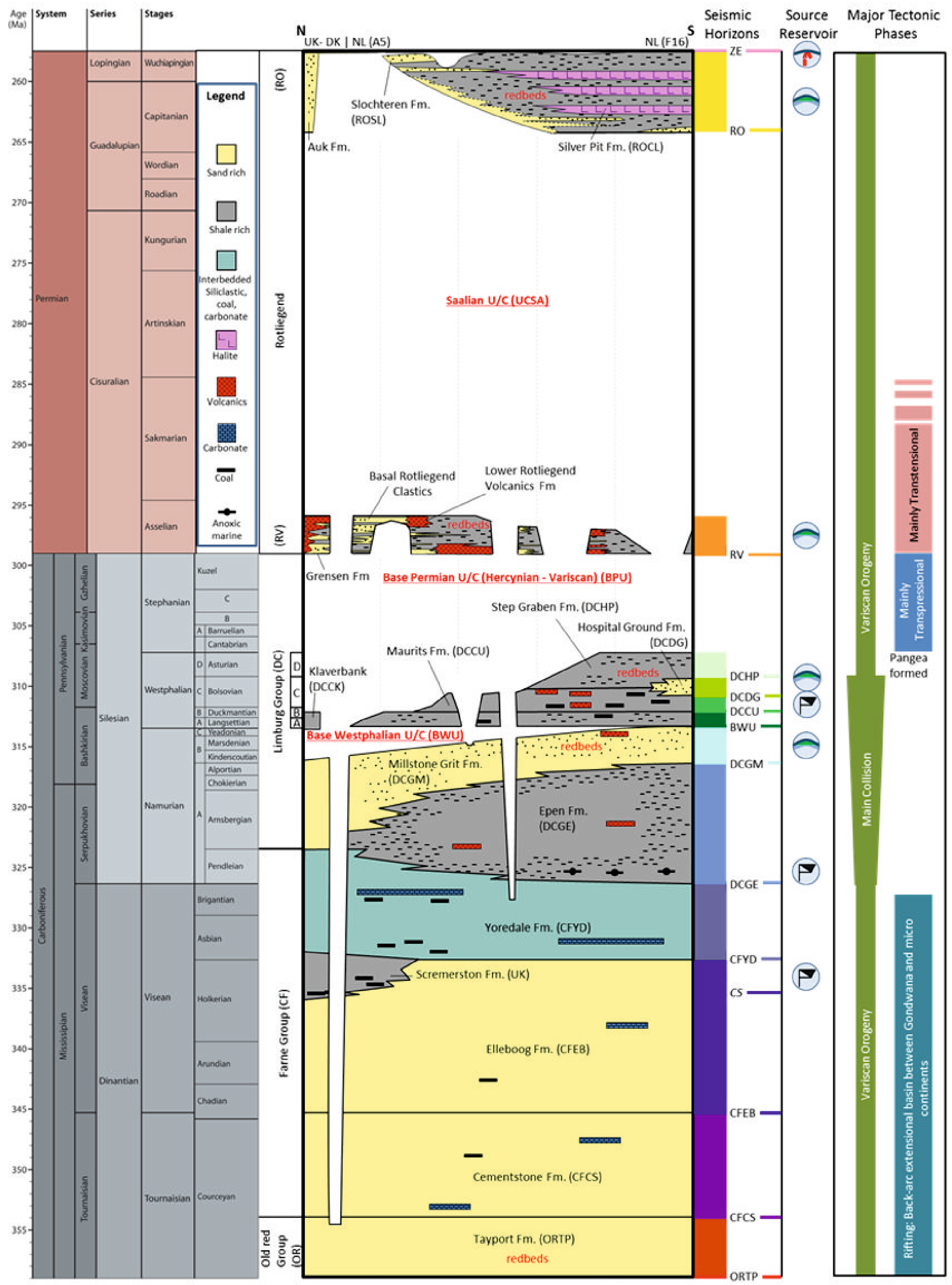
A) Lessons learned from the TNO Northern Offshore Project (De Bruin et al., 2015)



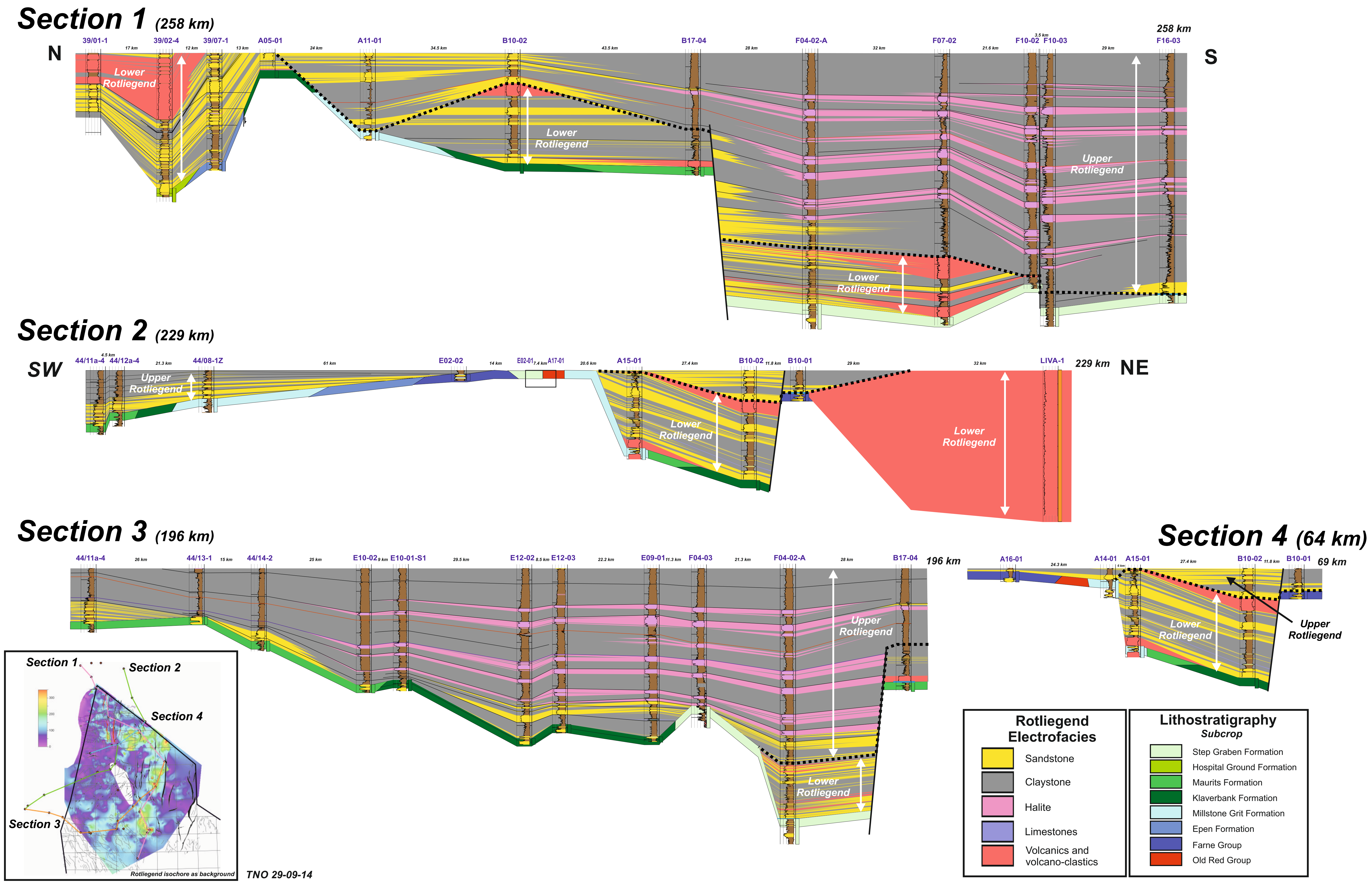
Above: Reservoir facies distribution in the western-central part of the Southern Permian Basin. A) The lower part of the Slochteren Formation and its equivalents. B) The upper part of the Slochteren Formation and its equivalents. Fields with Rotliegend reservoir are also shown. Modified from Gast et al. (2010).



Left: Stratigraphic setting of the Rotliegend in the Dutch northern offshore. This conceptual interpretation is based on tectono-stratigraphic results obtained in the present project. These conceptual models are vertically not to scale. A) NE-SW trending cross section through the Step Graben and the Elbow Spit High. B) N-S trending cross section, with a bend, across the eastern part of the Mid North Sea High (MNSH) and within the Step Graben. C) Location map with the red box indicating the project's study area. Black line shows the edge of the Dutch offshore. De Bruin et al. (2015)

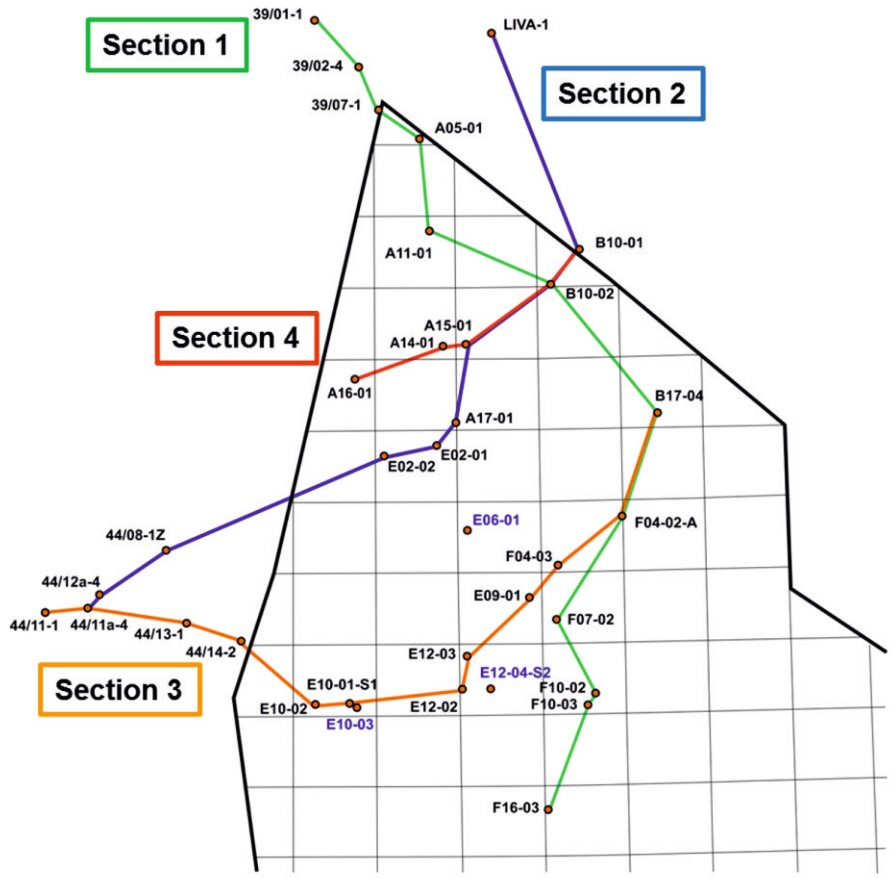


Above: Updated chronostratigraphical chart of the Carboniferous and Permian. From De Bruin et al. (2015), based on Kombrink et al. (2010) and Gast et al. (2010)

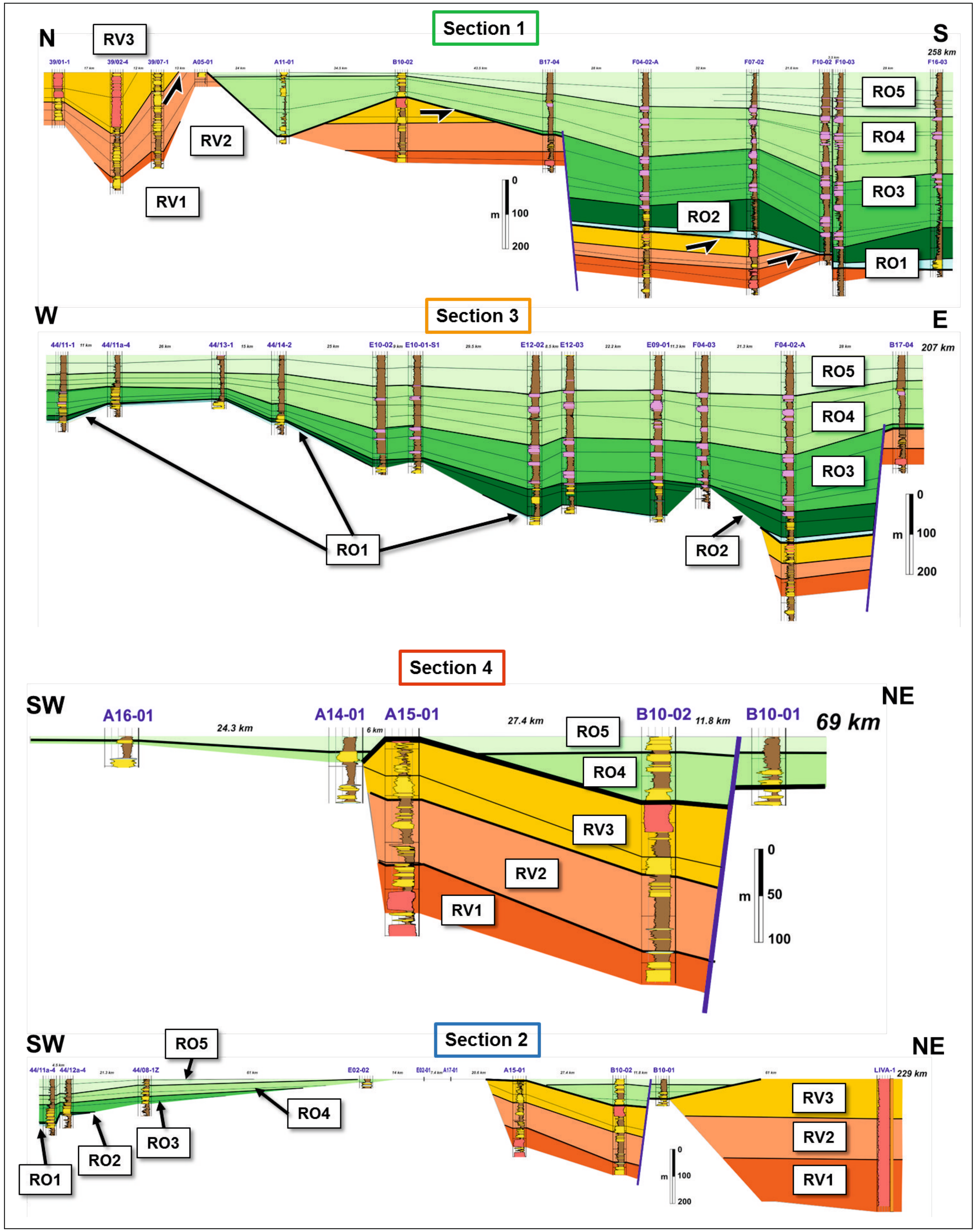


Above: Stratigraphic correlation panels of the Rotliegend in the Dutch Northern Offshore. The base Zechstein is used as upper datum. De Bruin et al. (2015)

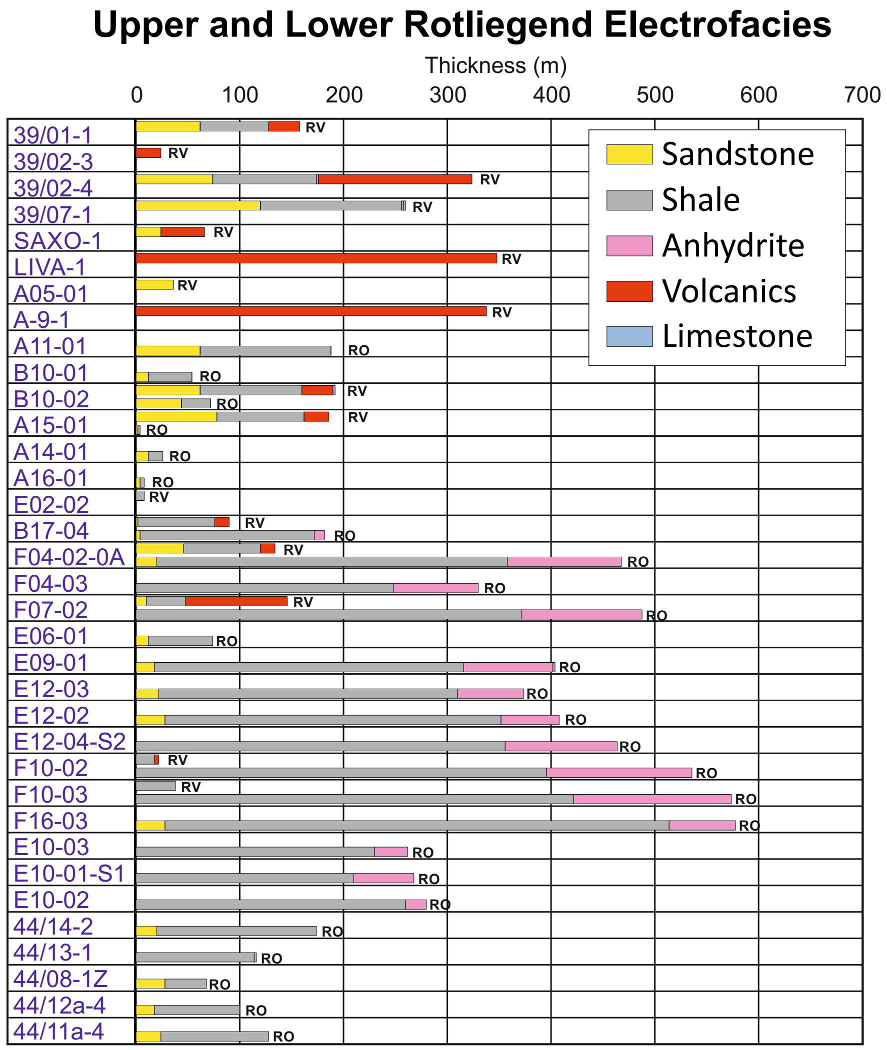
2. Geological setting

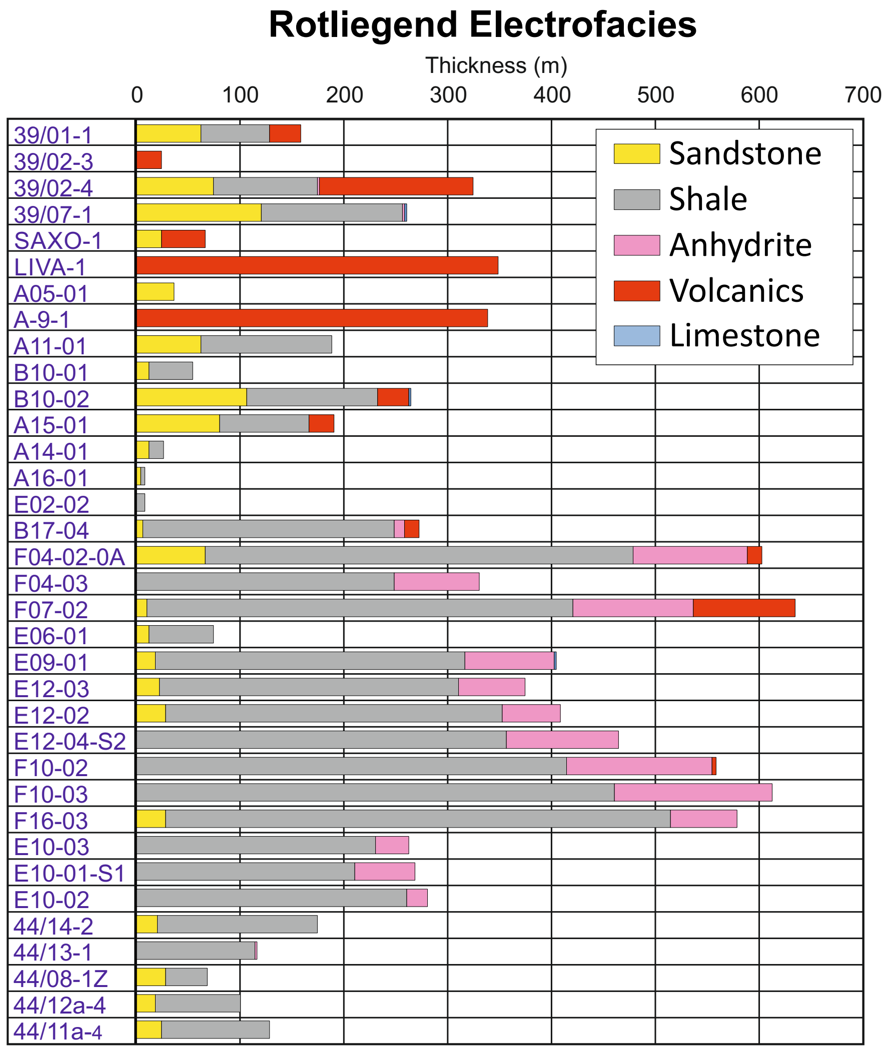


Above: Location map of the stratigraphic correlation panels. All key wells besides three (E10-03, E12-04-S2 and E06-01), that are located within the study area have been used to construct these panels.

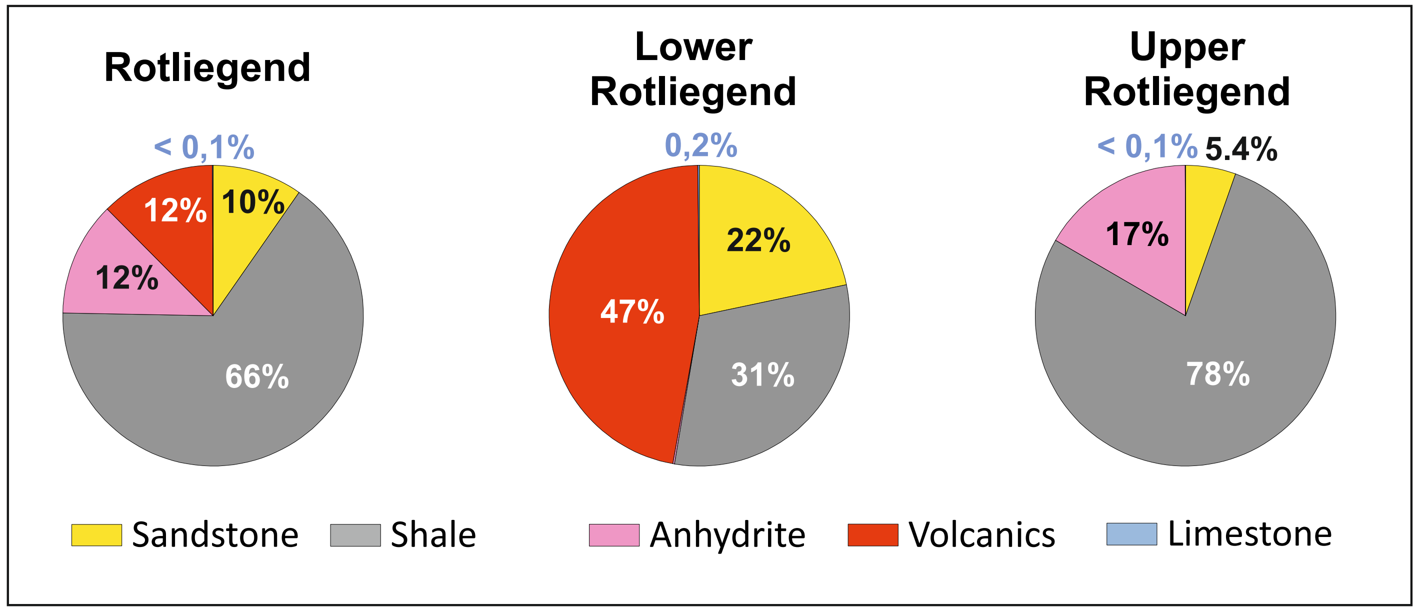


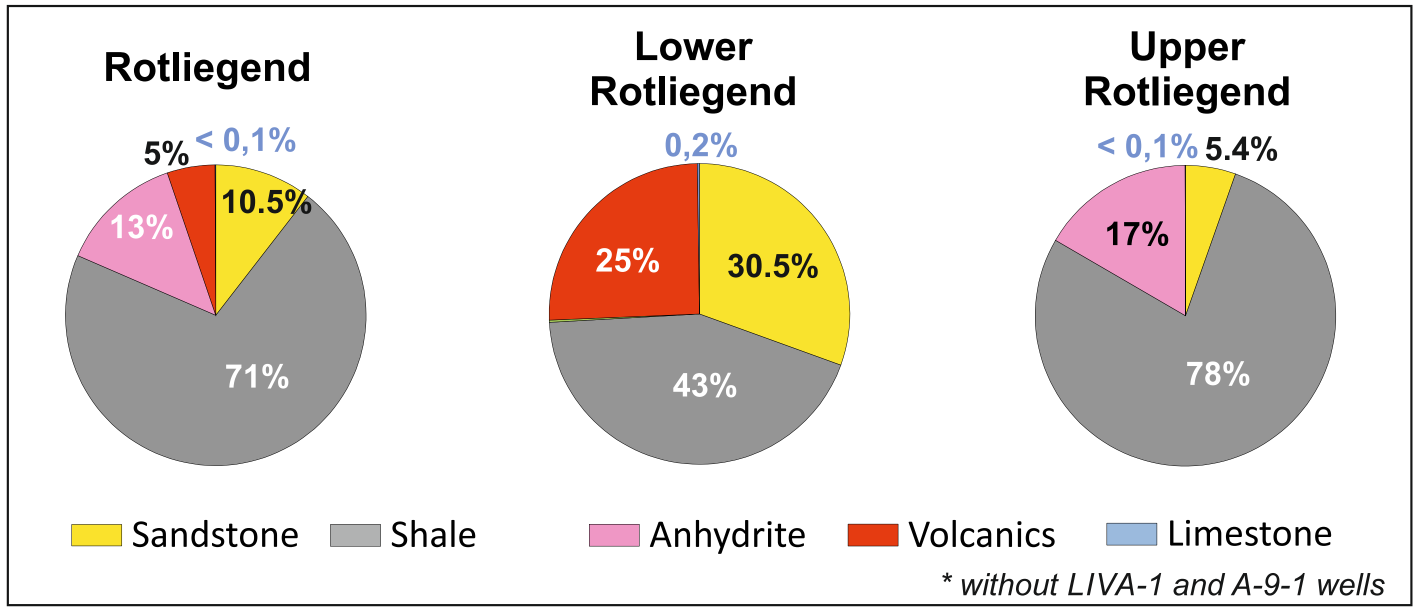
Right: Stratigraphic correlation panels illustrating the Intra Lower and Upper Rotliegend subdivisions (part 2). RV1-RV3 refer to three intra Lower Rotliegend subdivisions and RO1-5 refer to Upper Rotliegend subdivisions. Main truncations are highlighted with black arrows. See Figure above for the location.



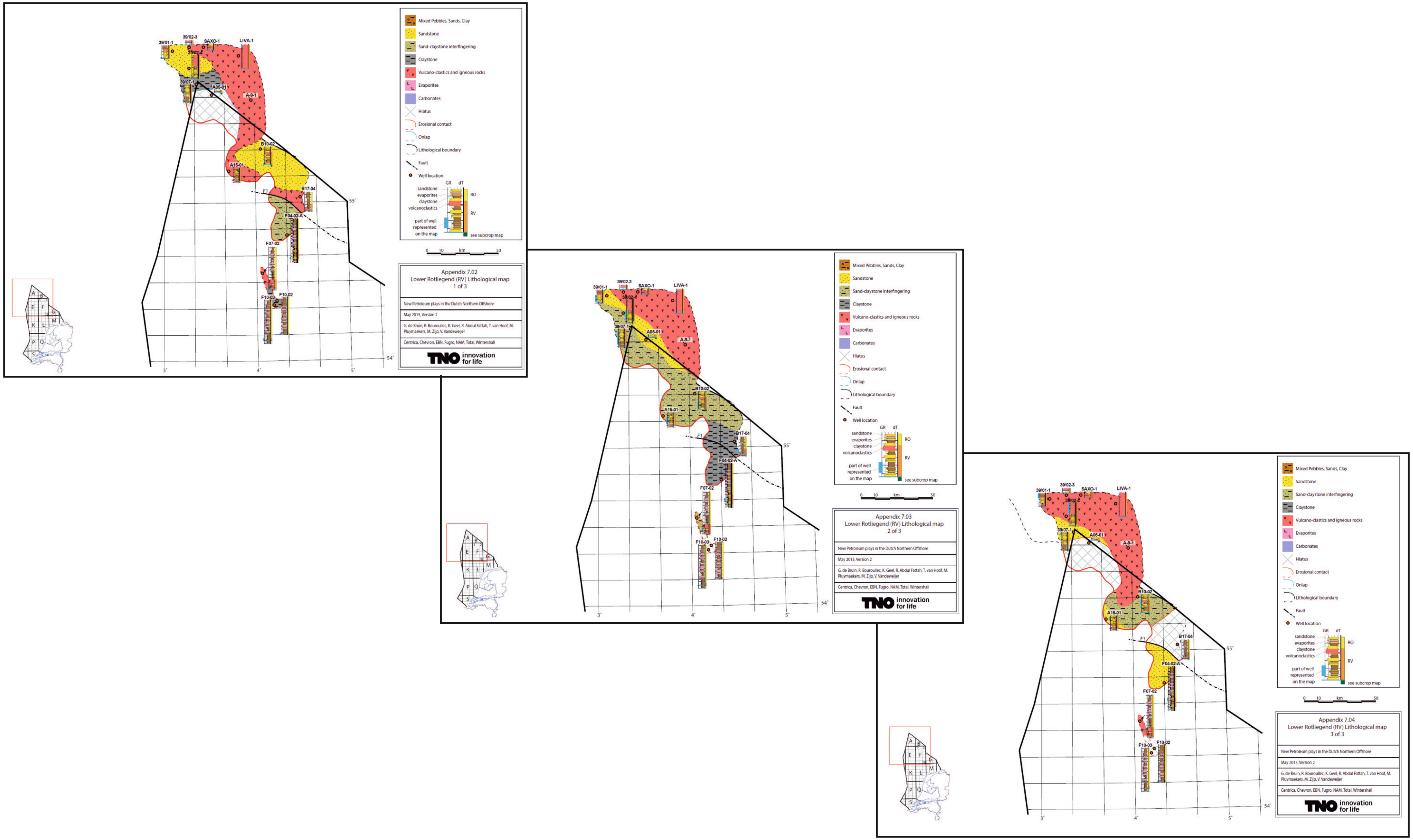


Left: Electrofacies results of the Rotliegend for all the wells located in the study area. 1) To the left: differentiated for the Upper and Lower Rotliegend for each well, and 2) to the right: for the entire Rotliegend for each well. The Rotliegend electrofacies thicknesses measured in the well are not corrected for deviation since no major deviated wells have been used in this study. RO= Upper Rotliegend, RV= Lower Rotliegend. Location of wells shown in Figure 3.2.



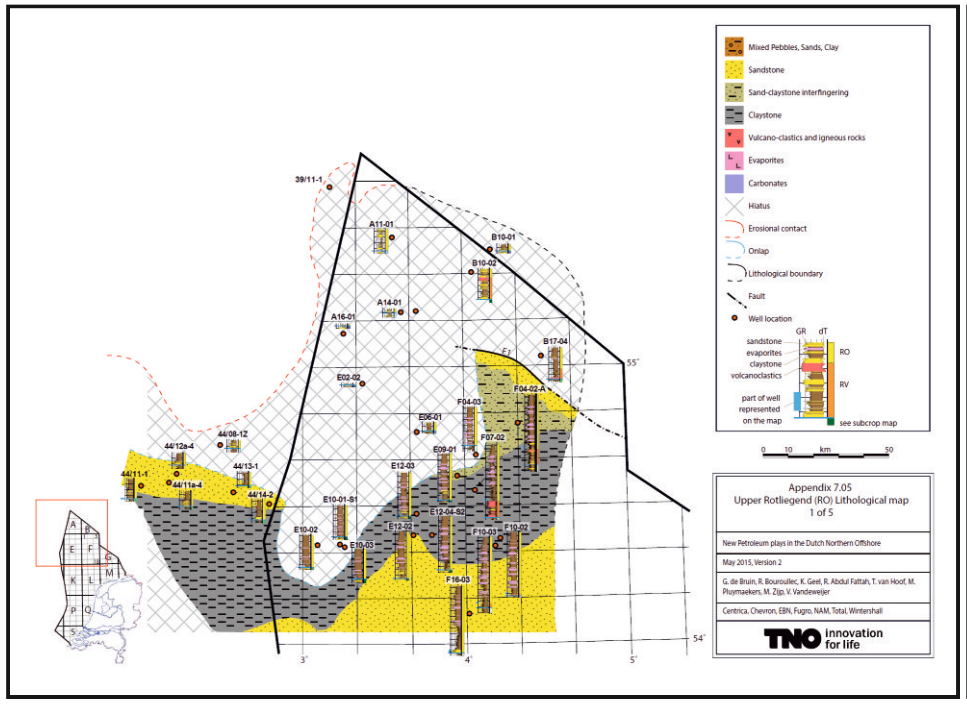


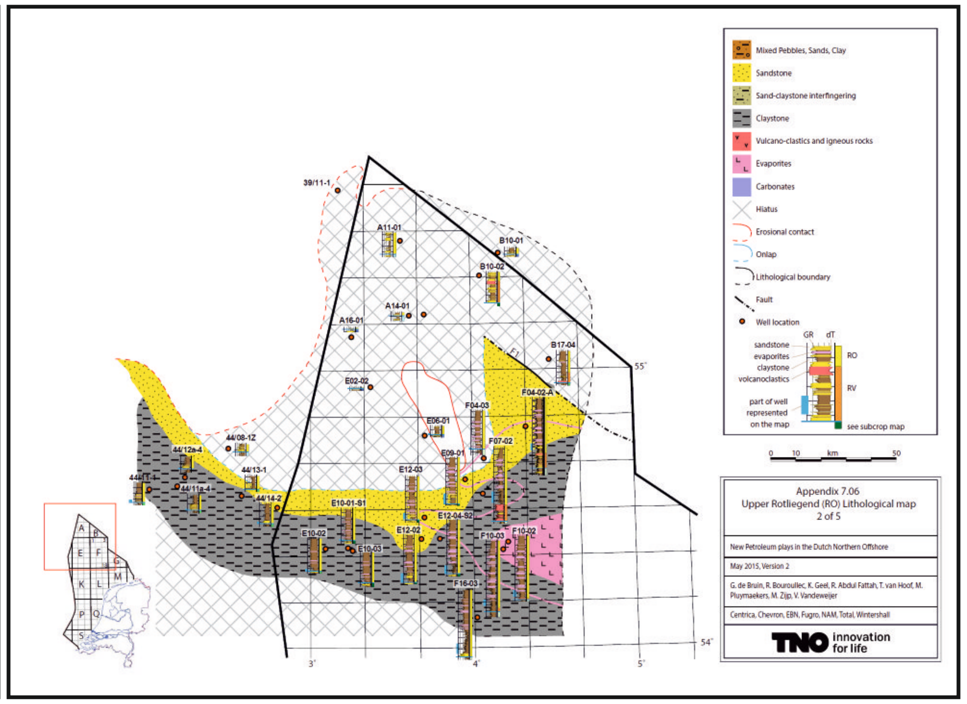
Above: Pie-charts documenting the relative proportion of the Rotliegend electrofacies. The entire database for the first row, and for the second row, all wells but one (* i.e. well LIVA-1, which is located in Denmark and consists of volcanics in the Rotliegend). Note that the amount of carbonate lithology in the Rotliegend is very low (overall less than 0.1%).

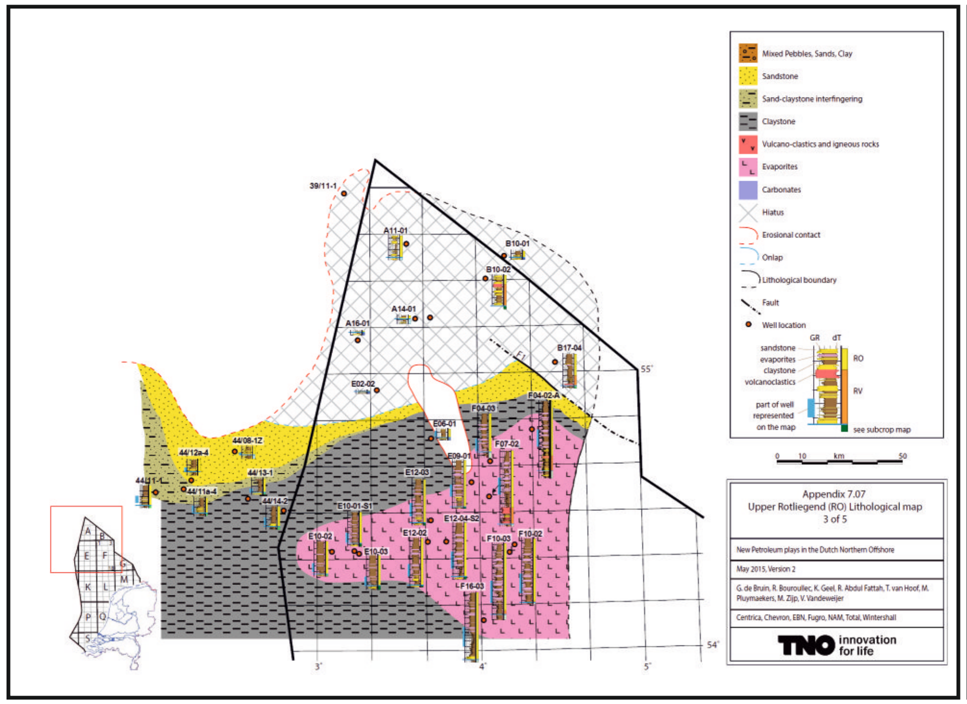


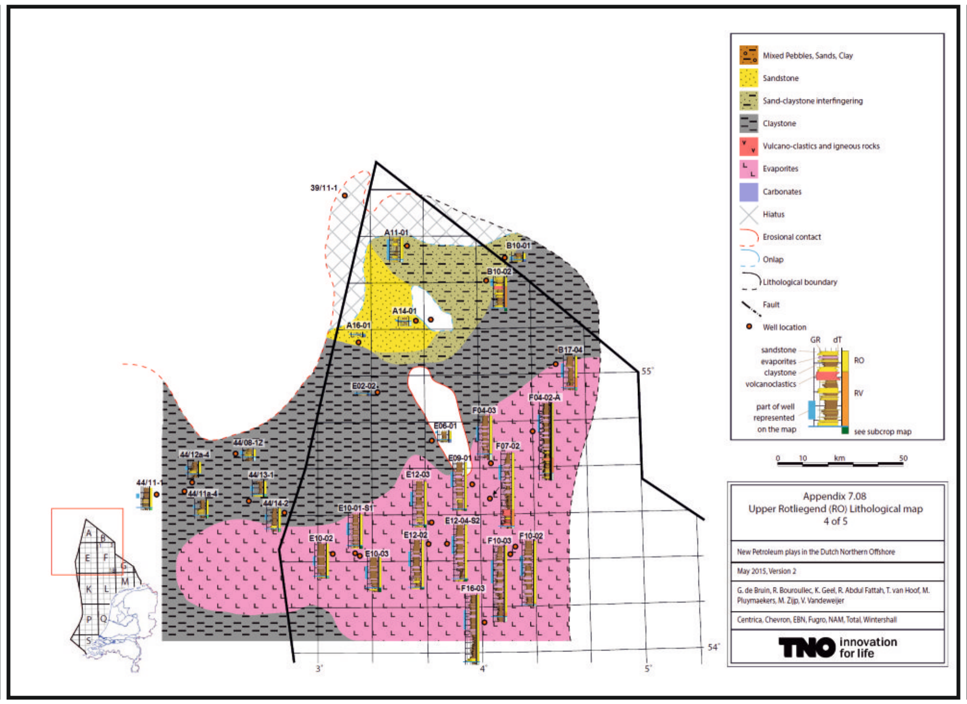
Above: Depositional maps of the preserved three units of the Lower Rotliegend. Seven lithofacies associations have been identified at well locations and extrapolated across the wells. Seismic data was used to map the aerial extent of each sub-division and to characterise the boundaries of each lithofacies (i.e. eroded, onlapping or laterally transitioning to other lithofacies associations).

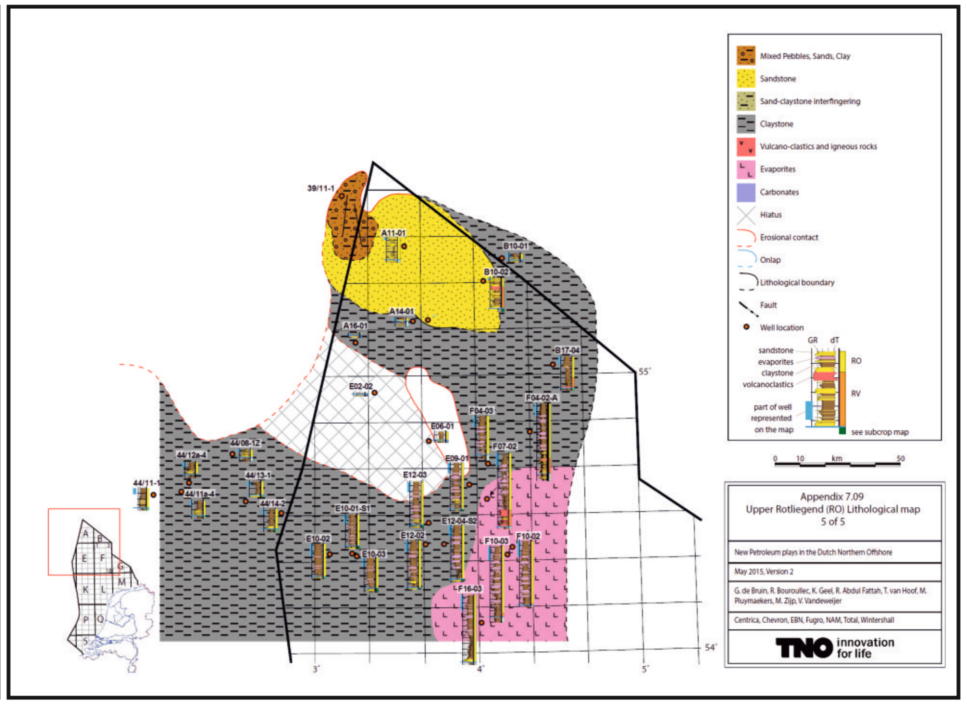
Right and below: Depositional maps of the preserved five units of the Upper Rotliegend. Seven lithofacies associations have been identified at well locations and have been extrapolated across wells. Seismic data was used to map the aerial extent of each unit and to characterise the boundaries of each lithofacies (i.e. eroded, onlapping or laterally transitioning to other lithofacies associations).



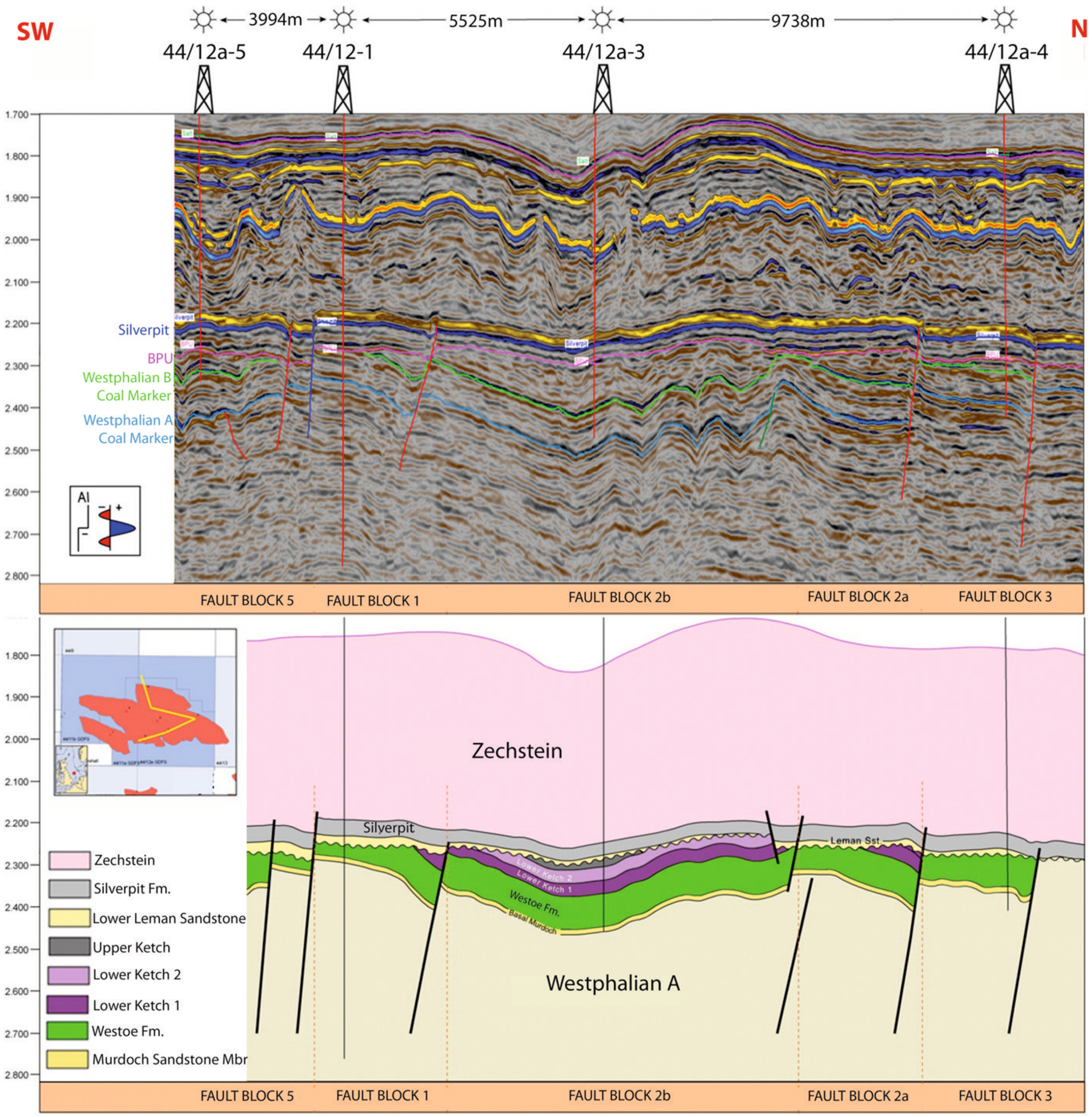




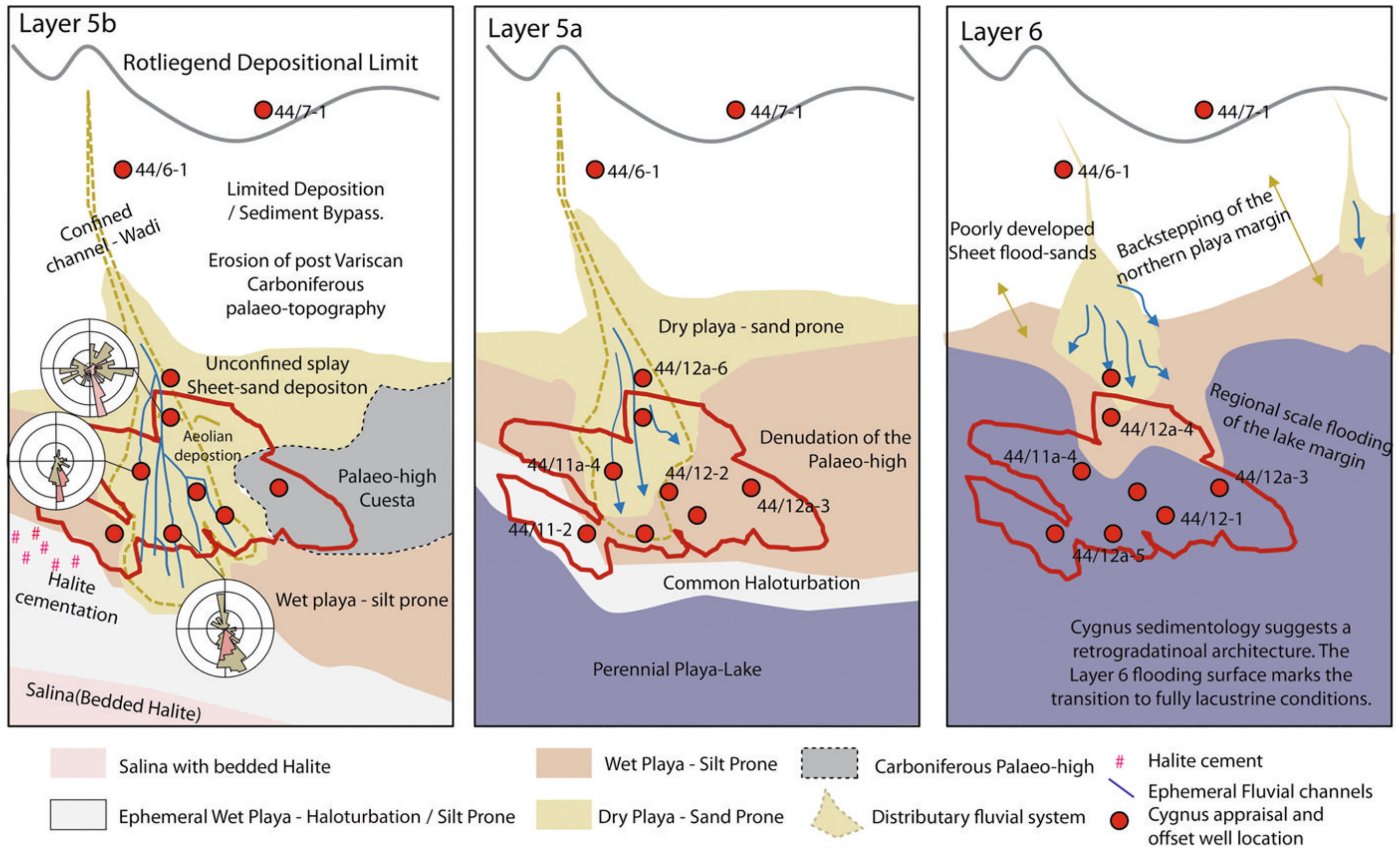




B) Lessons learned from the Cygnus Field (Catto et al., 2017)

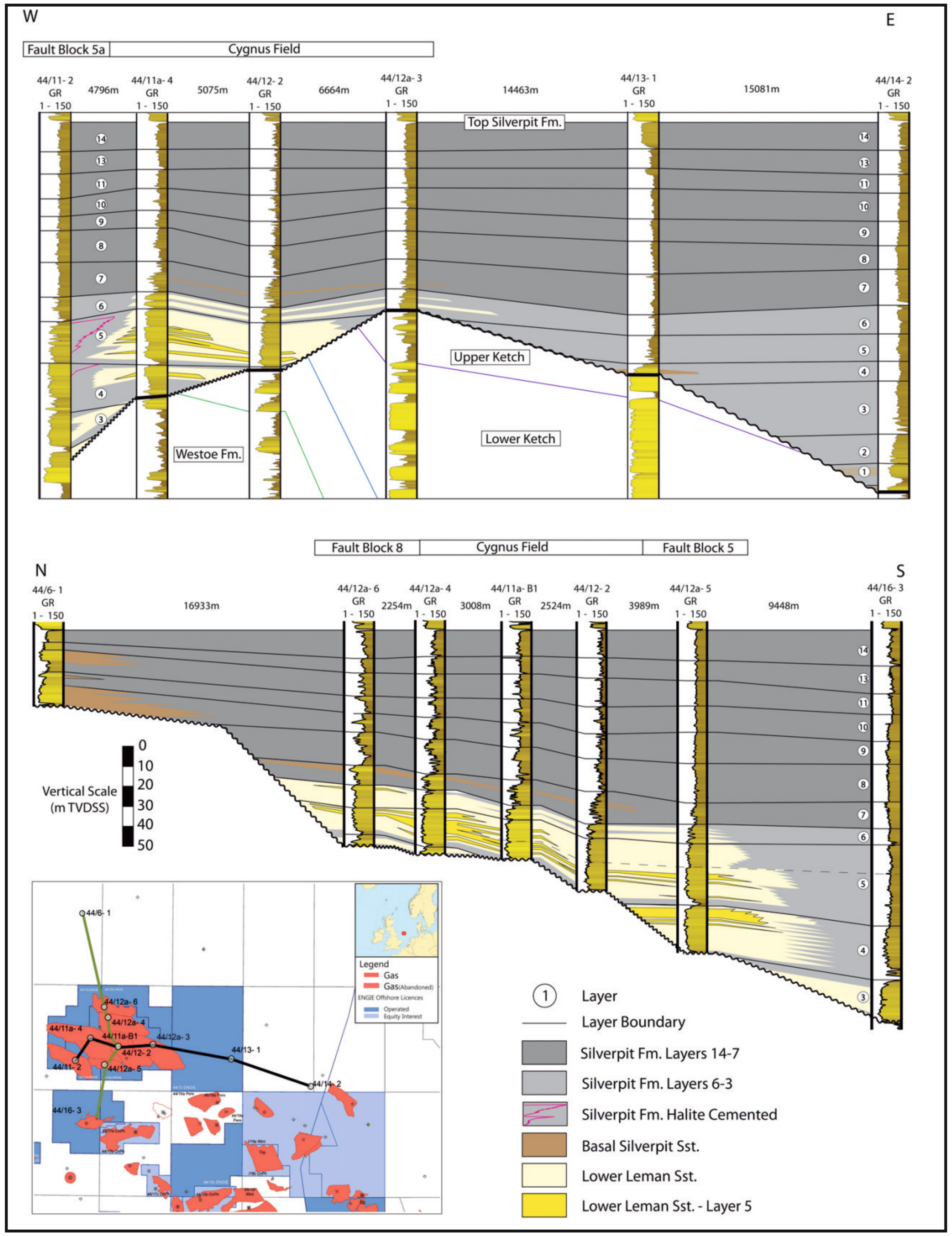


Above: Geoseismic and seismic cross-section through the Cygnus Field shows.a variable Base Permian subcrop of Westphalian strata. Catto et al., 2017.

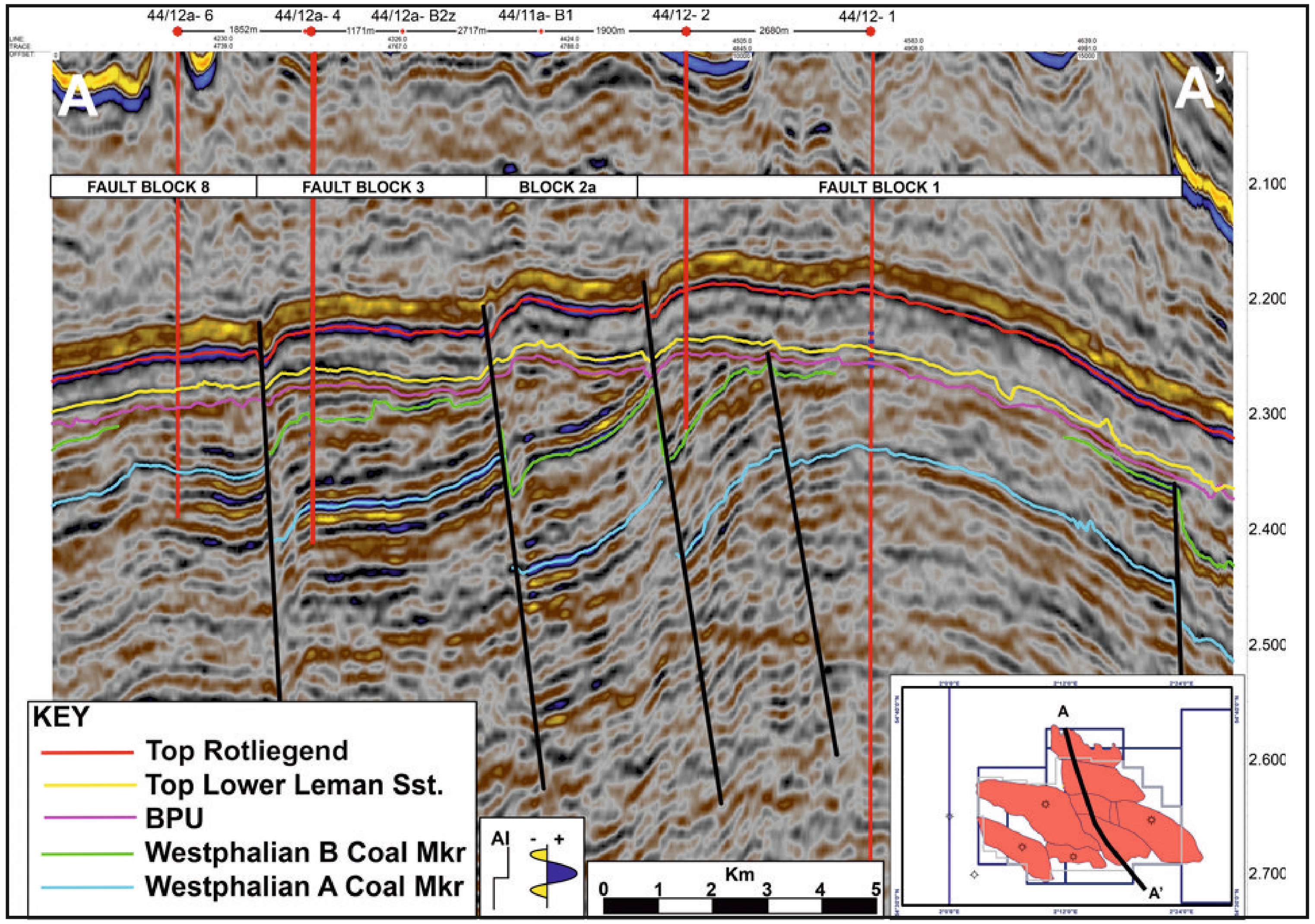


Above: Palaeogeographical reconstruction of the Lower Leman Sandstone showing the regression to the north and the regional-scale flooding of the lake margin. Layer 5 has been subdivided in this figure into 5a and 5b, representing the change from aggradational to upper retrogradational facies architecture. Layer 5b shows the best reservoir properties in the Cygnus Field. This interval is dominated by fluvial deposition from the north. At this stage the underlying topography is being infilled with more laterally continuous deposition which is observed across the field. Deposition was aggradational as sediment supply became equal with subsidence. The reservoir in this zone is overall very good quality, with more silt-rich deposits only observed in the most distal southern areas. During the upper part of Layer 5 (5a) there was an overall transgression from the playa lake to the south. Denudation of the 44/12a-3 palaeohigh occurred as the entire drainage systems retreated to the north to NE. Onlap to the north and increased shaliness typically results in deterioration of porosity and reservoir quality, particularly in the more southerly wells. In both Layer 5a and 5b, deposition became more basinwards with thicker deposits in the south, thinning to the north. Layer 6 represents backstepping of the northern margin, with transition from predominantly aggradational to retrogradational facies architecture in response to the overall wetter climatic conditions. Catto et al., 2017.

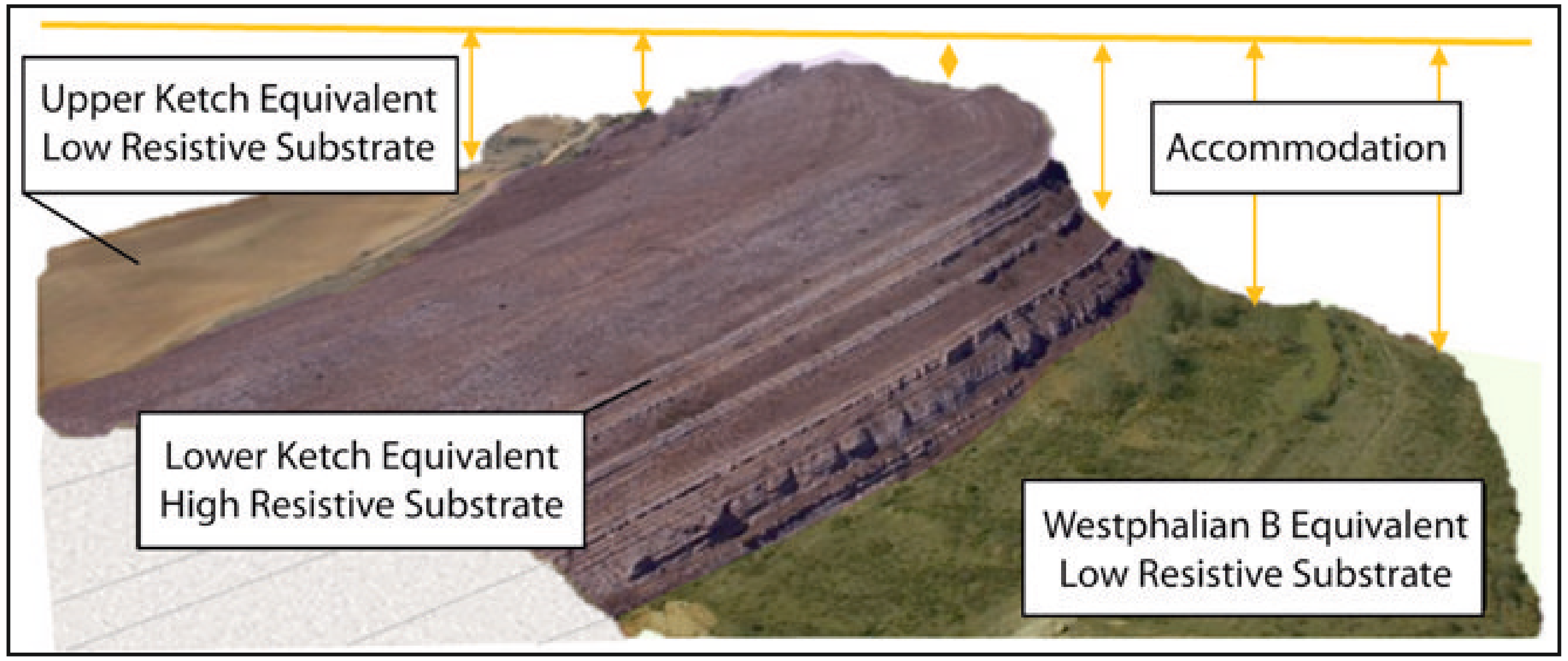
2. Geological setting



Above: Well correlations west to east (top) and north to south (bottom) showing the Rotliegend reservoir layering and the variable thickness that can be related to subcrop at the BPU. The primary reservoir layer is Layer 5, which can be subdivided into lower aggradational and upper transgressional packages highlighted by the dashed line. Catto et al., 2017.



Above: North–south seismic line across the Cygnus structure. Key seismic picks are highlighted as: Top Rotliegend, Top Lower Leman Sandstone, BPU, and Westphalian B and Westphalian A coals (seismic line courtesy of CGG). Catto et al., 2017.



Above: An example of a cuesta illustrating how a resistive Ketch substrate would form an asymmetrical ridge and could influence the subsequent sediment dispersal patterns. Catto et al., 2017.

C) Lessons learned from the Grensen Formation

The interval located between the Upper Flora Sandstone and an Upper Volcanic Unit.

Martin et al., 2002: "…the Grensen Formation is genetically distinct from the Carboniferous units. The Grensen Formation is more similar in lithology to the strata of the Lower Rotliegend Group"
Hayward et al., 2003: "**The Grensen Formation** is barren of organic material, but heavy mineral assemblages indicate a clear association with the Permian (C. Hallworth pers. Comm.) and the interval **has** therefore **been assigned a Lower Rotliegend Group**."

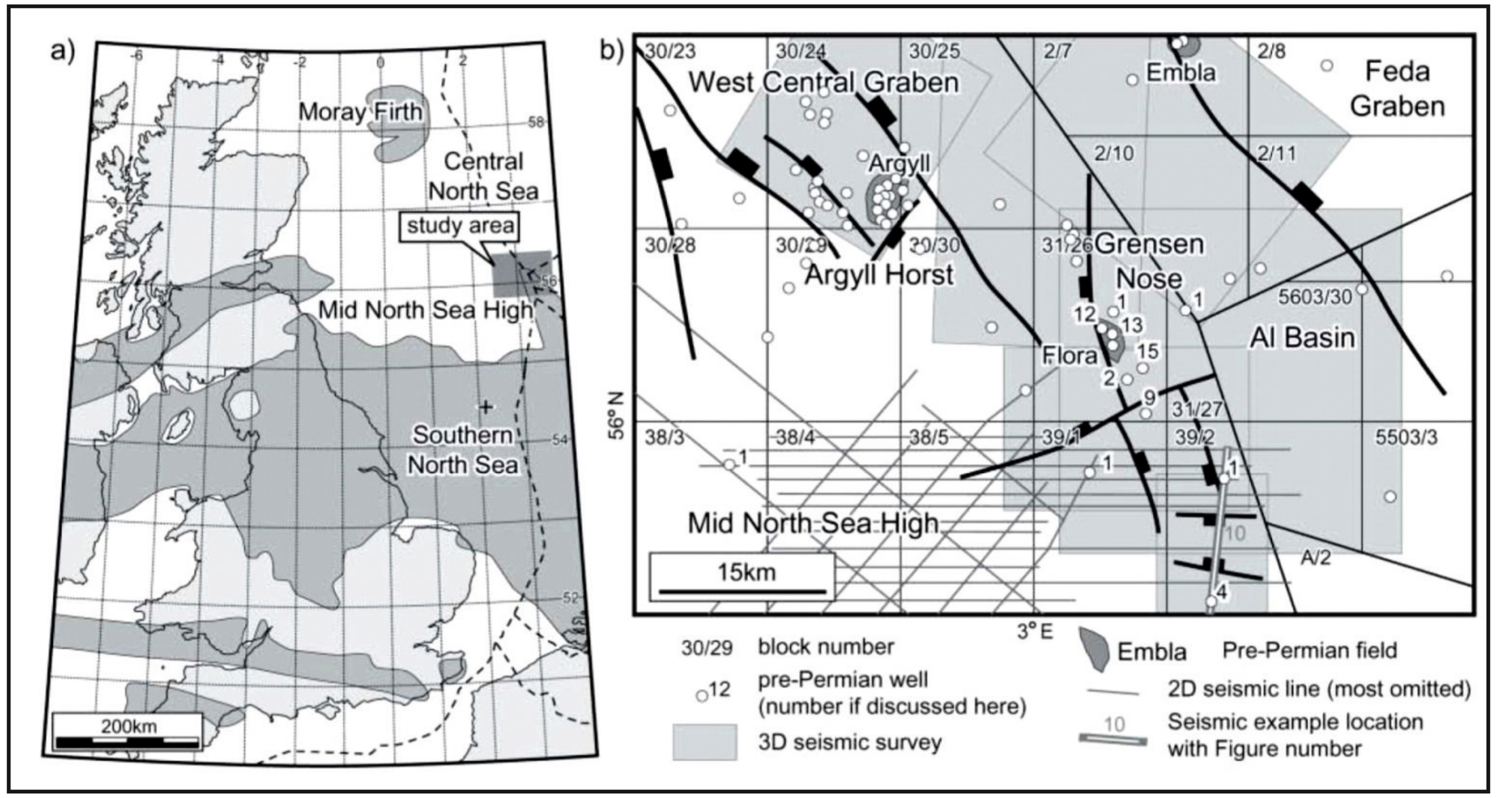
Stratigraphic context:
Lies conformably below the Upper Volcanic Unit (299 +/- 1,6 Ma). Unconformable (Asturic U/C) with the Westphalian Upper Flora Sandstone.

Age: Stephanian (Mennings, 2007) or **Asselian** (Permian) (Gradstein, 2004).

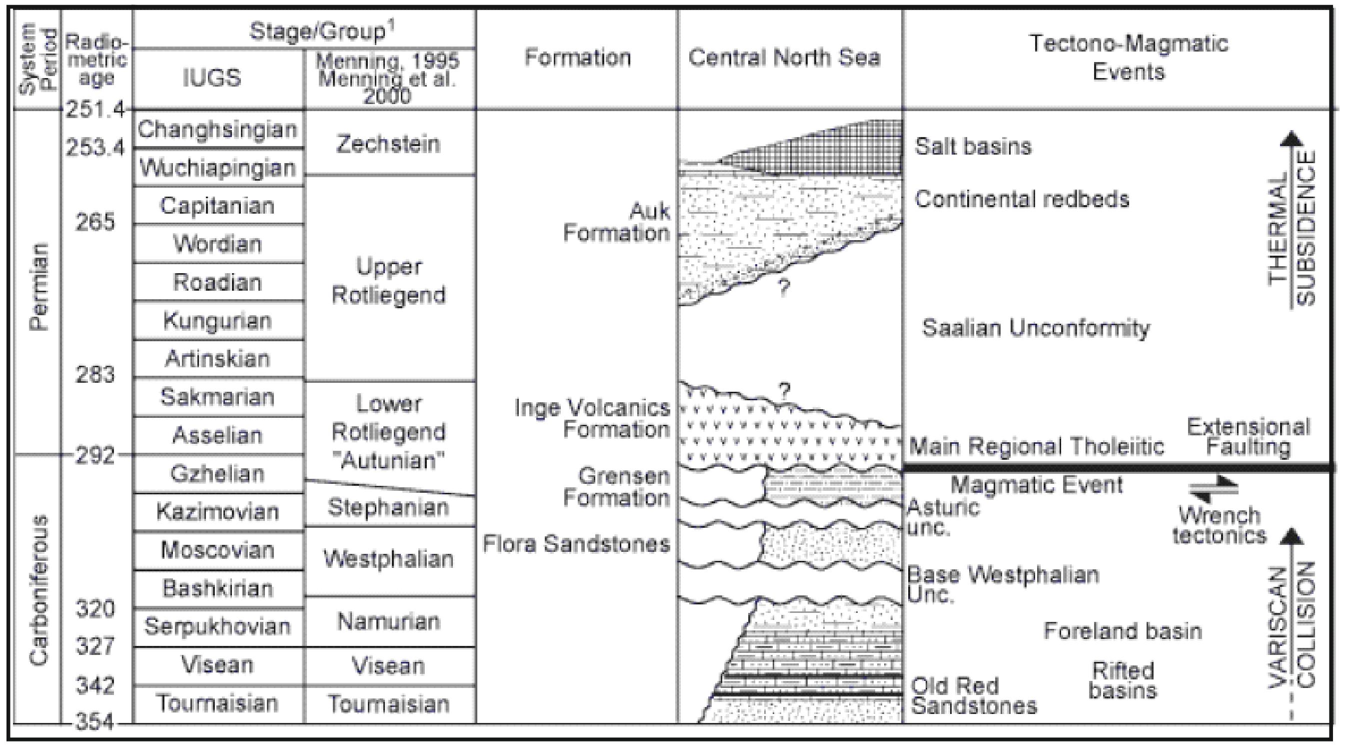
Lithology: Low net/gross succession, interbedded mudstone, siltstone and sandstone (no core).

Sediment transport direction (dipmeter): Unidirectional palaeocurrents toward the NE (low variance), indicative of a change in basin configuration (E-SE direction for older strata).

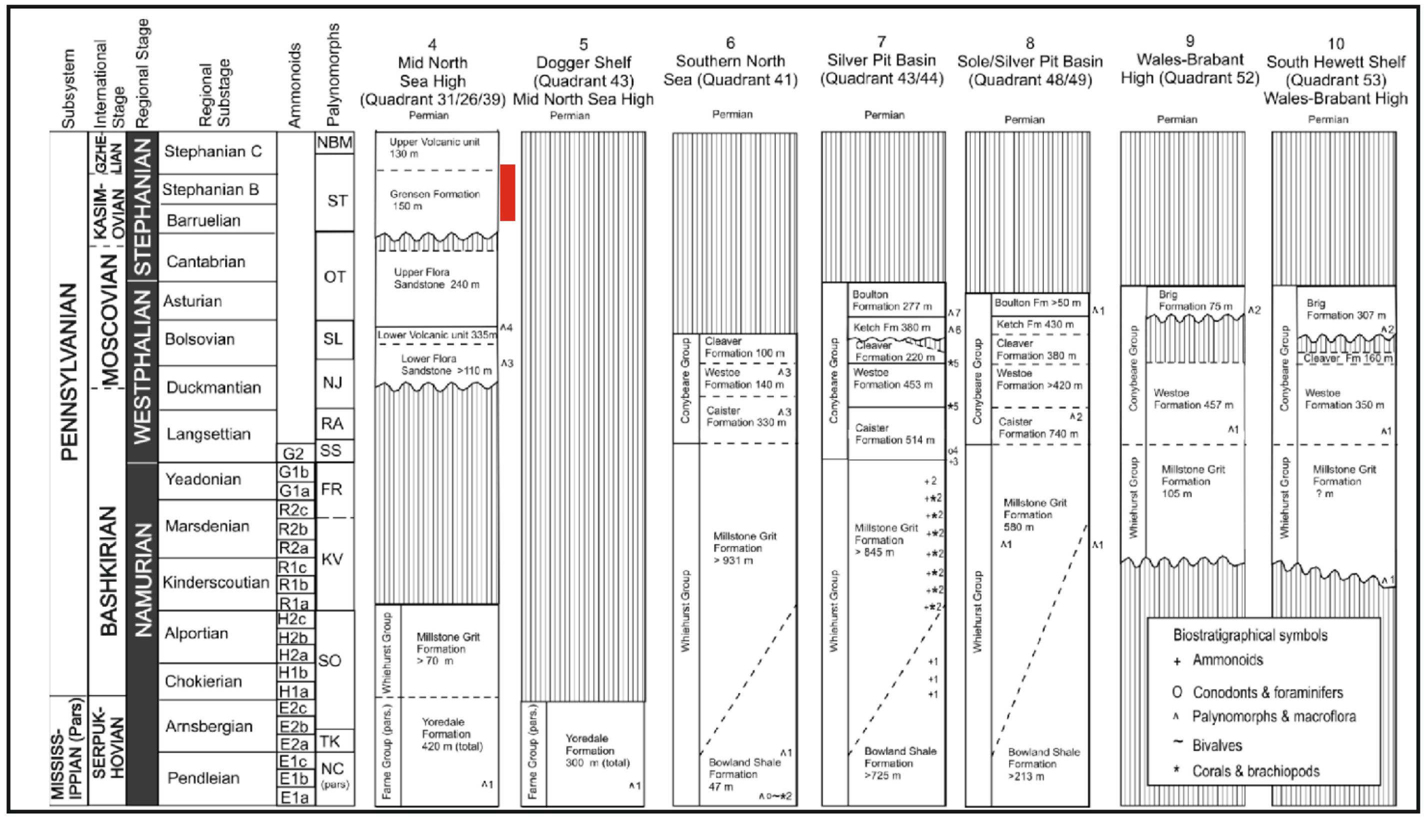
Depositional environment: Fluvial or alluvial depositional settings, arid climate.



Above: Upper Carboniferous and Lower Permian tectonostratigraphy on the southern margin of the Central North Sea. From Martin et al. (2002)



Above: Stratigraphic chart showing the main Carboniferous - Permian stratigraphy and related tectonic events in the Central North Sea. From Heeremans et al. (2004).The time scales used are from Menning (1995) and Menning et al. (2000), with the official timescale of the IUGS as a reference.



Above: Correlation of Carboniferous successions. From Waters et al. (2011).

How does the Grensen Formation relate to the Dutch northern offshore ?

The Lower Rotliegend consists of volcanics, volcanoclastics deposits and siliciclastic deposits and, therefore, is a valid new potential reservoir target in this part of the North Sea.

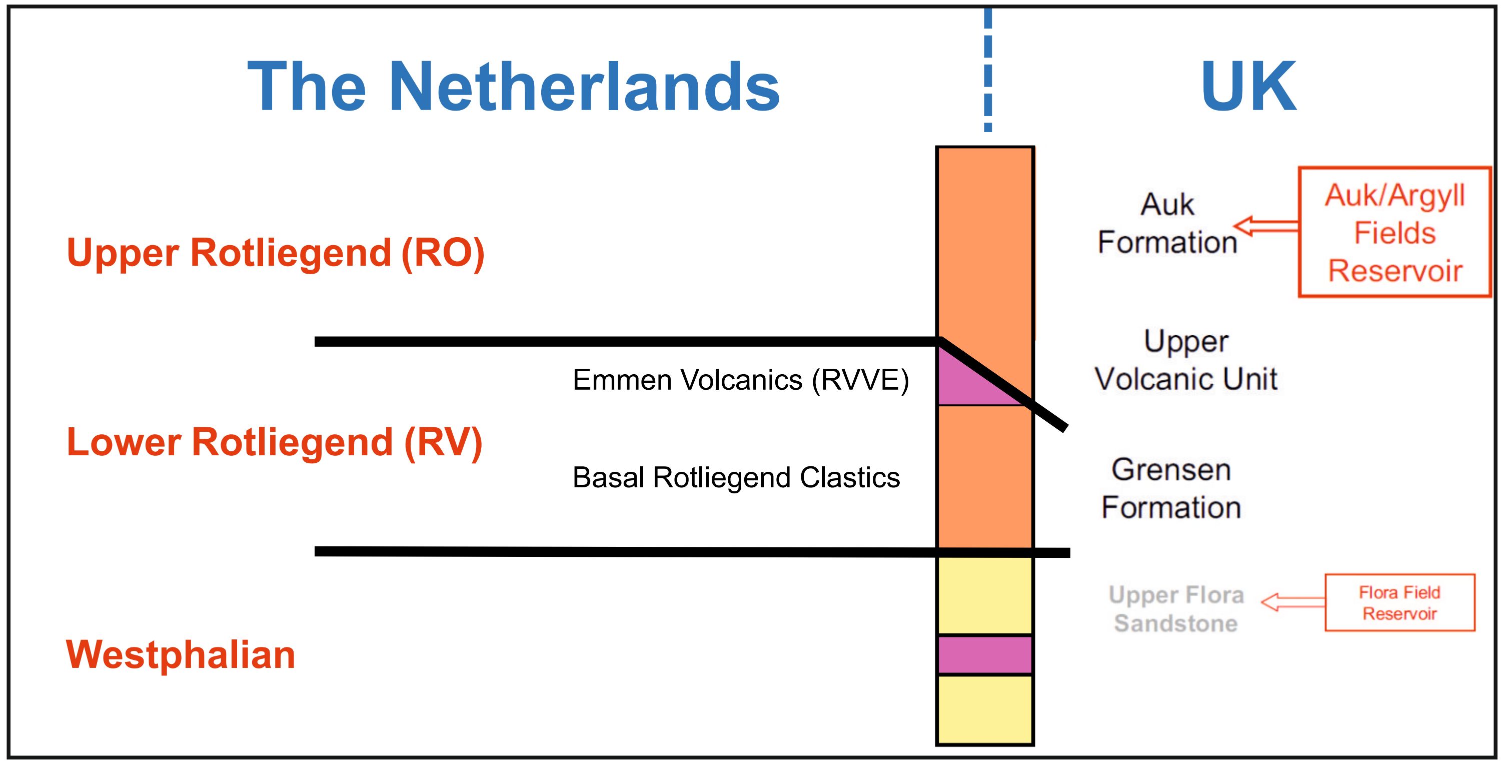
Age debatable (Stephanian or Early Permian):

- absolute age of the Carboniferous-Permian boundary varies depending on the chronostratigraphic charts used.
- Error bars on age dating using K-Ar dating methods introduce uncertainties in the age of the upper volcanic unit.
- Stephanian-age strata in this part of the world has not been clearly proven.

However, the Grensen Formation's…

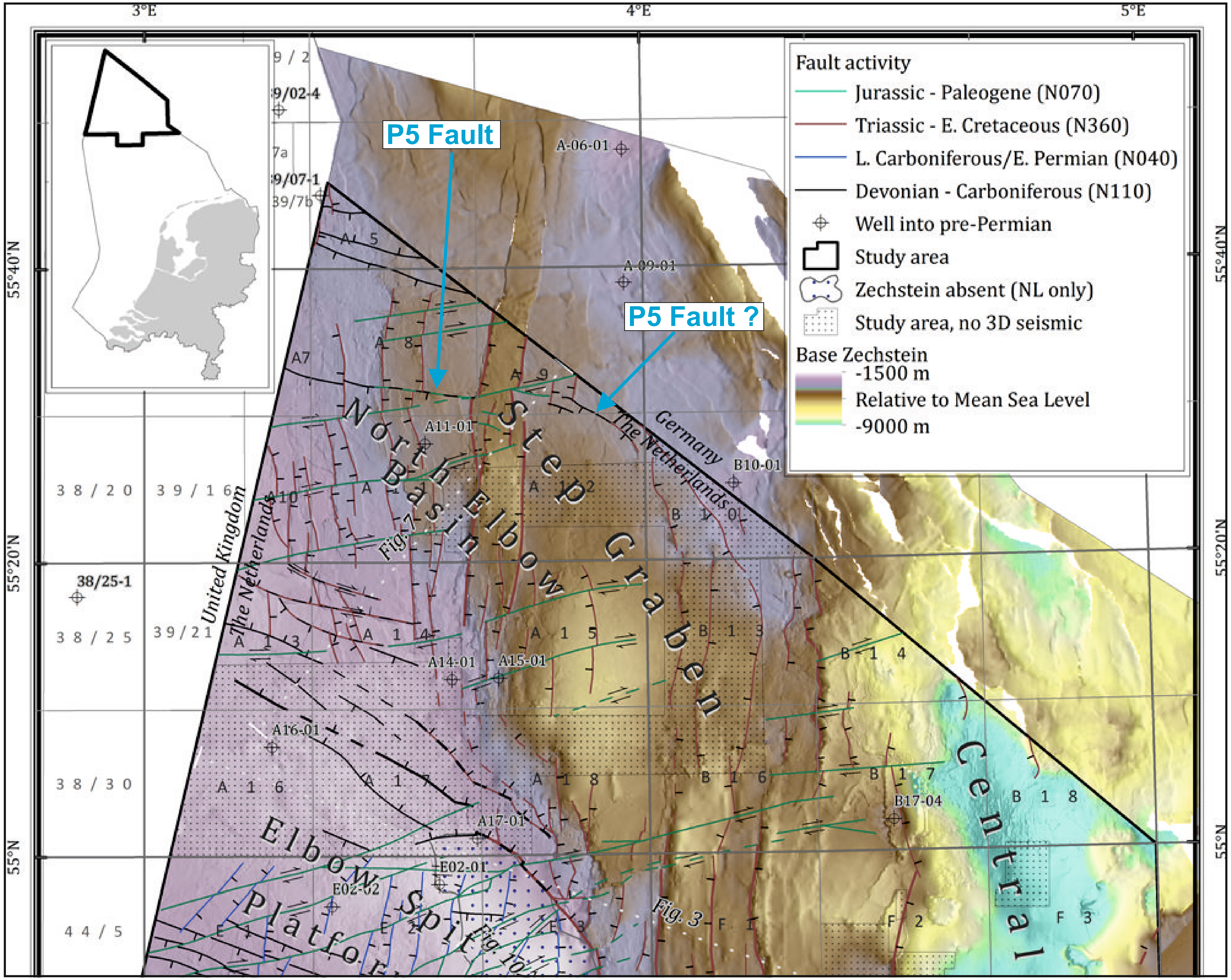
- lithology,
- depositional environment,
- sediment dispersal pattern,
- heavy mineral assemblage and,
- its similarities with the Basal Rotliegend Clastics in the Northern Offshore of the Netherlands,

… suggest that the Grensen Formation is most likely equivalent to the Lower Rotliegend, in the Northern Offshore of the Netherlands.

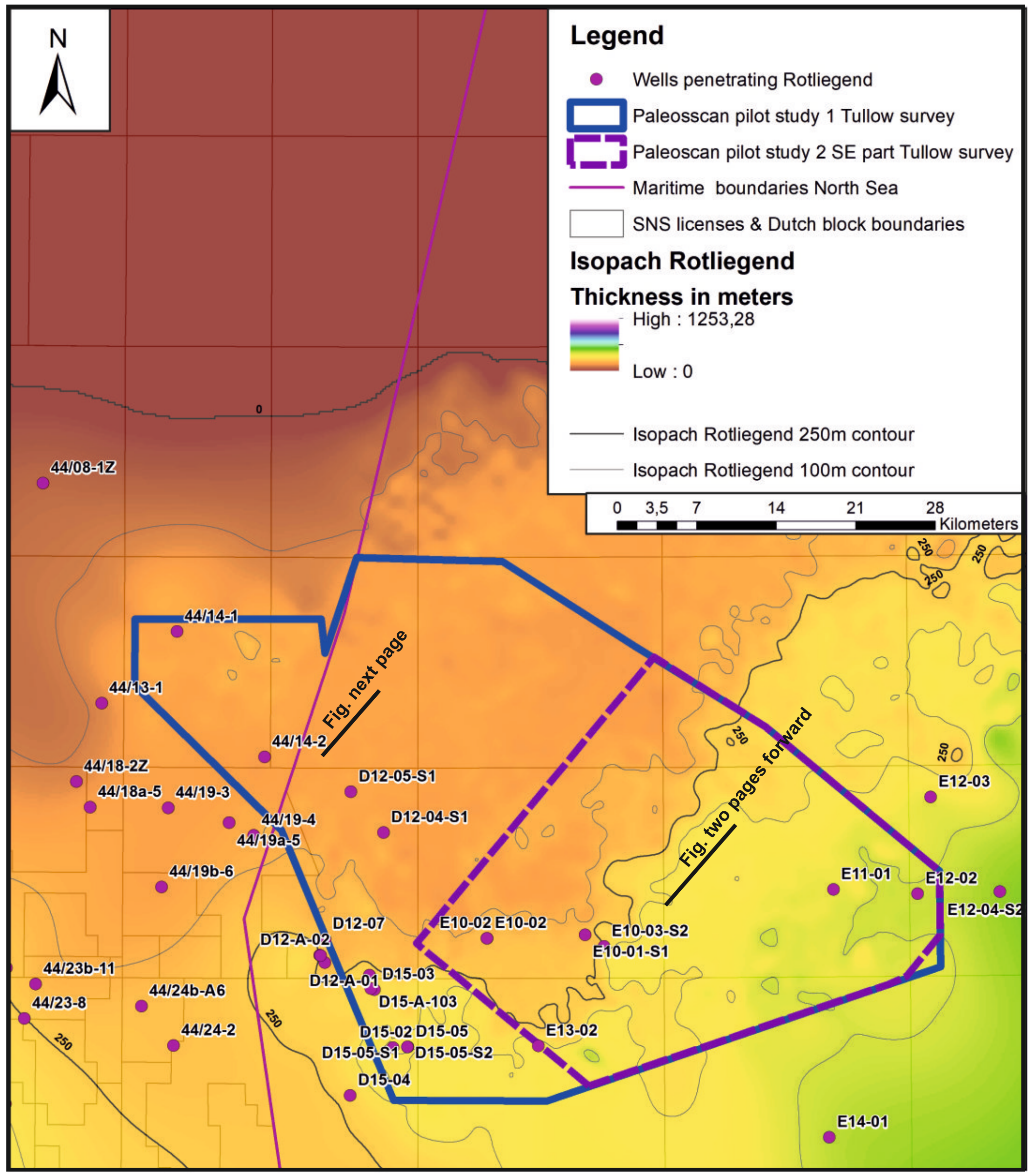


Above: Lower Permian lithostratigraphical equivalence between Dutch Northern Offshore and the UK Eastern Offshore. From De Bruin et al.(2015).

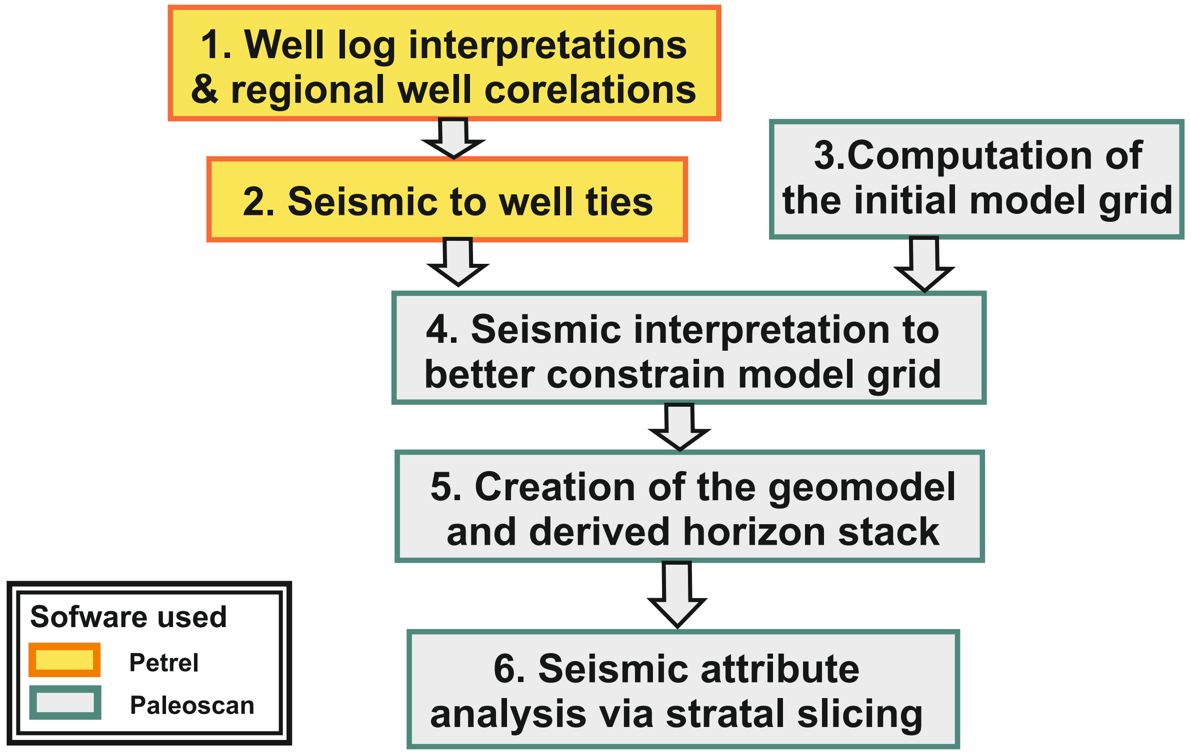
D) Structural framework for the northern Dutch offshore



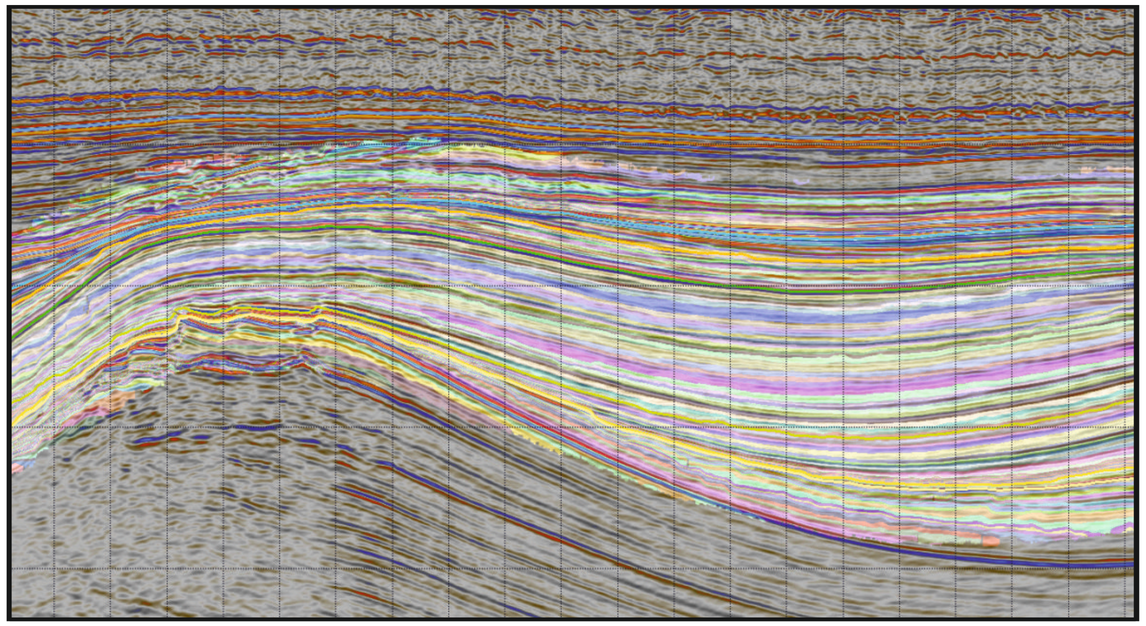
Left: Structural framework for the northern Dutch offshore. Faults are shown at the Base Permian level or, in case of older activity, at the topmost affected horizon. Along with faults, the depth to the base of the Zechstein Group is shown; where the Zechstein is absent, the base of the first younger unit is shown. Faults are coloured according to their activity (see legend); reactivated faults are outlined by dashed lines. Modified from Ter Borgh et al., 2019a and b. Note that the P5 Fault interpreted in the Paleo Five Project (Houben et al., 2020) is shown on this figure. For more information see following pages.



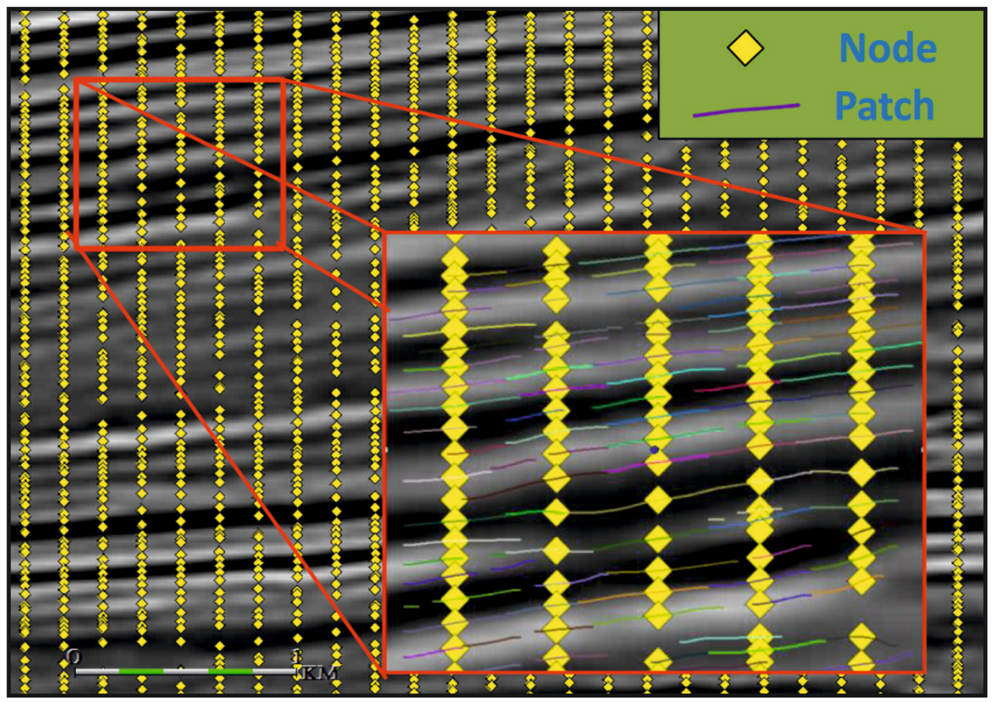
Left: Two pilot studies were performed by using Paleoscan software as part of this project. One pilot study was performed for the Rotliegend interval of the entire Tullow survey, the other pilot study was performed for the Rotliegend interval in the southeastern part of the Tullow survey (see map below). Map indicating the location of he Paleoscan pilot studies that were performed as part of this project.



Above: The workflow that is used to apply seismic attribute analysis via stratal slicing in Paleoscan. A key part of this workflow is the creation of a so called Relative Time Geomodel (RTM) and derived horizon stack, to which the seismic attribute analysis is applied. This RTM is made up of distinct layers, where each layer represents an isochronous interval, implying that the layer was deposited during the same time period. From the RTM a so called horizon stack is created, which is made up of densely packed individual horizons to which stratal slicing and seismic attribute analyses can be applied. The section below explains the procedure regarding the construction of the geomodel and the derived horizon stack. For more information is referred to the PaleoScan manual.



Above: To create the geomodel, first an initial model grid was computed from the seismic cube Example of a cross section through a geomodel (RTM). The individual layers represent isochronous time intervals. RTM not from this study. Note; interval not for Rotliegend in current study area.

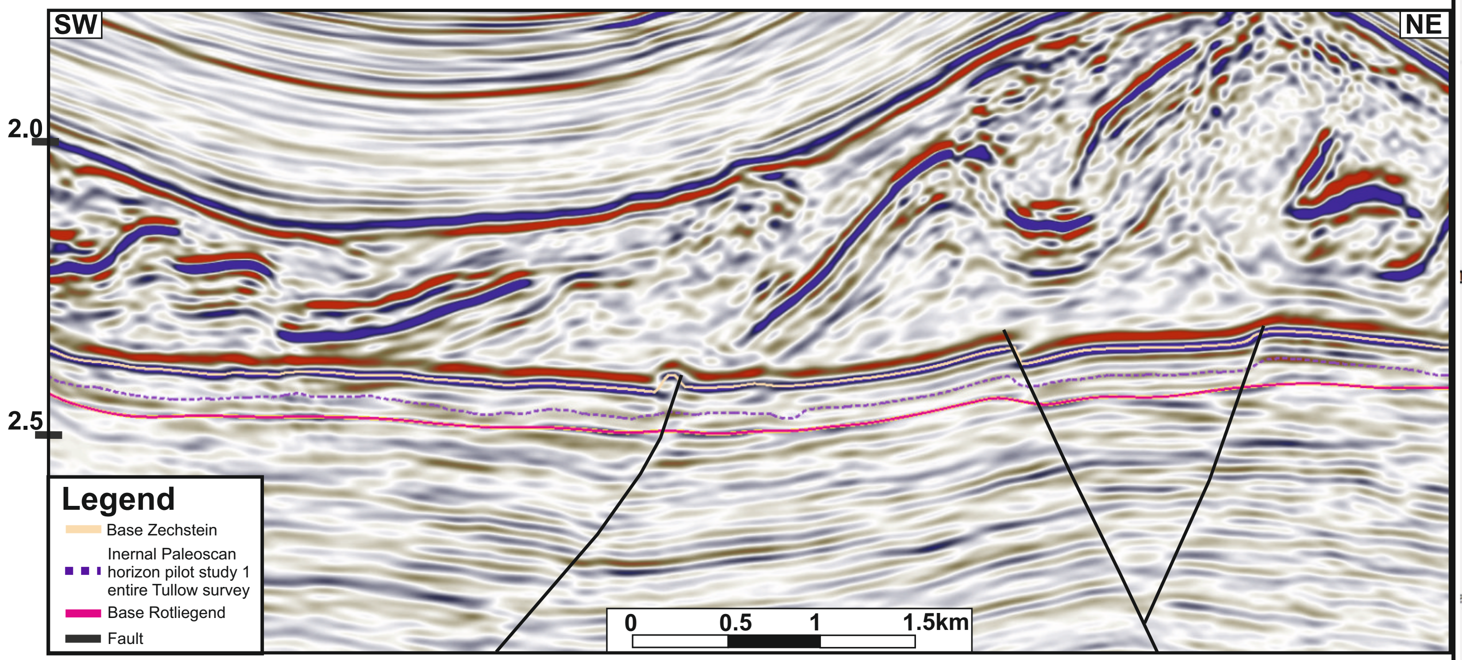


Left: This initial model grid is composed of nodes, which can be seen as elementary seismic horizon patches. The nodes are linked together depending on the degree of similarity of the patches. Some pre-set parameters influence the extent to which the nodes are initially linked by the model. These are: the correlation threshold, the interpolation size and the link probability. A correlation threshold of 0% means that two horizon patches can be linked even without any similarity. A correlation threshold of 20% means e.g. that two patches can only be linked if their similarity is 20% or higher. In a structurally complex setting, a higher correlation threshold allows for a higher degree of certainty in the linkage of patches.

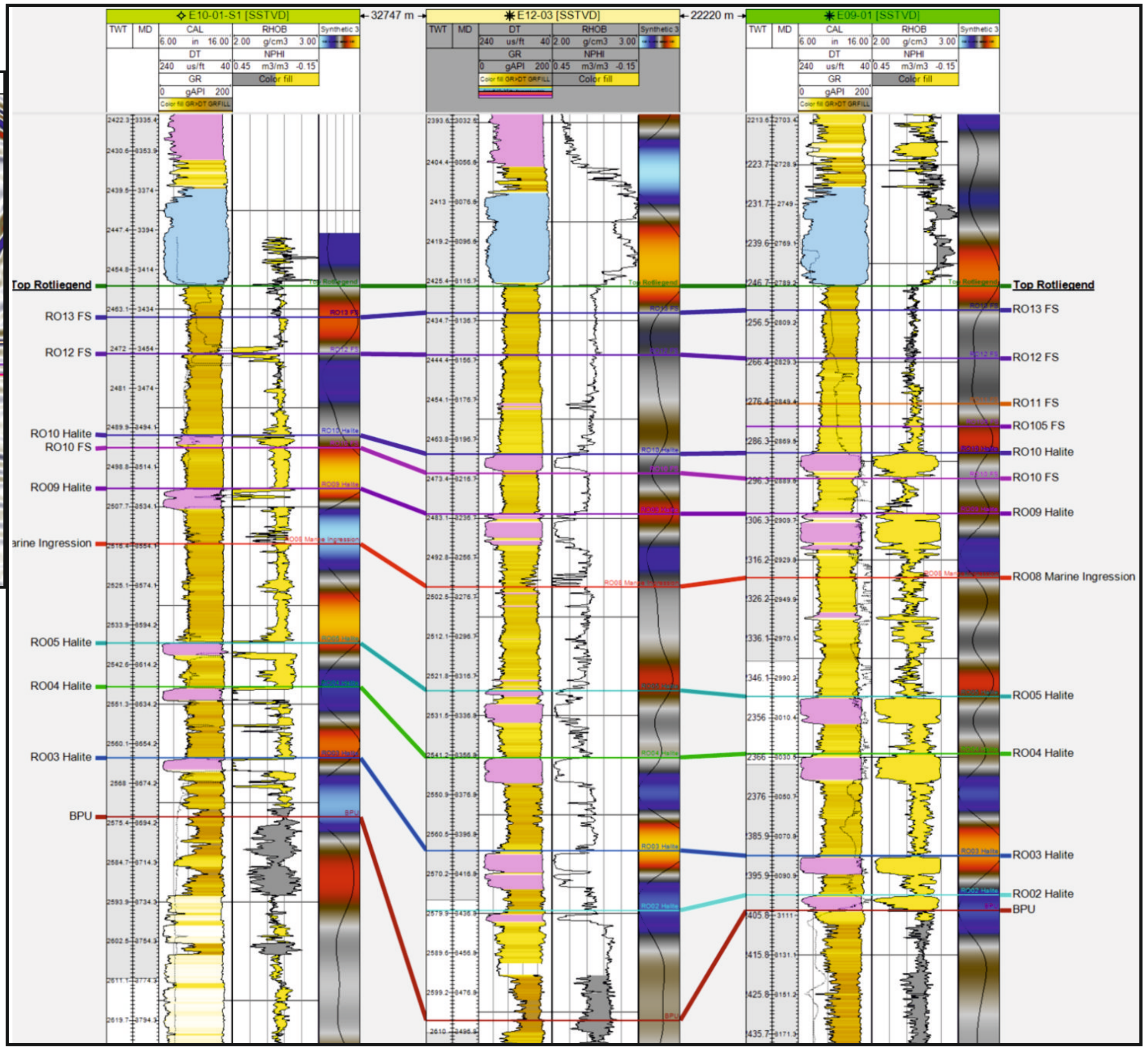
The interpolation size refers to the number of bins around a node that PaleoScan allows for the connection of patches. A higher interpolation size allows the software to take a larger area into consideration for the possible linkage of patches. The link probability finally corresponds to the rate of connectivity within the model grid. If the link probability is set high, the model grid only links areas where various nodes with a high degree of similarity are present. For the geomodel of pilot study 2, a correlation treshold of 20%, an interpolation size of 7 and a link probability of 7 were chosen.

The initial model grid is solely based on software calculations. In structurally complex settings however, the model is not capable of linking the correct patches across faults, erosional surfaces and other zones of geological complexity. For the entire Tullow survey, it turned out to be a very time consuming task to link all the internal Rotliegend patches in a correct way. Even if a lot of time and effort would have been invested in this task, it would be questionable if all the internal Rotliegend patches could be linked in a correct way, as it is often unclear what seismic patches are time equivalent and hence should be linked to each other in order to properly constrain the geomodel (see figure below). Surely, large areas in the Tullow survey lack well controll and the gradual thinning of the Rotliegend towards the north, in combination with the seismic resolution and internal Rotliegend complexities, causes the seismic signal to vary between areas, obstructing a coherent intra-Rotliegend interpretation.

Because it was not possible to create a propper geomodel, incorporating all the internal Rotliegend complexities for the entire Tullow survey. RMS attribute maps for the entire Tullow survey were only created for the Base of the Zechstein, as well as the Base Permian Unconformity (BPU).
A better constrained model grid could be interpreted in a smaller, southeastern part of the Tullow survey (pilot study 2 in the map in previous page). In this area, the Rotliegend is thicker than in the rest of the Tullow survey. Additionally a number of wells are present in and directly around this area that were used to link the seismic to the wells in order to better understand the seismic signal. For this purpuse, synthethic seismograms were generated for the wells E10-01-S1, E12-03 and E09-01 (see figure below).

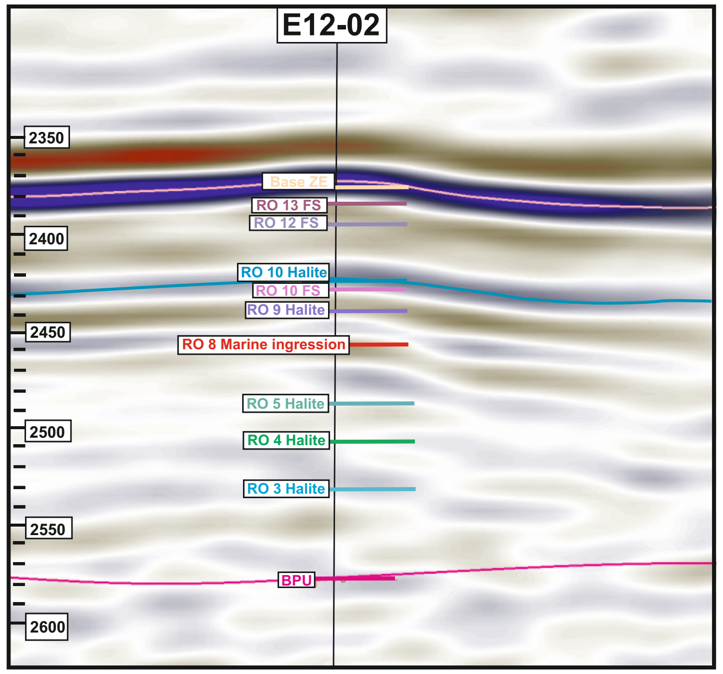


Above: SW-NE seismic line illustrating that a Paleoscan horizon (indicated by the dashed purple line), resulting from the computed geomodel for pilot study 1, can't follow a continuous seismic reflector. In this example, it is unclear if the Paleoscan horizon in the southwestern part of the section, is properly linked to the northeastern part of the section. See previous for the location of the seismic line.



Above: Synthetic seismograms of the wells E10-01-S1, E12-03 and E09-01 (See map on previous page for the location of these wells).

The synthetic seismograms indicate that towards the east of the case study area (i.e. where the wells E12-03 and E09-01 are located), the RO09 and RO10 halites are distinguishable seismic events. This is also the case for the far eastern part of the study area (see figure below). However, in most of the pilot 2 study area (see synthetic of the well E10-01-S1, previous page), the signal of the RO10 and RO09 halite merges into one event (a peak indicated in red for the polarity adhered for the synthetics). It was possible to steer the model grid onto this event and to extract an RMS amplitude map for the RO10-RO09 halite event in this area, in addition to the RMS maps of the Base Zechstein and BPU. The signal below the RO9-RO10 halite is very blurry and discontinous



Left: Inset of seismic around well E12-02. Note that the RO10 and RO09 halites are distinct events at this well. Also note the discontinuous seismic signals below the RO09 halite, which inhibit the creation of a well constrained geomodel in this interval.

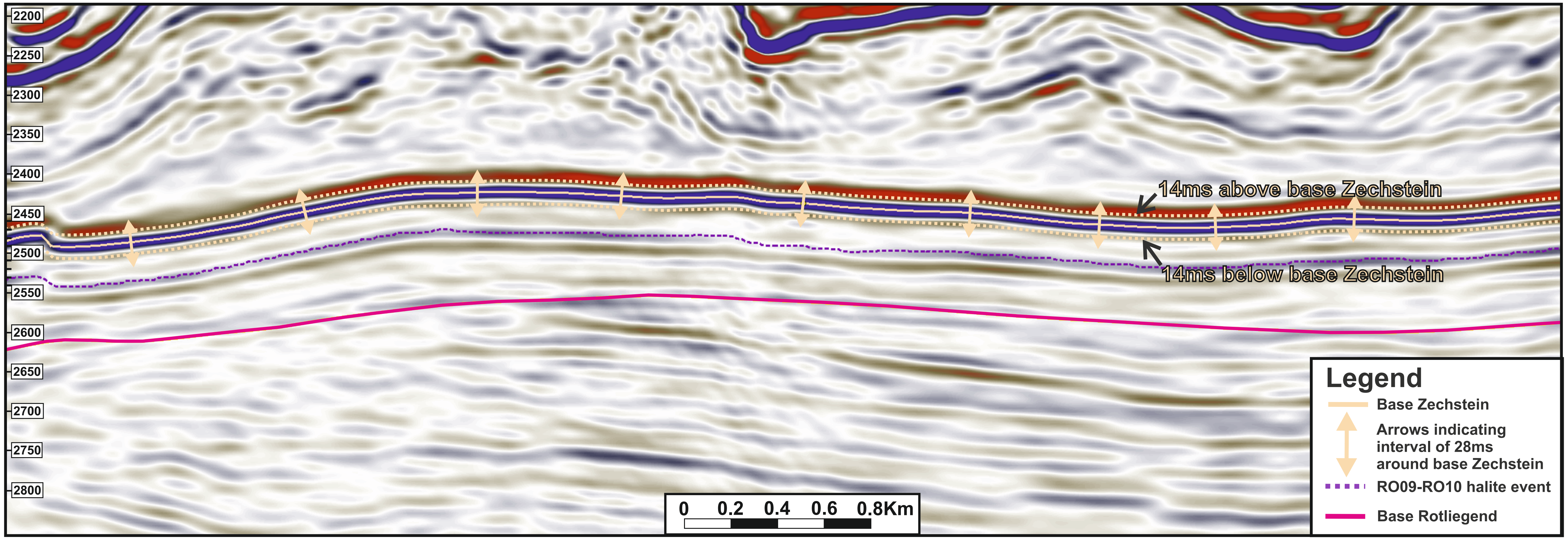
RMS attribute mapping

In total, a horizon stack containing 60 internal Rotliegend horizons was derived from the geomodel that was constrained in the southeastern part of the Tullow survey (referred to as pilot study 2). It is noted that the horizons below the RO09-RO10 event (which is represented by horizon 40 from the horizon stack) are not properly constrained due to the discontinuous seismic signals in this interval. In pilot study 2, the Root Mean Square was calculated for the seismic horizon representing the RO09-RO10 halite event. The RMS was also calculated for the Base of the Zechstein and the BPU, which were already mapped for the entire Tullow survey.

RMS is a post-stack seismic attribute that computes the square root of the sum of squared amplitudes divided by the number of samples within the specified window used. A sample window of 7 was chosen for the calculation of the RMS amplitude maps; meaning that the RMS was calculated over a window of 28ms around the horizon of interest (i.e. 14ms above and 14ms below the horizon of interest, see figure below, where this is illustrated for the base of the Zechstein).

The RMS attribute enhances and highlights heterogeneities in seismic amplitude, frequency and continuity of seismic reflectors. Amplitude changes can mimic lithological changes, both laterally and vertically and can therefore e.g. be used to reconstruct sedimentary distribution patterns. However, the heterogeneities highlighted by attributes can be of different origin as well. It is the interpreter's task to differentiate potential geology-related patterns from artefacts, noise (e.g. tuning), or seismic interpretation mis-picks. Hence, when interpreting seismic attribute maps, identified features were also checked on 2D seismic cross sections to validate or discard the interpretation of possible geobodies.

Below: Seismic line illustrating the interval over which the RMS was calculated (as indicated by the arrows). See Fig. 1 for the location of the seismic line.

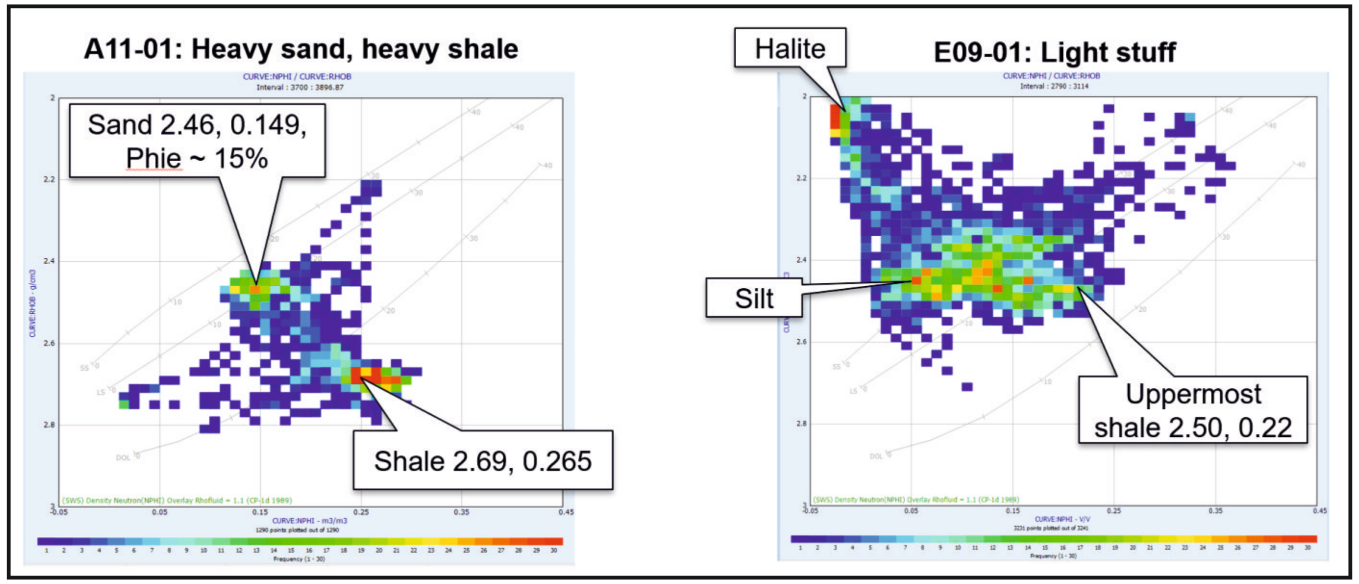


In this chapter, ten regional well correlation panels are shown (Panel 1 to 10). They display the main recognized stratigraphic markers and show the internal variability of the Rotliegend across the study area, including stratigraphic thinning and thickening as well as lithological heterogeneities.

Beside these results, some new information regarding the lithological composition and sediment transport direction are also shown in the Master PPT Presentation. Below is a list of the main questions and results:

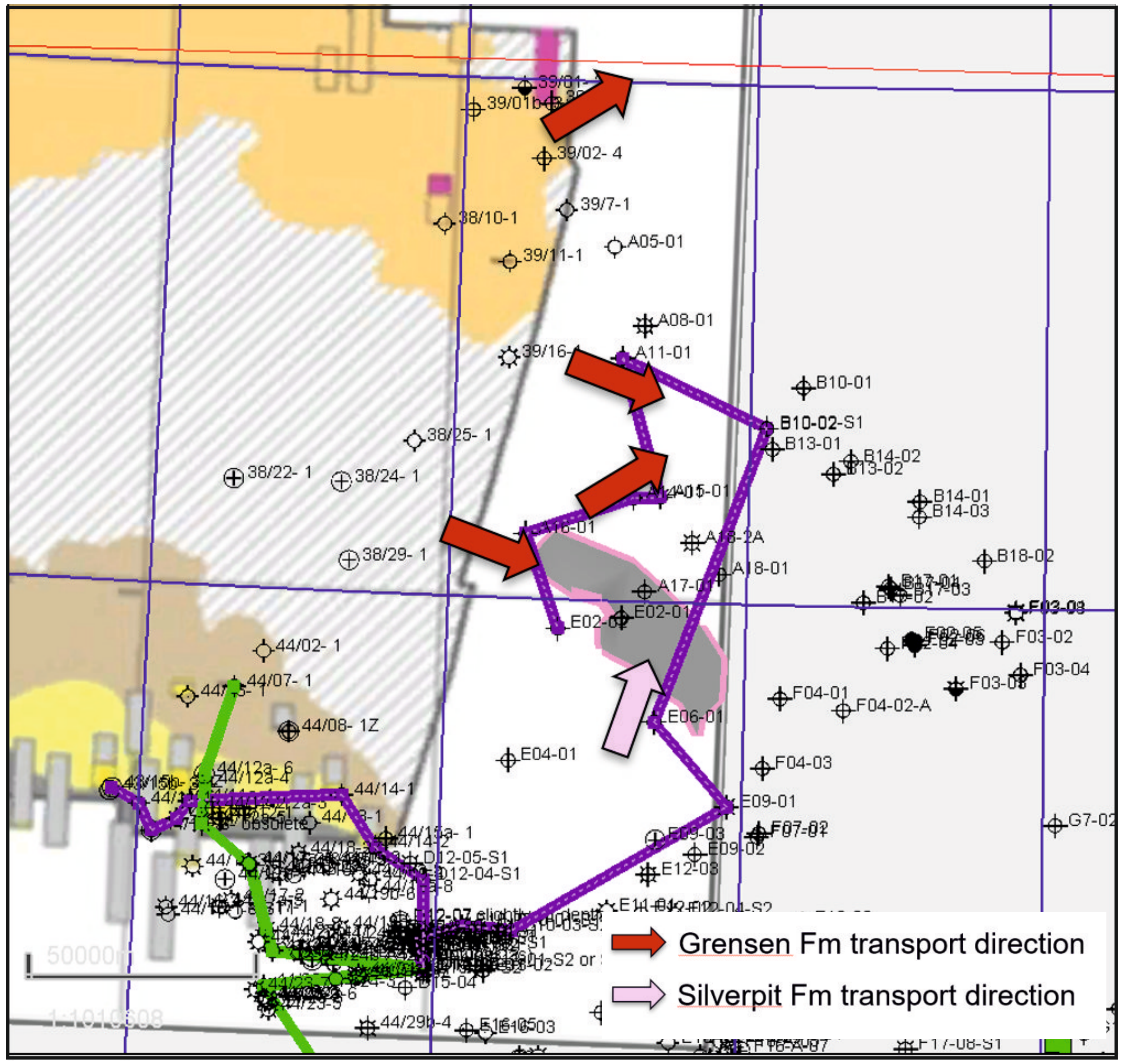
- Correlating from the Silverpit Basin onto and into the ESH is problematic.
  1) A11-01 and A15-01 are almost twins: both display a sand – shale sequence that can be easily correlated.
  2) Correlating the classic Silverpit sequence to A11-A15 is not straightforward:
     - flooding and ingression surfaces seem to be missing in A11-A15
     - Sand & shale lithology (as recorded by NeuDen) in A11-A15 is really different from the silty-salty Silverpit shales

- Is the Rotliegend in A11-A15 Lower Rotliegend (aka Grensen Fm)? The petrographic information seems to indicate that the Rotliegend in wells A11-A15 is different from the Rotliegend encountered in well E09-01 for example (see figure below).



Above: Differences between key wells, a possible indicator of having Lower Rotliegend present in wells A11-01.

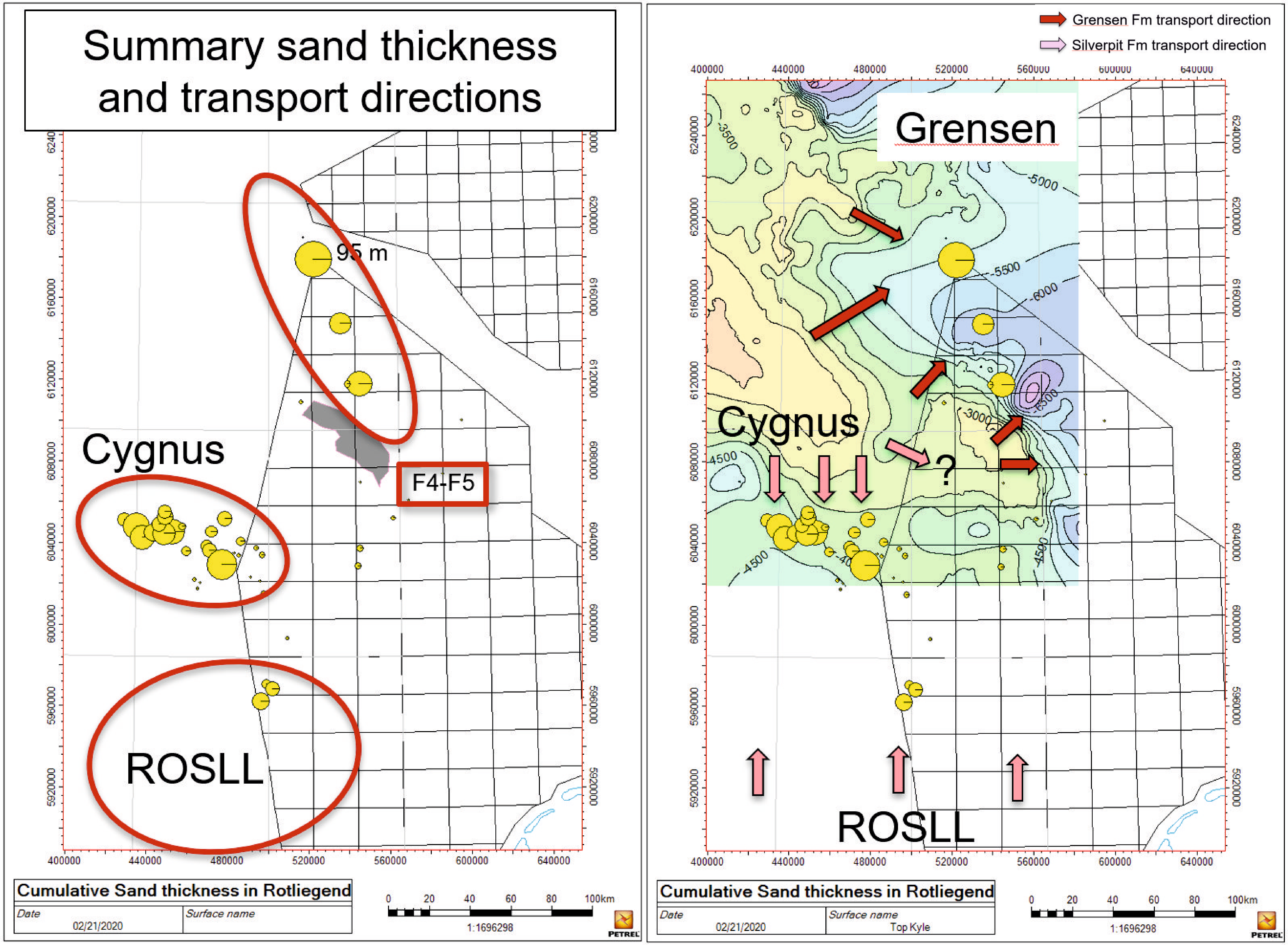
Summary of transport directions as determined from dipmeter logs (this study and published work (e.g. Martin et al. (2004). Quote "Sedimentary processed dipmeter data from the Grensen Formation in well 39/2-4 have delineated unidirectional palaeocurrents towards the NE with a low variance". Below the map show the summary transport direction compiled from dipmeter data and published work. The cumulative sand thickness map including the regional proposed sediment transport direction results, are show on next page.



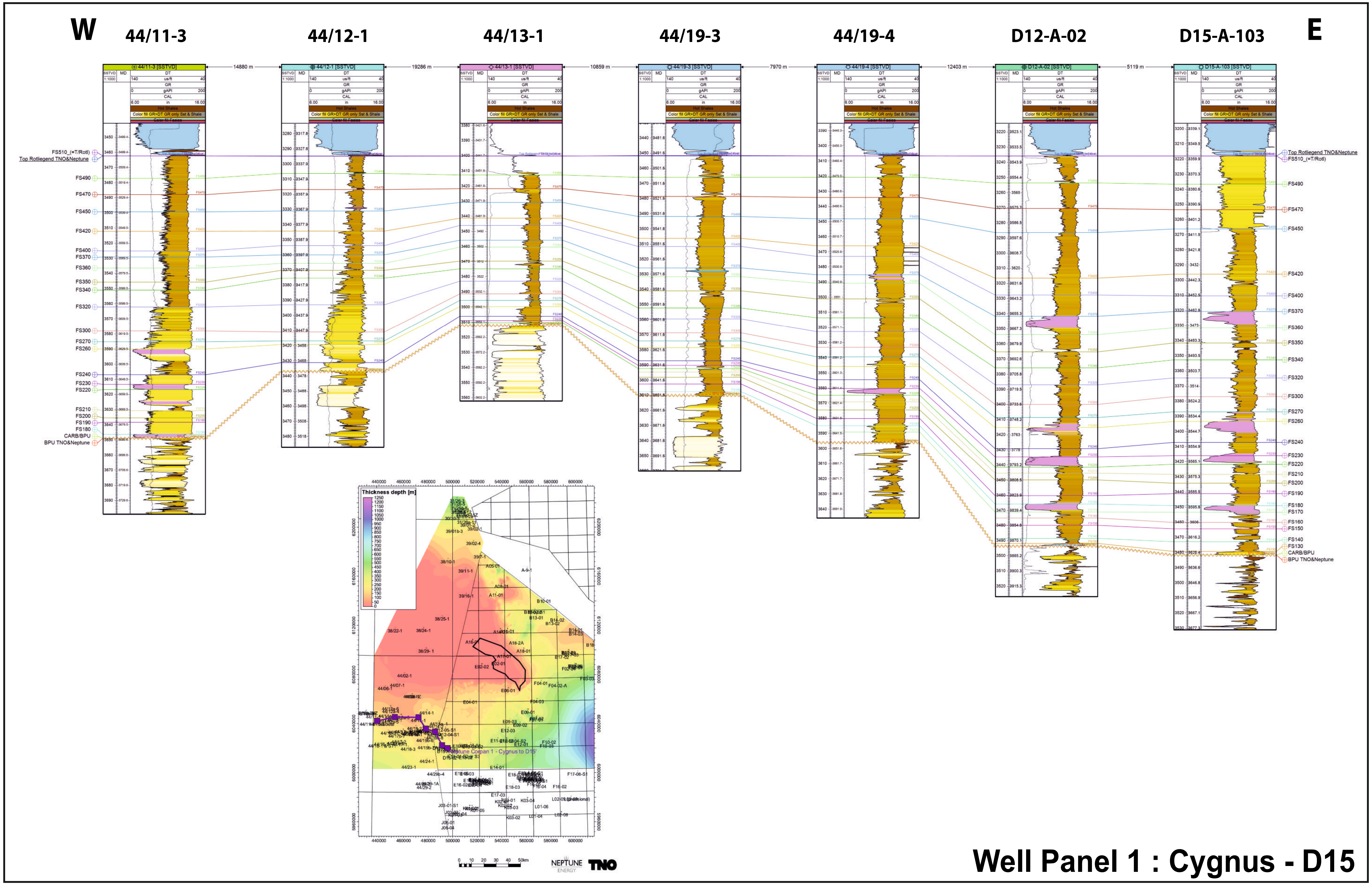
Above: Inferred sediment transport direction

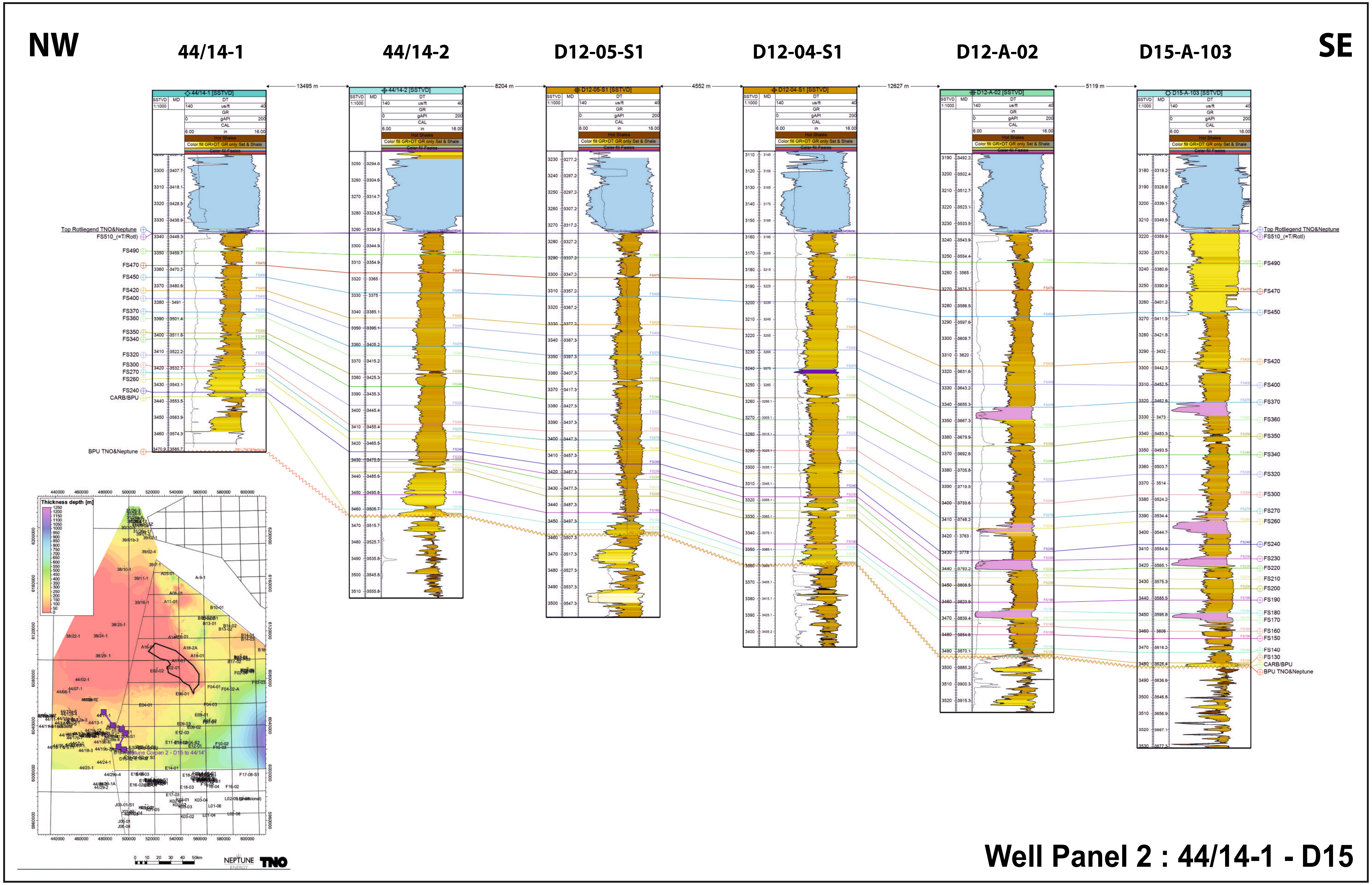
Main lessons learned regarding the sand distributions around MNSH - ESH

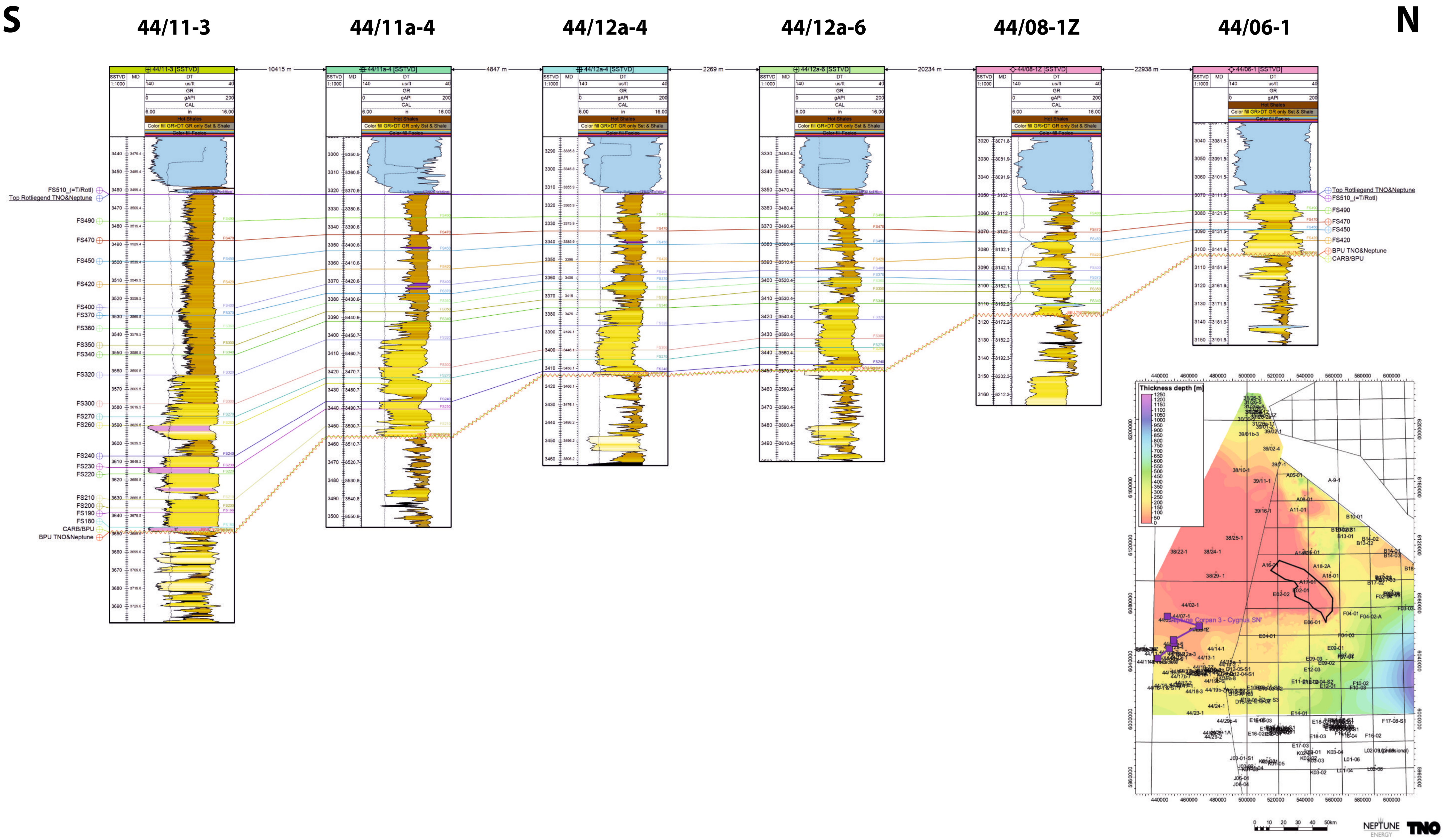
- The Rotliegend sequence deposited in the A blocks, especially A08-A11 belongs most likely to the Grensen Formation (of Lower Rotliegend age). The age of the sands in A14-A15 is uncertain, can be Upper or Lower Rotliegend.
- This fluvial sequence contains good sands and we consider it the primary reservoir sand in this region.
- The Grensen Formation is petrophysically and lithologically different from the Silverpit Formation, especially the shales. Correlation with nearby Silverpit wells is difficult.
- The southwestern flank of the ESH (E02 – E06 area) may contain Cygnus-type sands


Summary sand thickness and transport directions
95 m
Cygnus
F4-F5
ROSLL
Cumulative Sand thickness in Rotliegend
Date 02/21/2020
Surface name
1:1696298
Grensen Fm transport direction
Silverpit Fm transport direction
Grensen
Cygnus
?
ROSLL
Cumulative Sand thickness in Rotliegend
Date 02/21/2020
Surface name Top Kyle
1:1696298

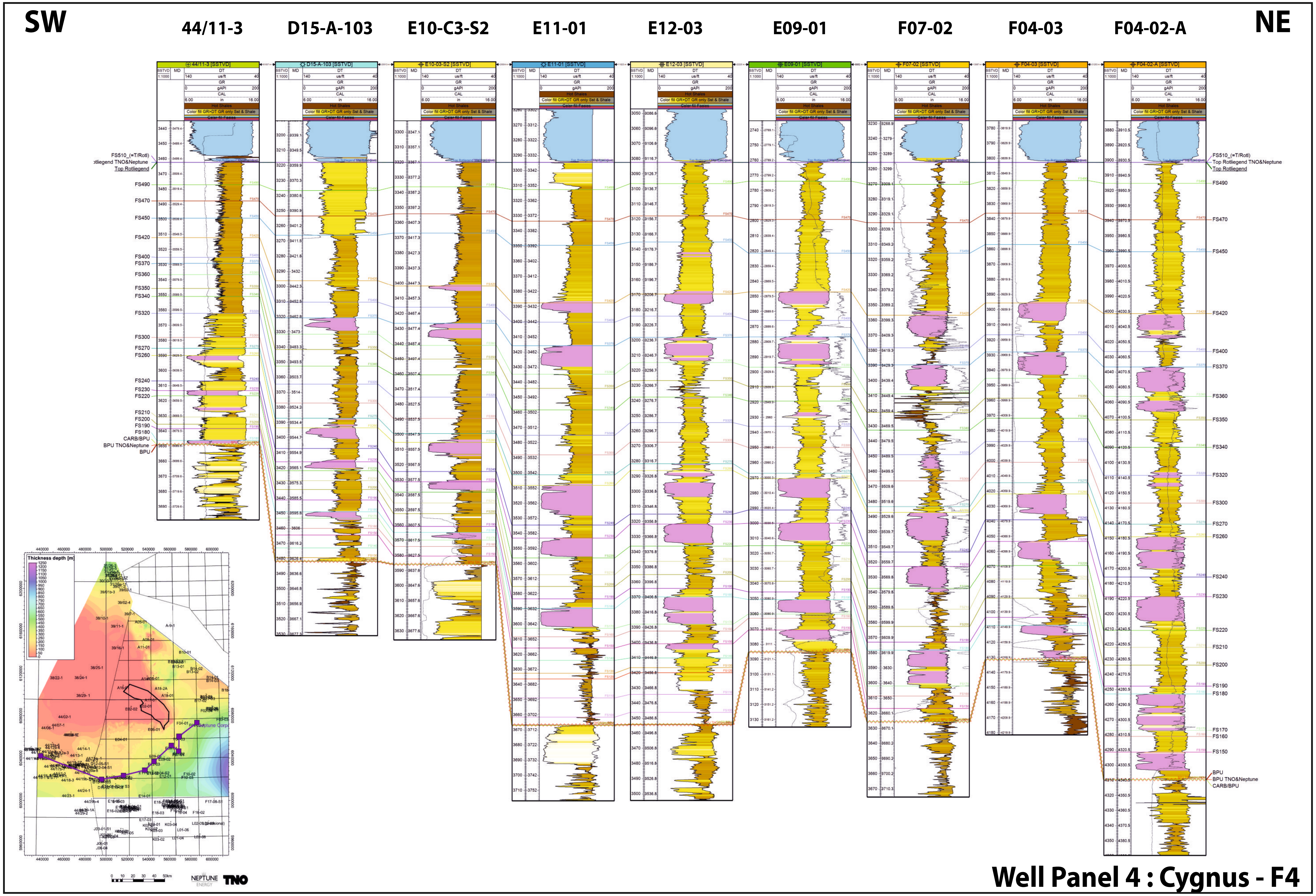
In this section, ten well correlation panels are shown, highighting the internal stratigraphic markers recognized by Neptune and TNO geoscientists. Key beds and events, such as halites and maximum flooding surfaces are used for the high resolution stratigraphic correlation. Cyclolog studies also provided addotional correlation constrains for this exercise.

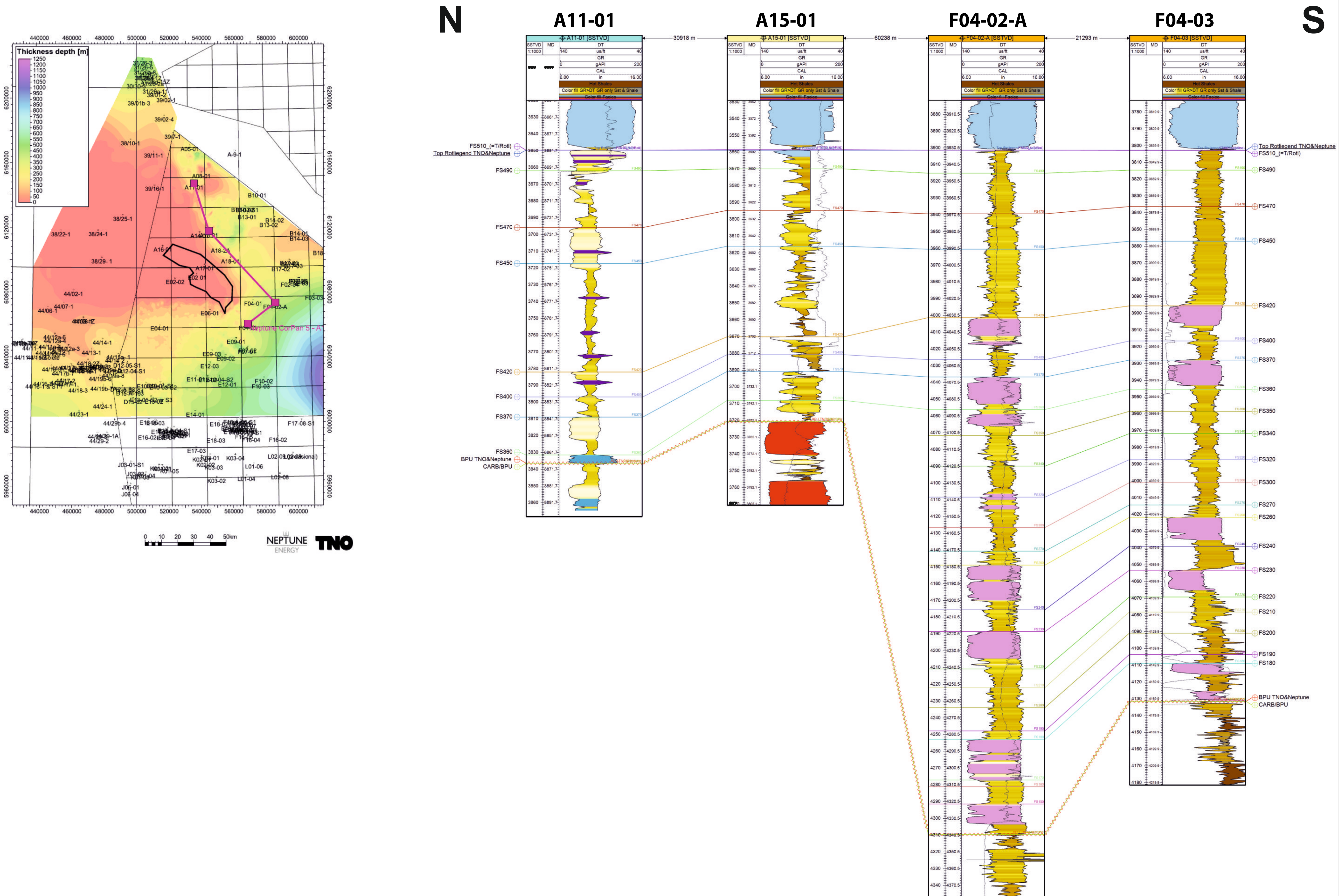



NW
44/14-1
44/14-2
D12-05-S1
D12-04-S1
D12-A-02
D15-A-103
SE
13495 m
8204 m
4552 m
12627 m
5119 m
Top Rotliegend TNO&Neptune
FS510_(=T/Rotl)
FS490
FS470
FS450
FS420
FS400
FS370
FS360
FS350
FS340
FS320
FS300
FS270
FS260
FS240
CARB/BPU
BPU TNO&Neptune
Thickness depth [m]
NEPTUNE ENERGY
TNO
Well Panel 2 : 44/14-1 - D15

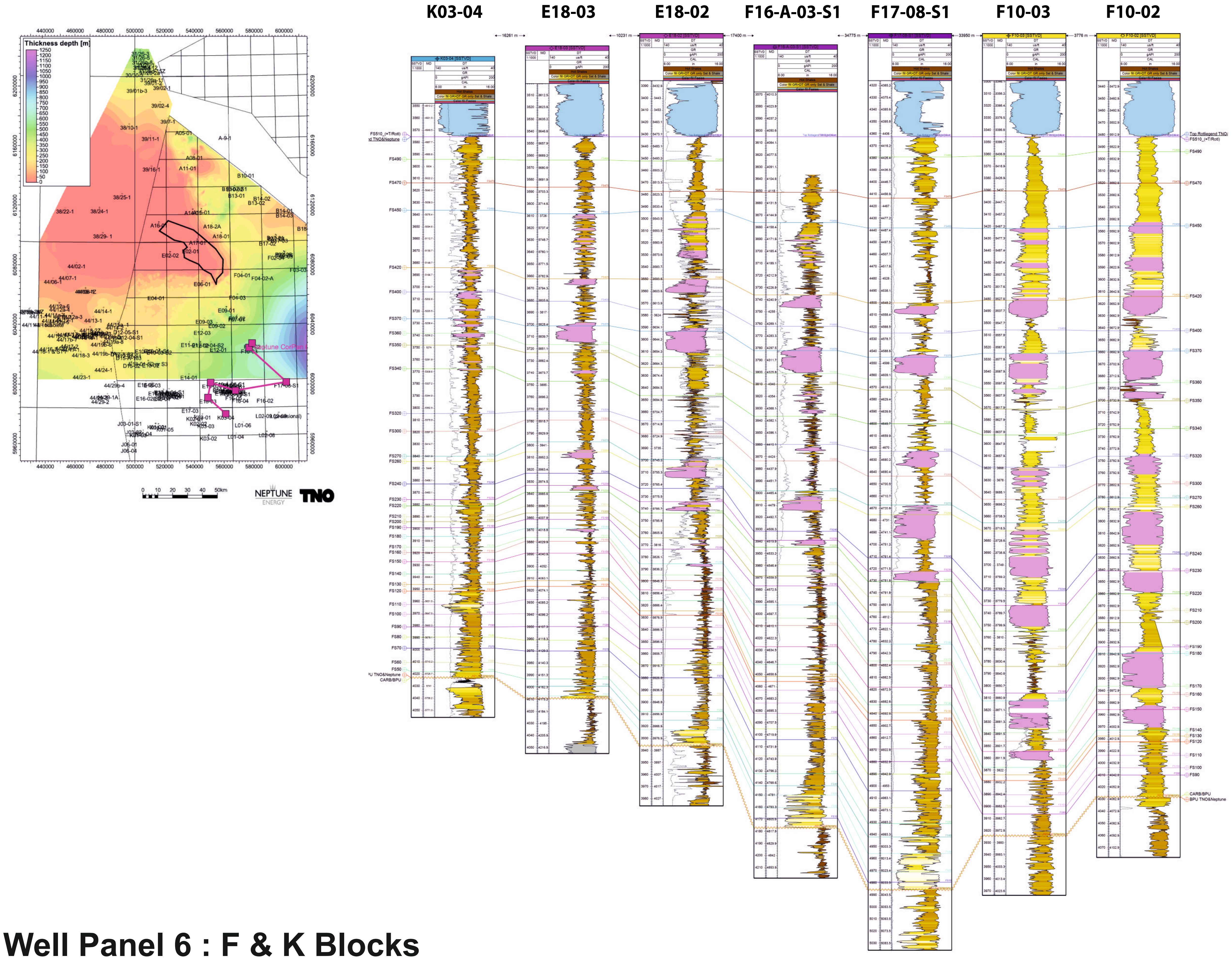


Well Panel 3 : Cygnus N-S

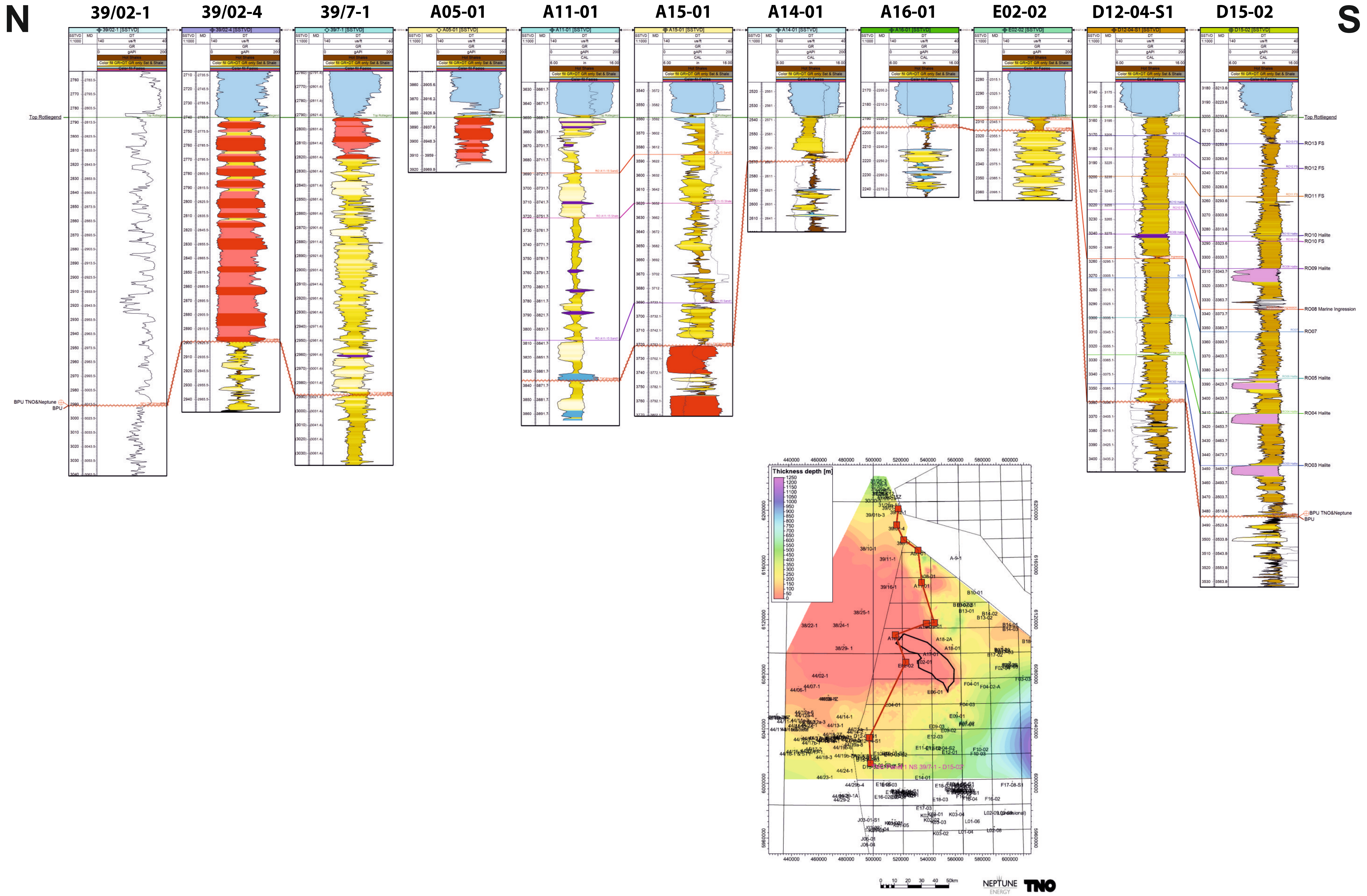

SW
44/11-3
D15-A-103
E10-C3-S2
E11-01
E12-03
E09-01
F07-02
F04-03
F04-02-A
NE
Well Panel 4 : Cygnus - F4



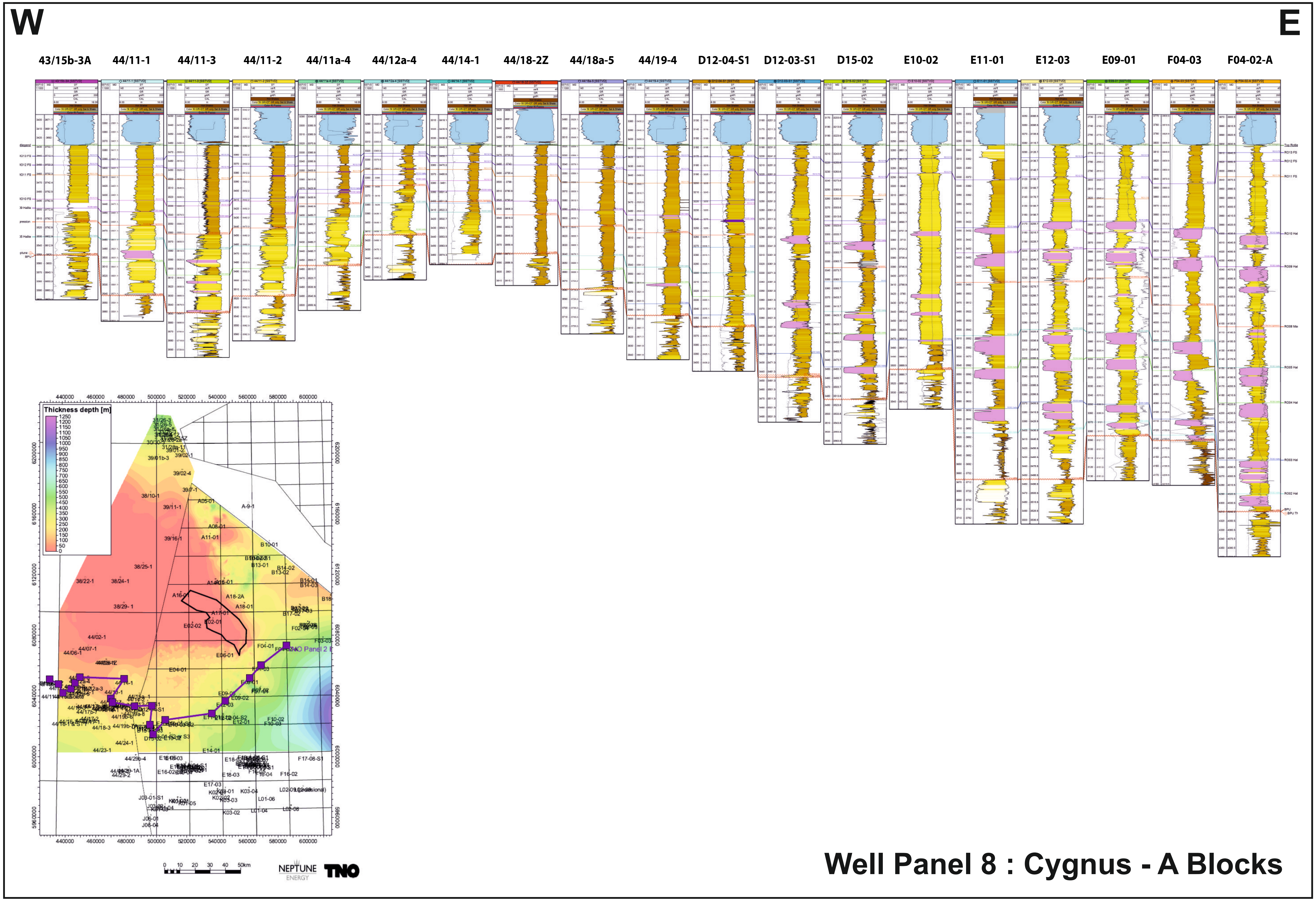
Well Panel 5 : A & F Blocks



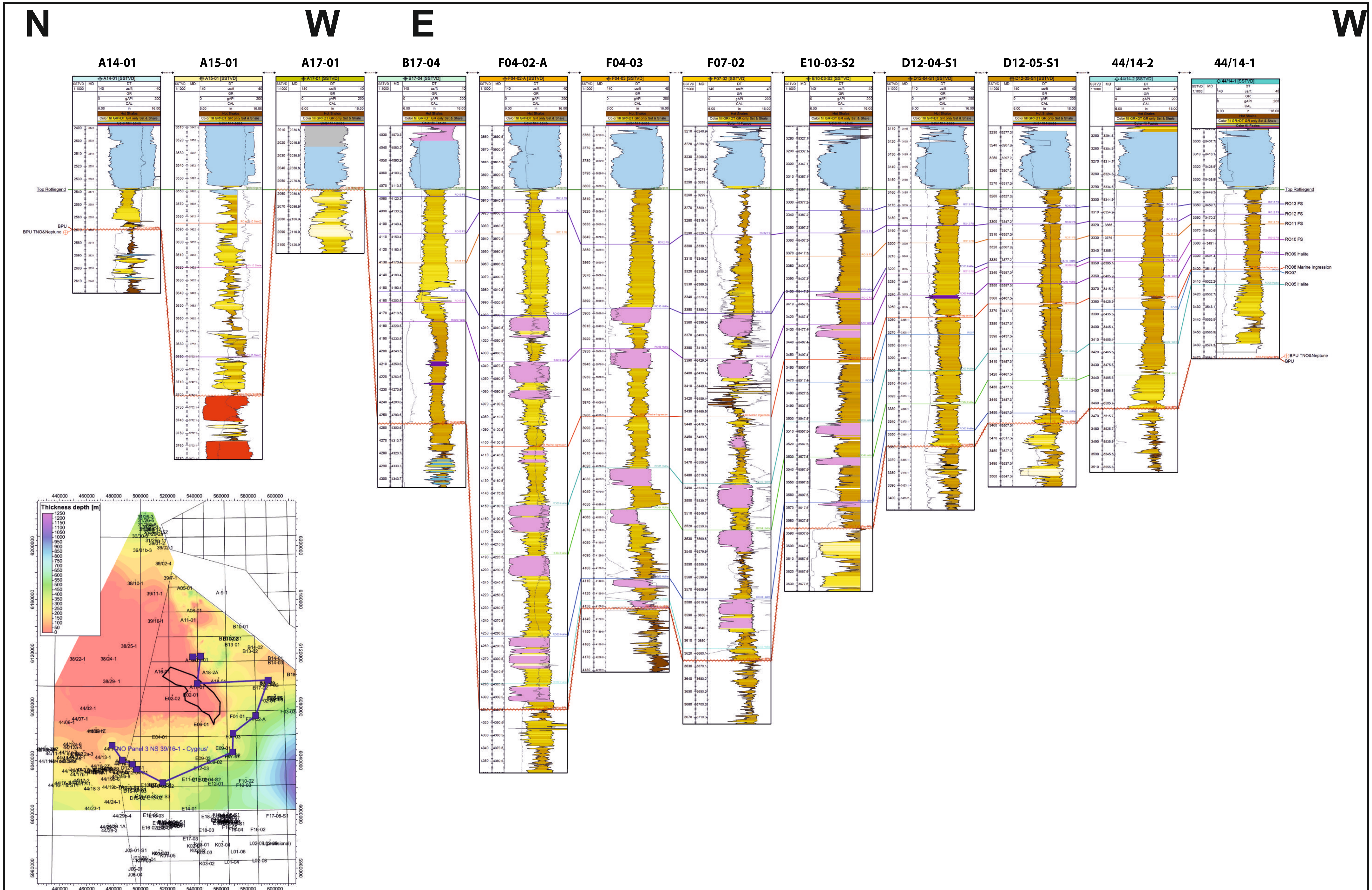
Well Panel 6 : F & K Blocks



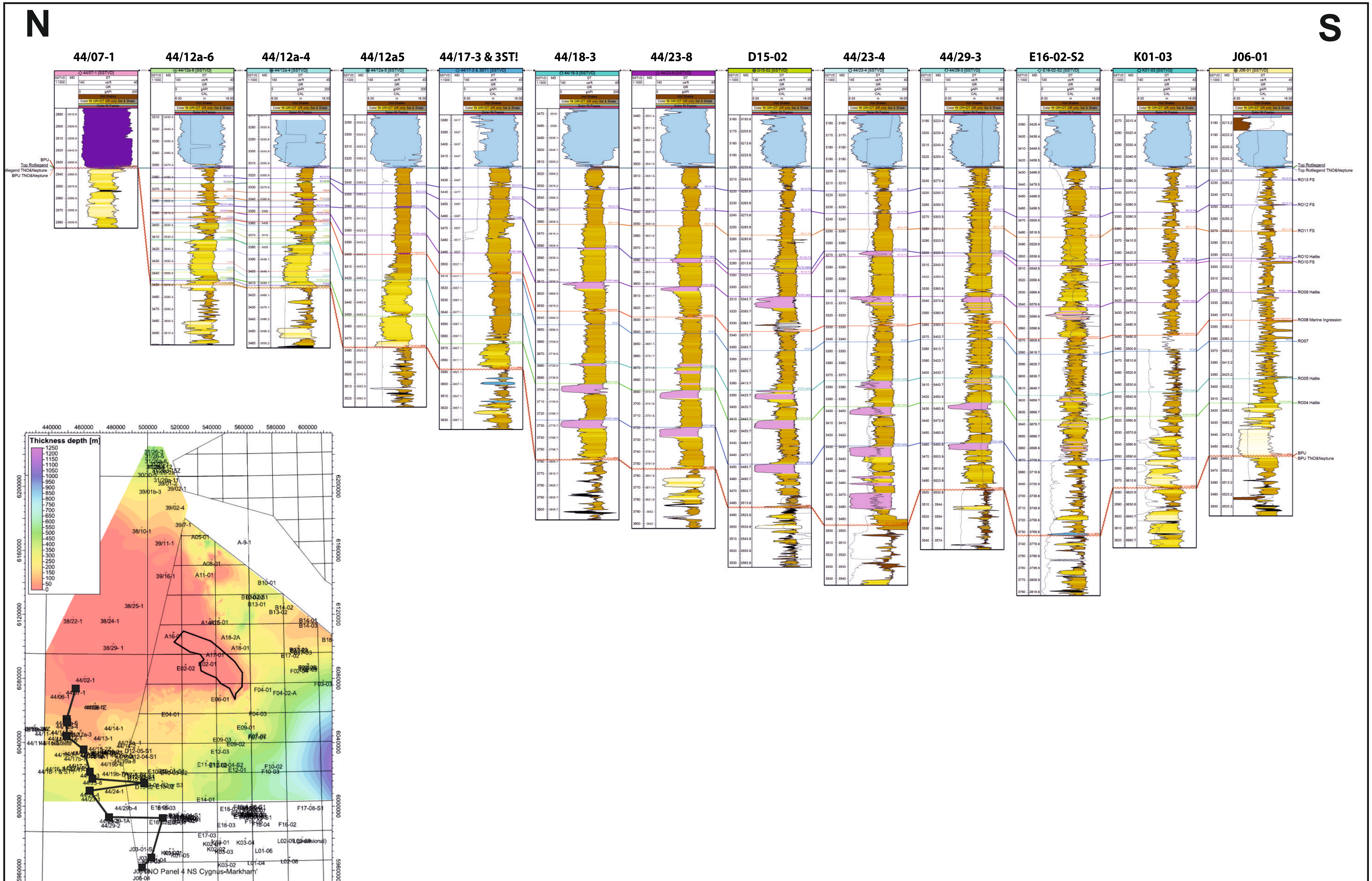
Well Panel 7 : 39/02 - D15



Well Panel 8 : Cygnus - A Blocks

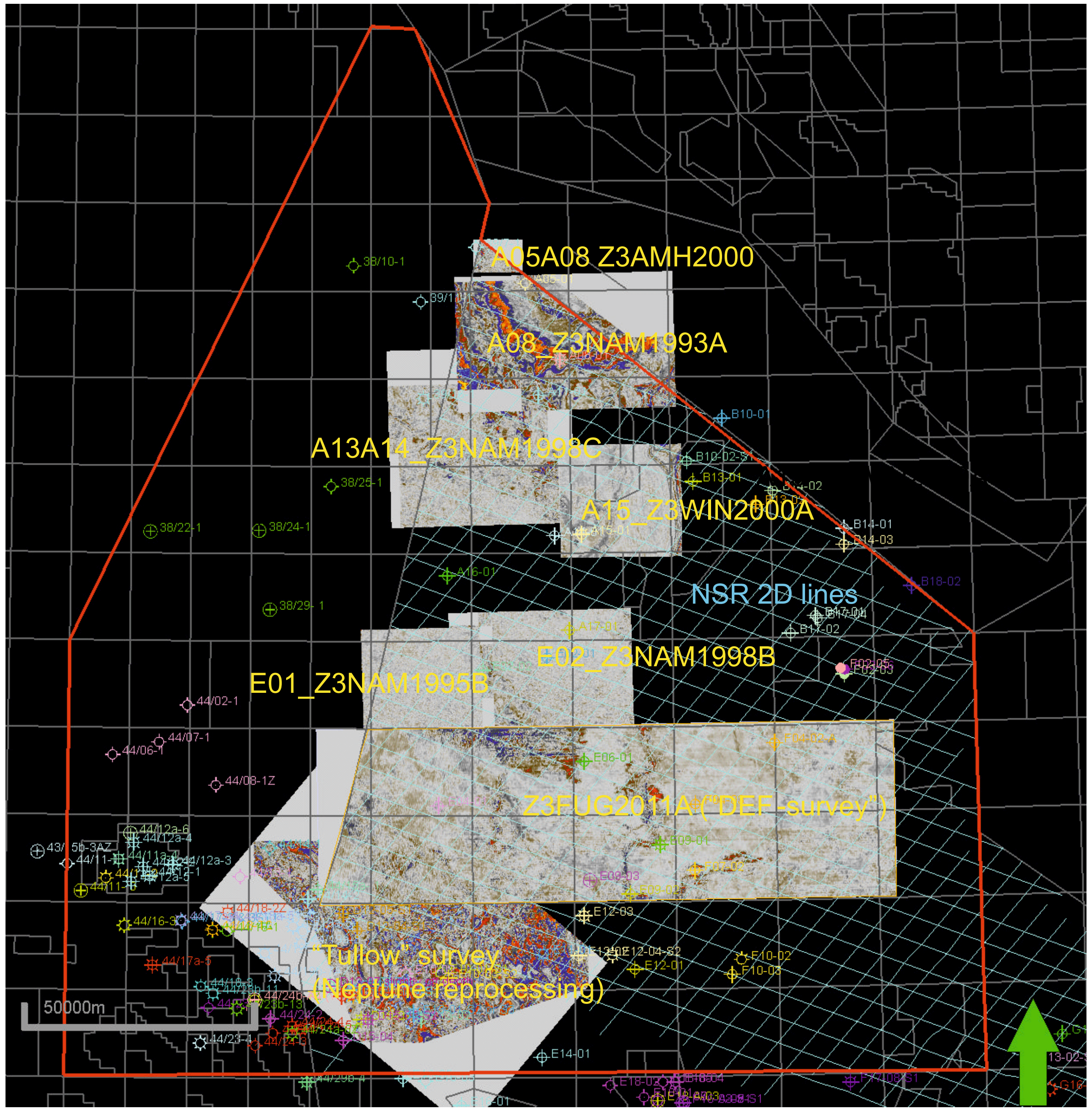


Well Panel 9 : A14 - Cygnus



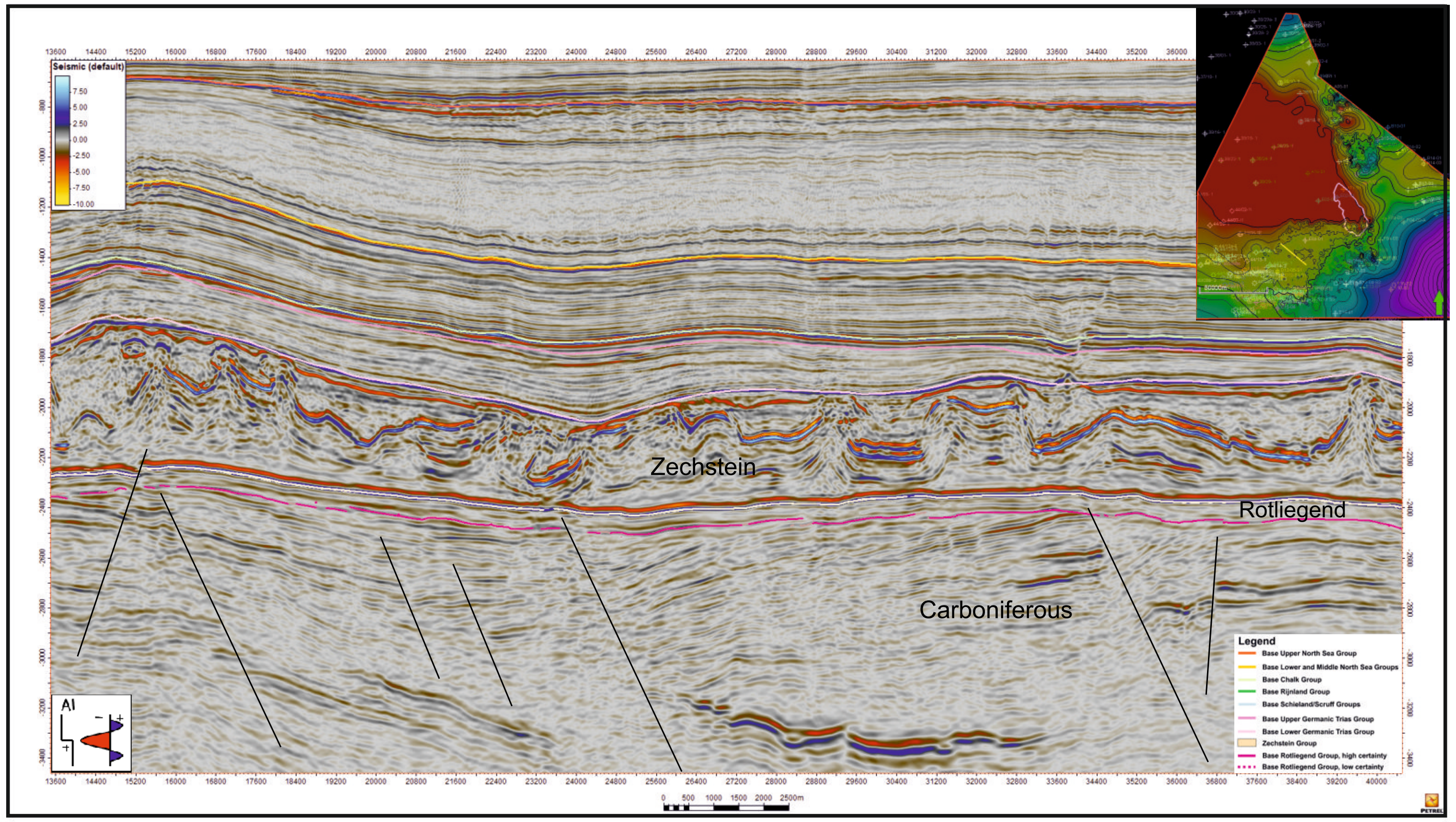
Well Panel 10 : Cygnus-Markham

The main results of the seismic interpretation is show in this chapter. The master PPT presentation shows additional and complementary information such as synthetics and incremental steps for the construction of the key maps.

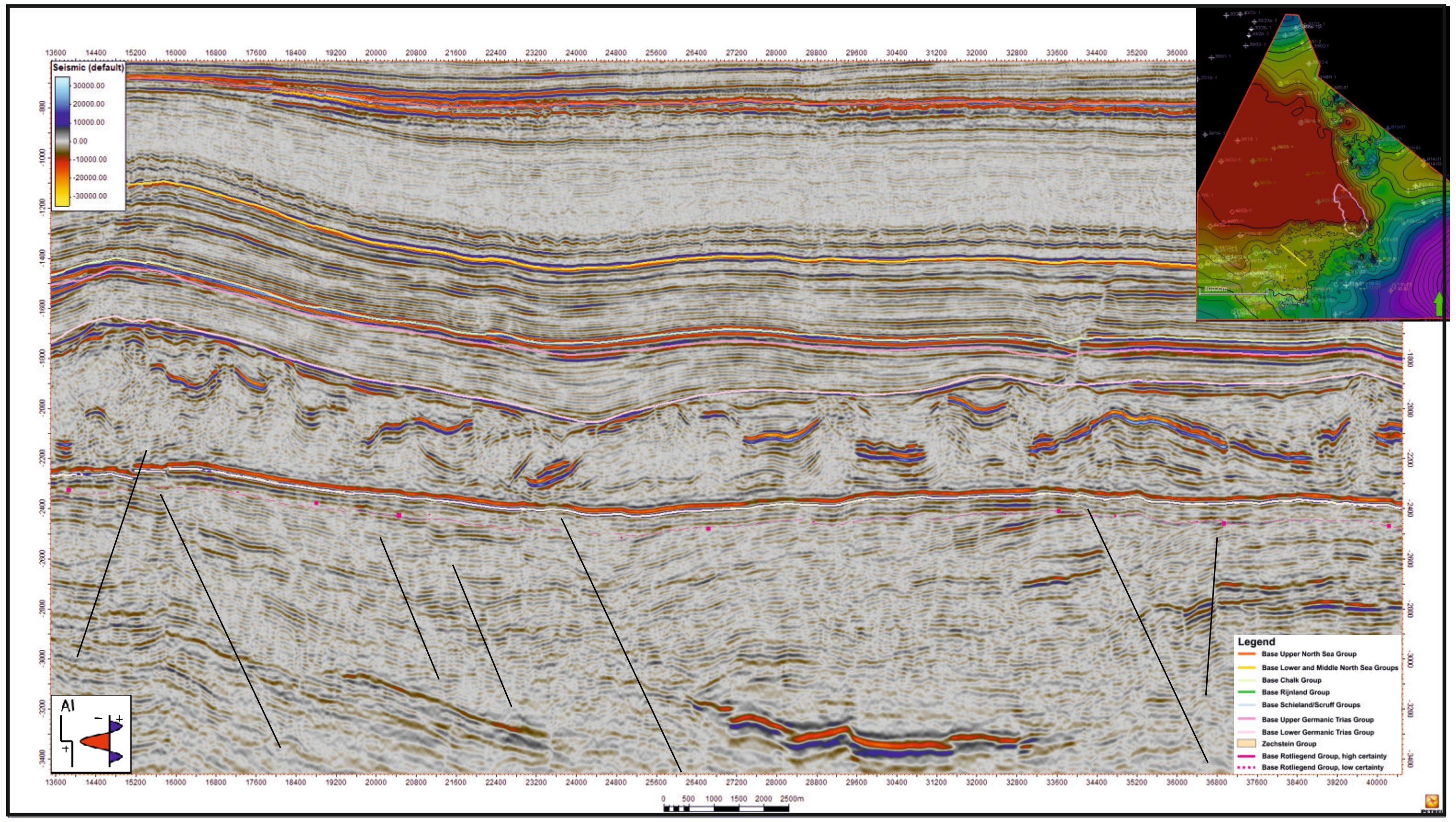


Above: Seismic surveys used in the project. Timeslices of the 3D surveys are displayed to show exactly where signal data is present. In blue the 2D NSR survey is shown. 8 (3D) surveys assessed on which 2 BPU was systematically interpreted (DEF and Tullow). On 3 surveys locally BPU interpreted (A08, A13A14 and A15). E01 and E02 surveys no Rotliegend thickness above seismic resolution. A05A08 survey too poor data to allow interpretation. NSR data scanned but only very locally BPU interpreted

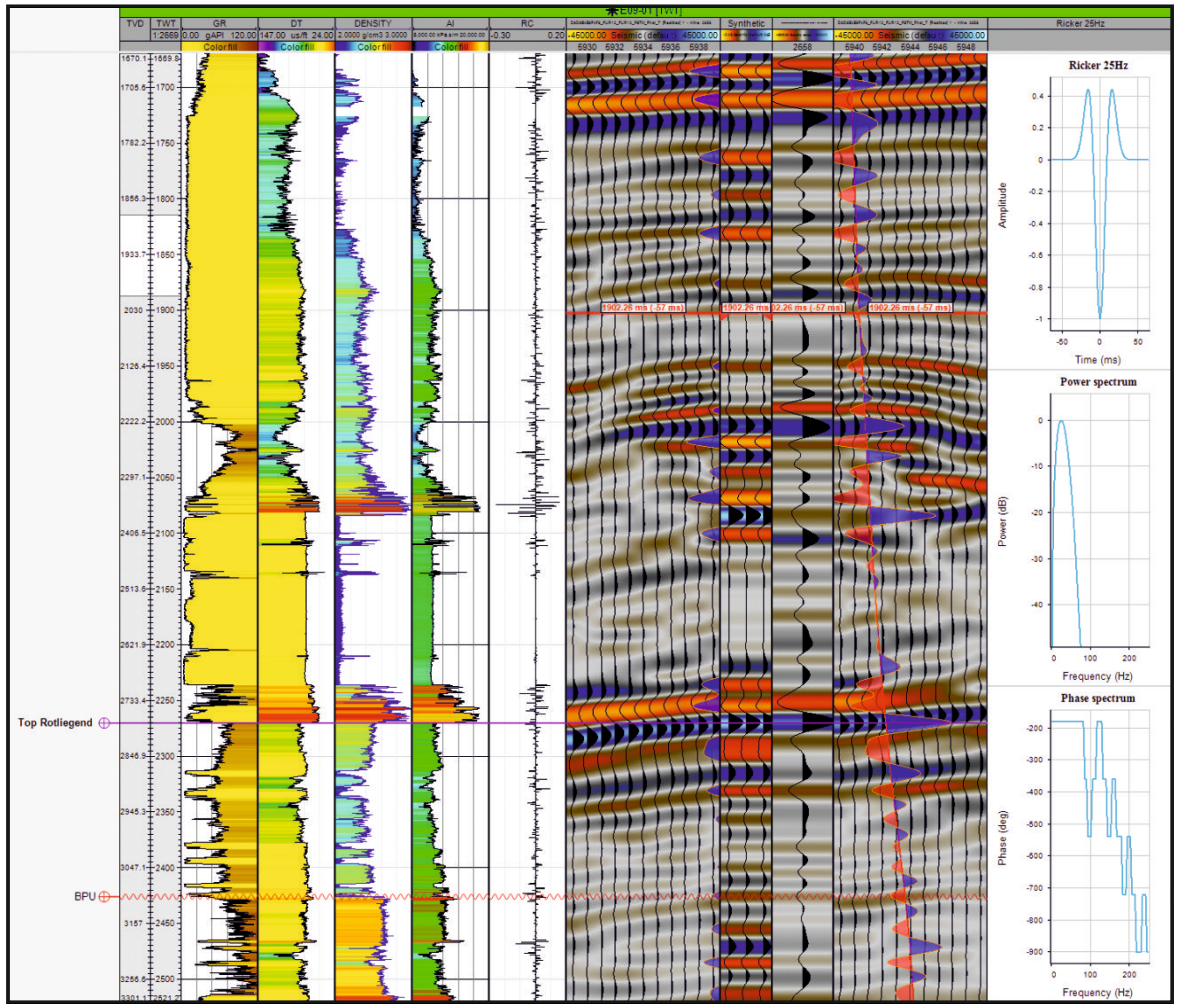
Below: Example of a seismic line from the Tullow Survey. Top and base Rotliegend interpreted on a random NW-SE section showing the BPU angular unconformity. Rotliegend has relatively transparent seismic facies while subcropping Carboniferous has depending on location a reflective or transparent seismic facies. The very bright amplitudes at 3300 ms are probably intrusives.



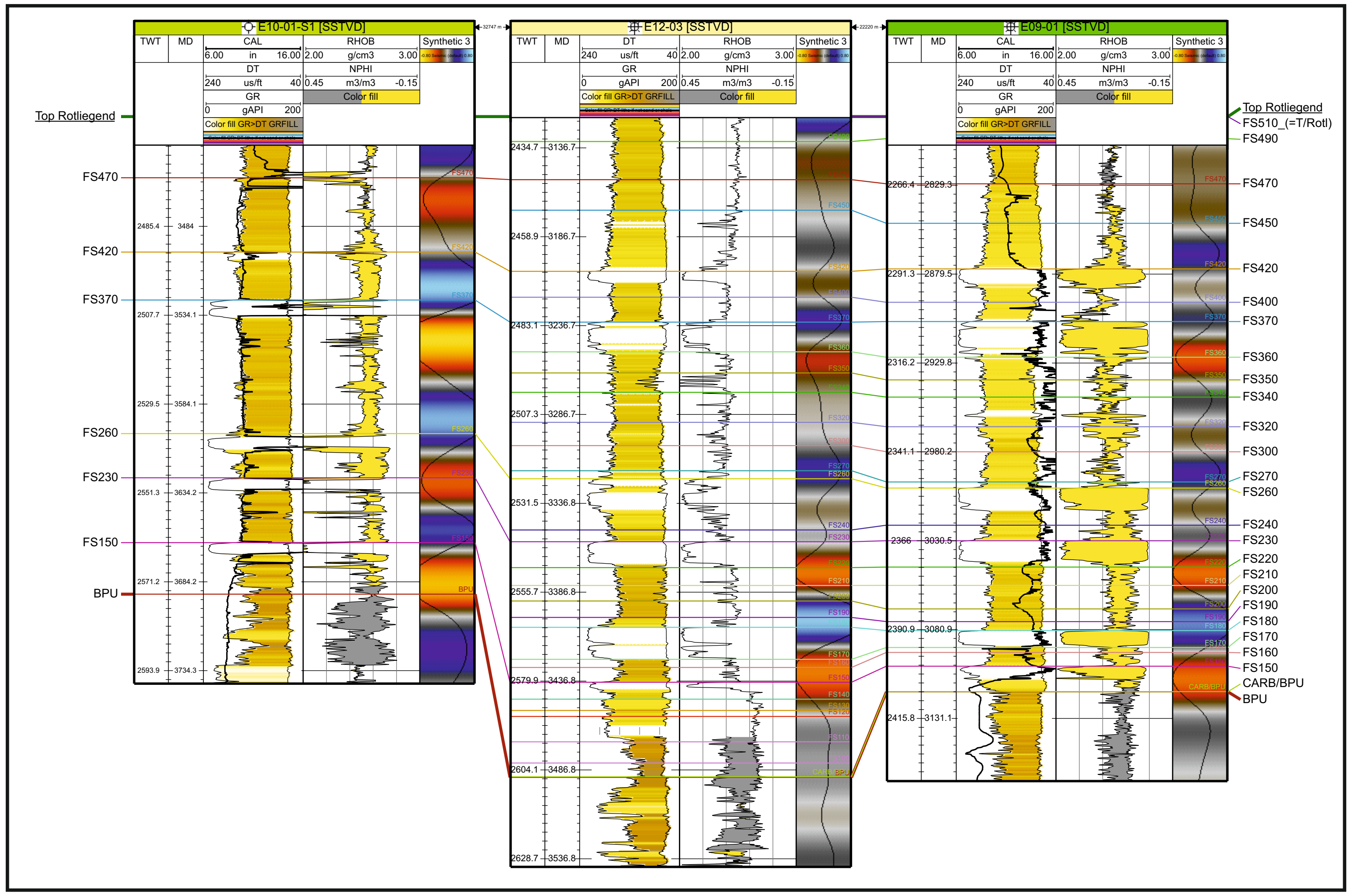
Below: Same seismic line than figure above, but from the DEF Survey. Same section as previous figure but coming from the DEF survey. The seismic image of the Tullow survey is more crisp and the imaging of dipping anhydrite rafts in the Zechstein is clearly better. Also at BPU and Carboniferous level the imaging of the Tullow survey is superior over the DEF survey.



5. Seismic interpretation

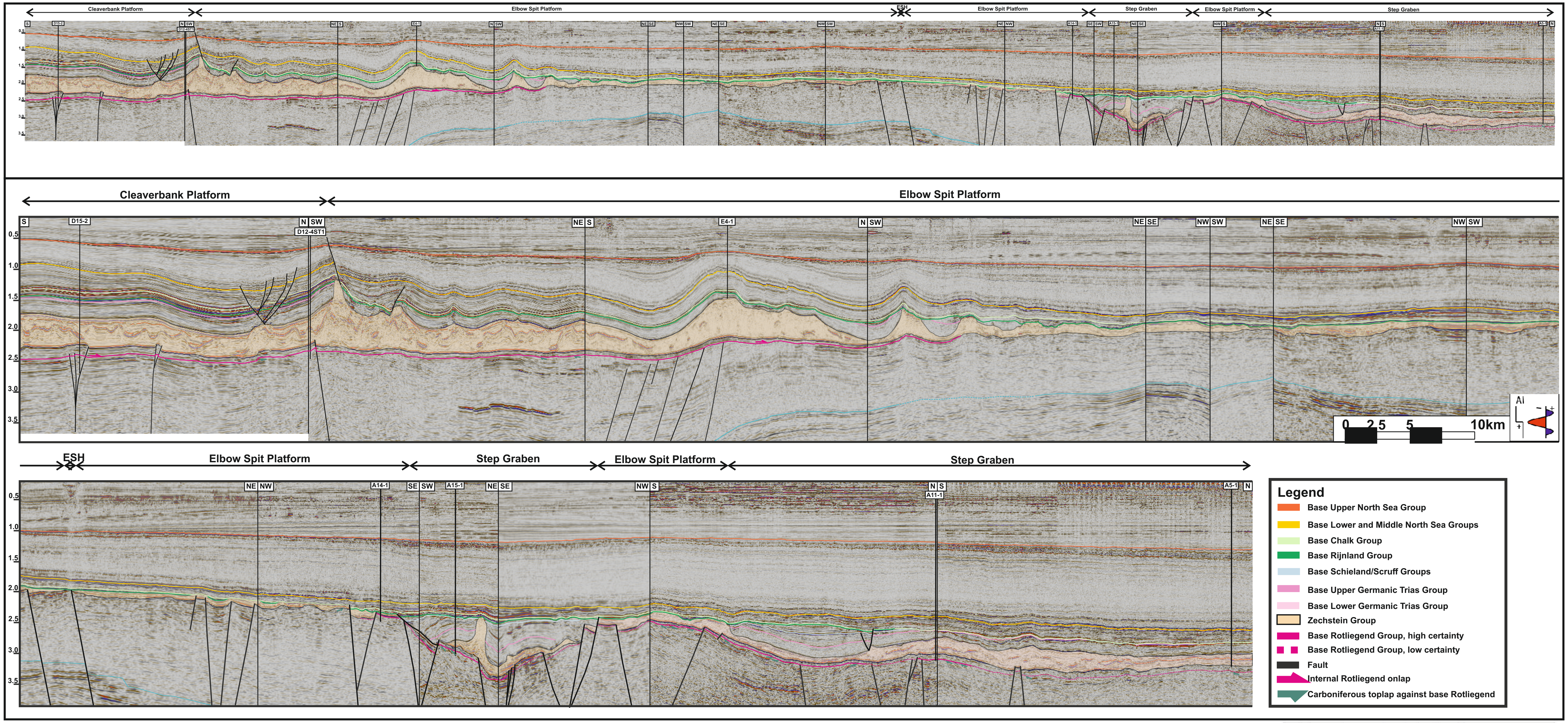


Above: Synthetic of the well E09-01 showing an overall reasonable match with the DEF survey. The low frequency loop below base Zechstein seen rather consistently in the DEF survey is also present in the synthetic. Below this event a rather transparent Rotliegend does not give good correlatable events. Good synthetic-seismic match in overburden. BPU as trough due to higher density Carboniferous (but lower velocity). If dense uppermost claystone Carboniferous would not have been present, BPU would probably lie on a peak (lower velocity). Properties of subcropping Carboniferous are crucial for understanding the BPU seismic response.

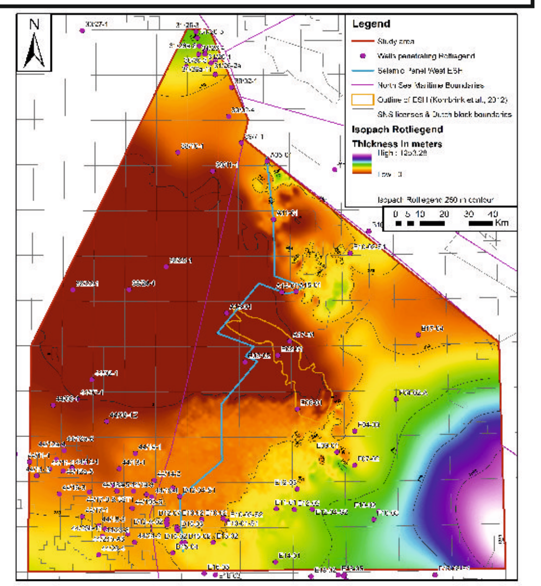


Above: Correlation panel with synthetics showing expected seismic response of three wells in the E-blocks. Halite layers can be correlated on both wells as on synthetic seismic. Individual halites are mostly too thin to have top and base coinciding with peak and trough. Stacking of halites determines the interference pattern. If sequence and thicknesses of halites do not change (significantly) halites can be correlated using seismic data.

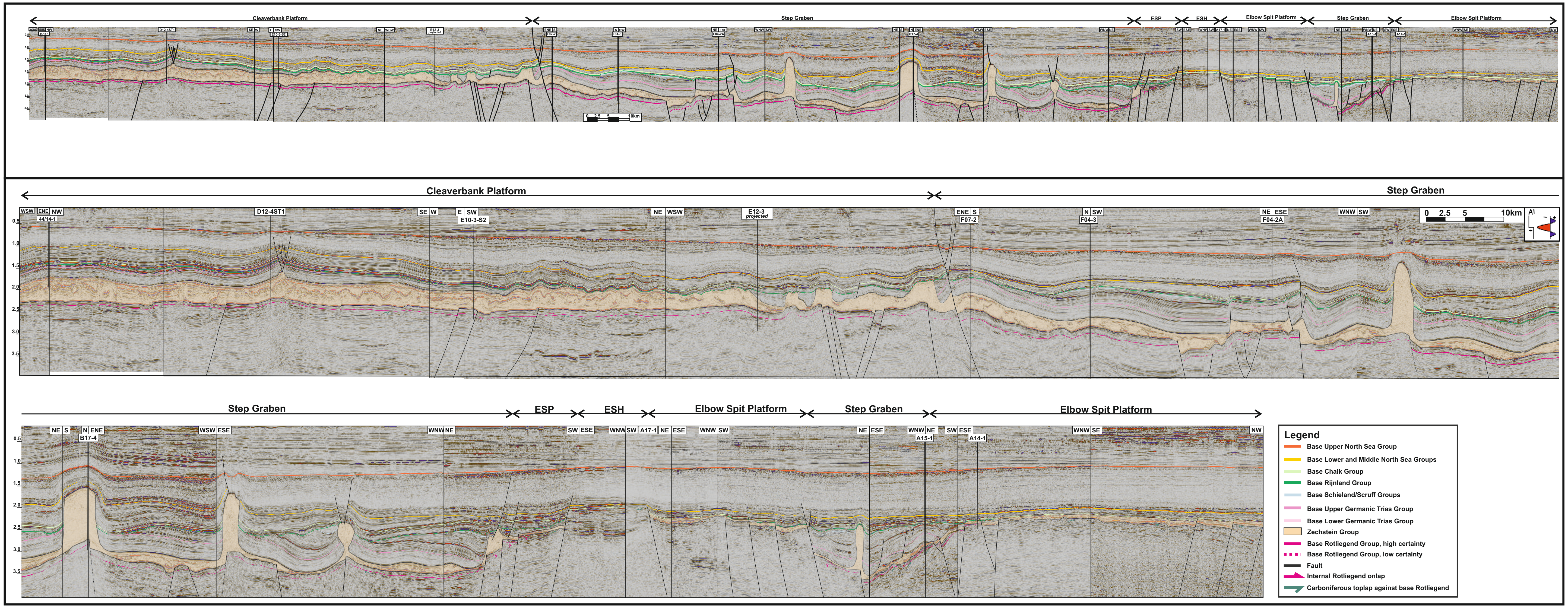
Regional Seismic Panel A



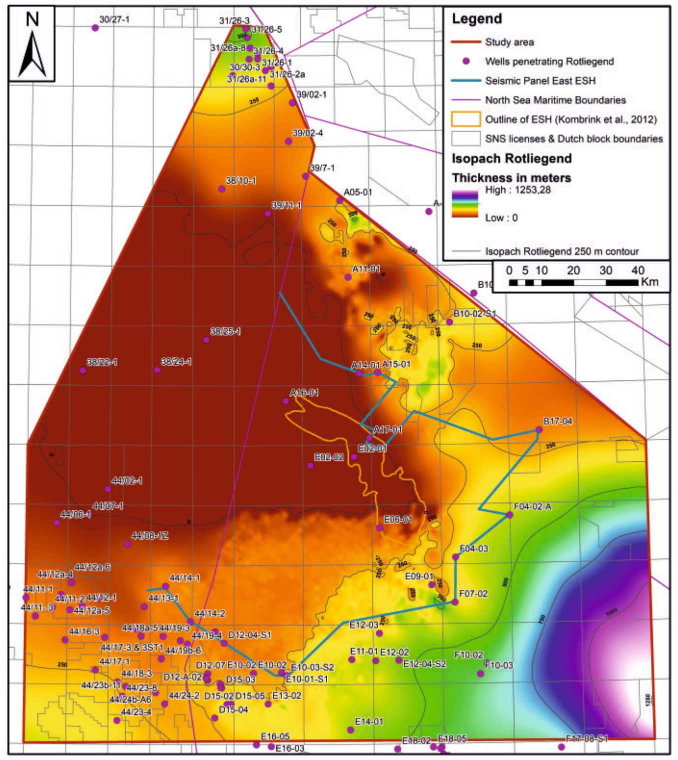
Above: Regional Seismic Panel A is roughly trending N-S; running from the Cleaverbank Platform in the south towards the Step Graben in the north, thereby crossing the western part of the Elbow Spit High (or eastern part of the wider Mid North Sea High). At the southern margin of the Elbow Spit High, an intra Rotliegend onlap configuration can be observed, which is indicated by the pink arrows. The northern paleo basin margin coincides with a structurally more complex transition and appears to be characterised by steeper thickness gradients compared to the southern margin . The Panel has a total length of 225,3km and intercepts six wells that penetrate the Rotliegend (D15-02, D12-4-S1, A14-1, A15-1, A11-1).



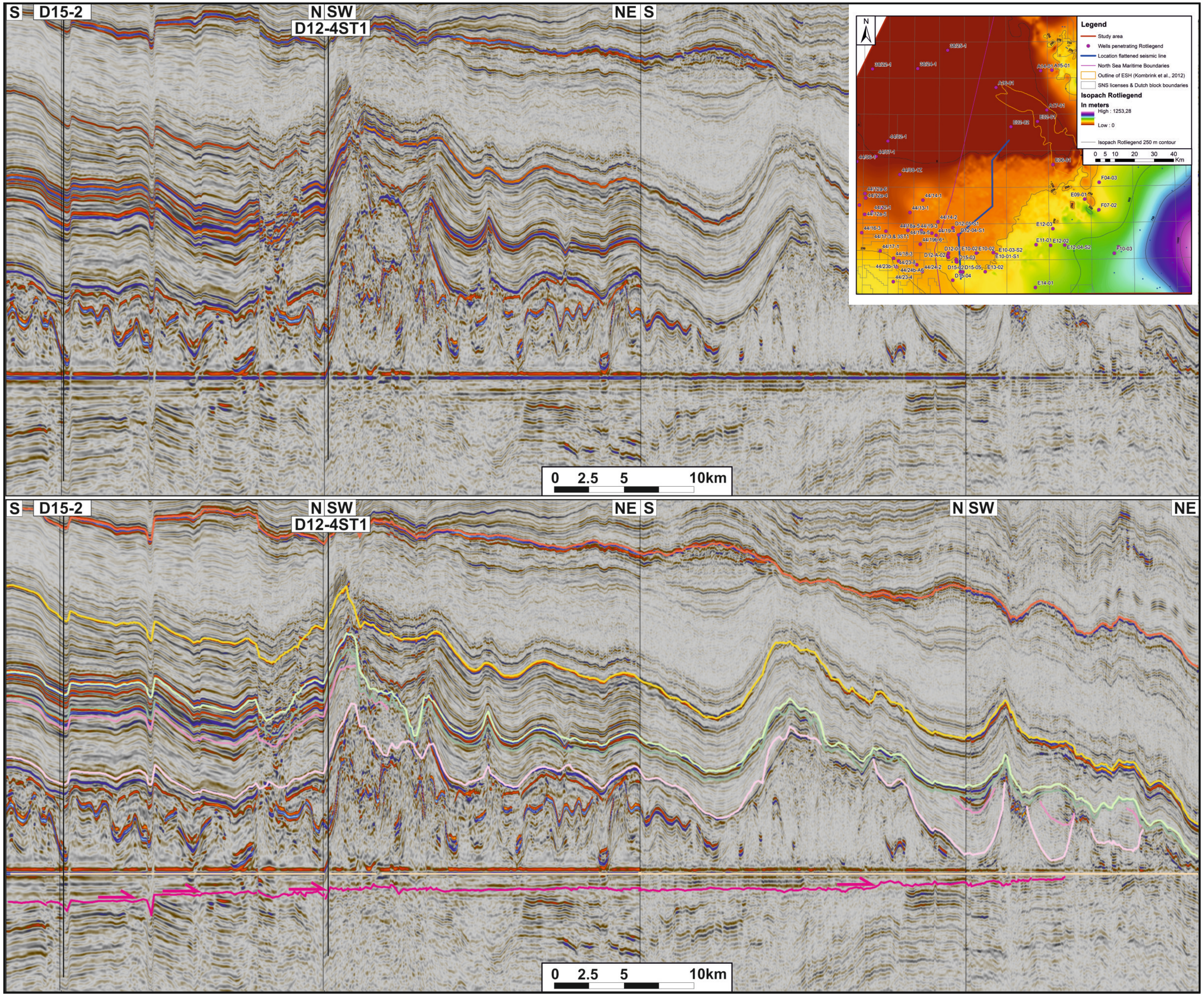
Regional Seismic Panel B



Above: Regional Seismic Panel B follows a semicircular trajectory around the edge of the wider Mid-North Sea High, thereby crossing the Elbow spit high on its northeastern flank to illustrate the complex transition in this area from the paleo basin onto the paleo high. The panel has a total length of 326,3km and intercepts 10 wells that penetrate the Rotliegend (44/14-1, D12-4-S1, E10-3-S2, E12-3, F07-2, F04-3, F04-2A, B17-4, A15-1, A14-1).

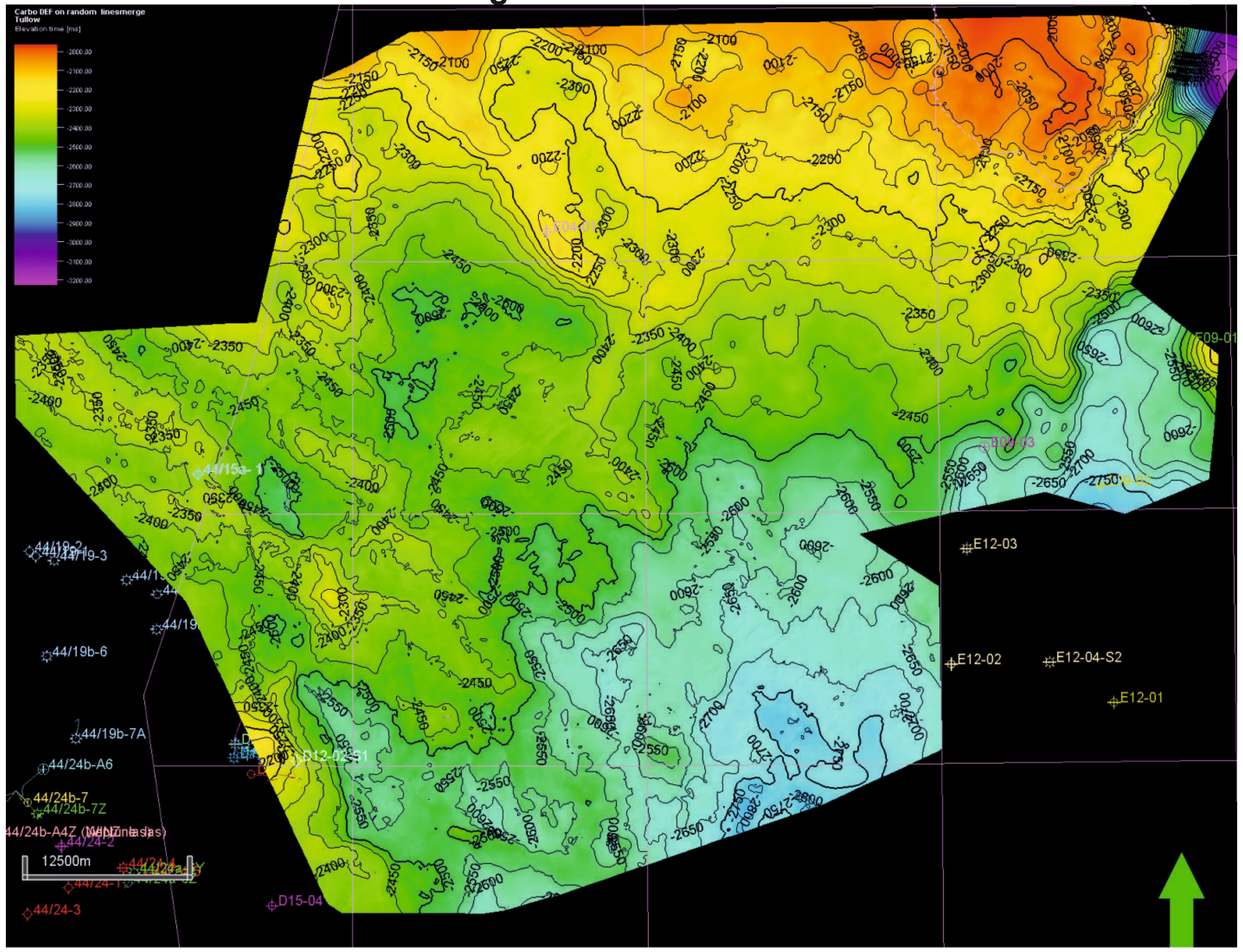


South of the Mid North Sea High

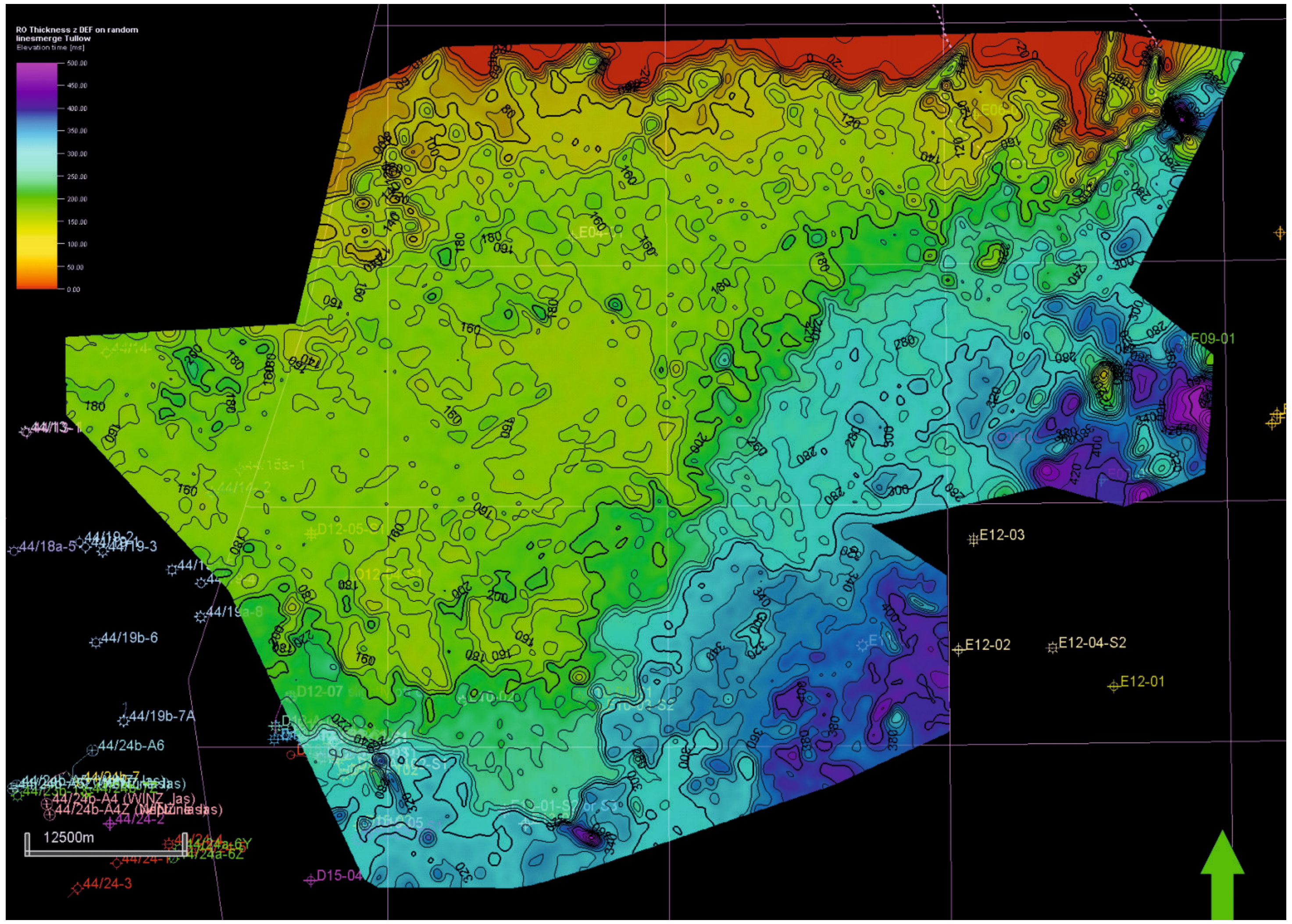


Right: Un-interpreted and interpreted flattened seismic line south of the Elbow Spit High. Section flattened on the base of the Zechstein with a Vertical exaggeration of 15 (VE15x), showing basal onlap configuration south of the Elbow Spit High.

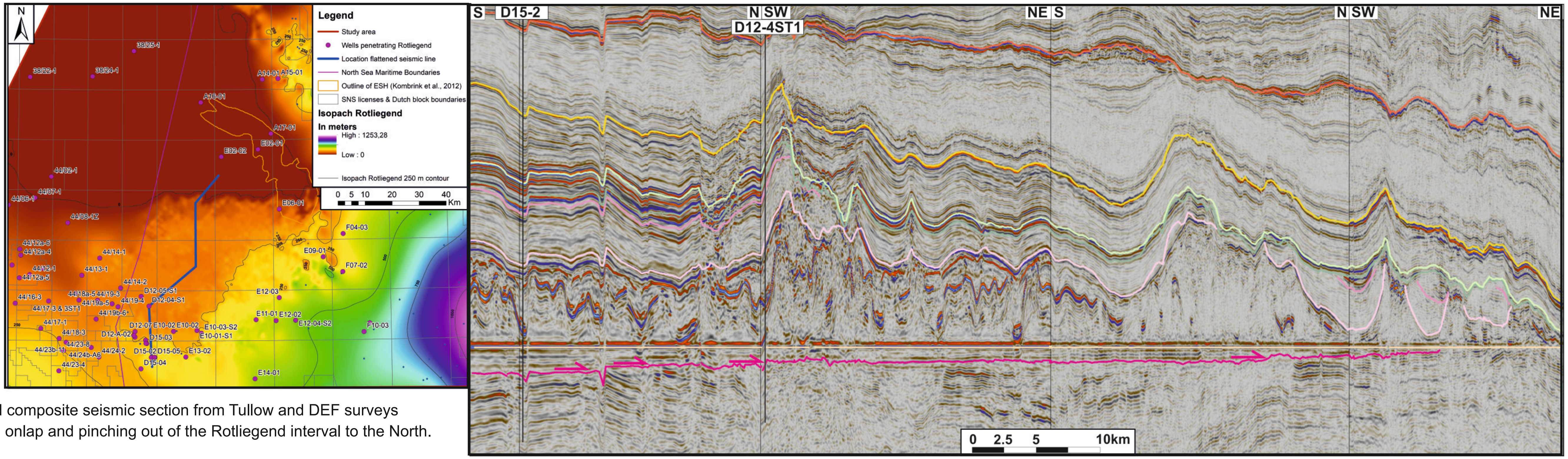
South of the Mid North Sea High



Above: BPU time depth map in the combined area of the DEF and Tullow surveys.

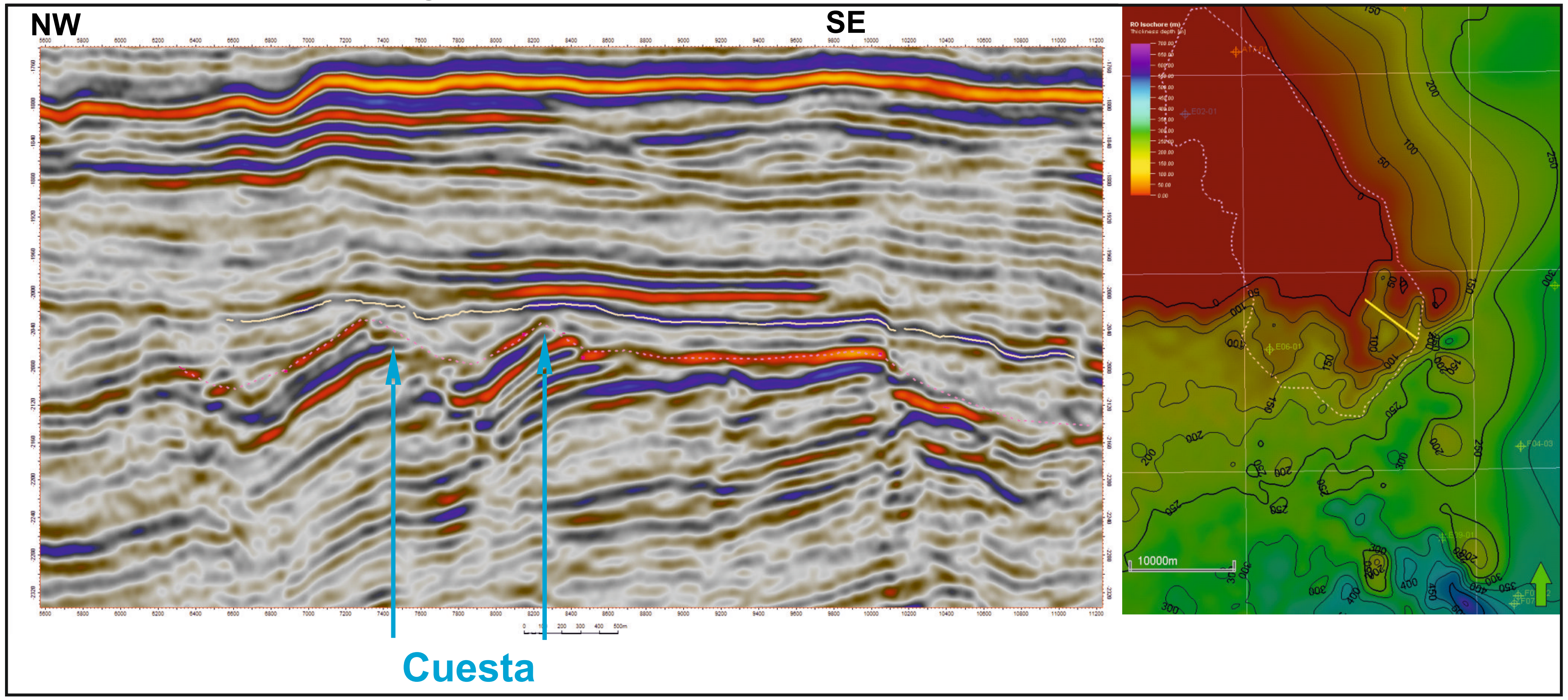


Above: Thickness of Rotliegend (m) derived from TWT interpretation in the combined area of the DEF and Tullow survey. A constant Rotliegend velocity of 4350 m/s was used.

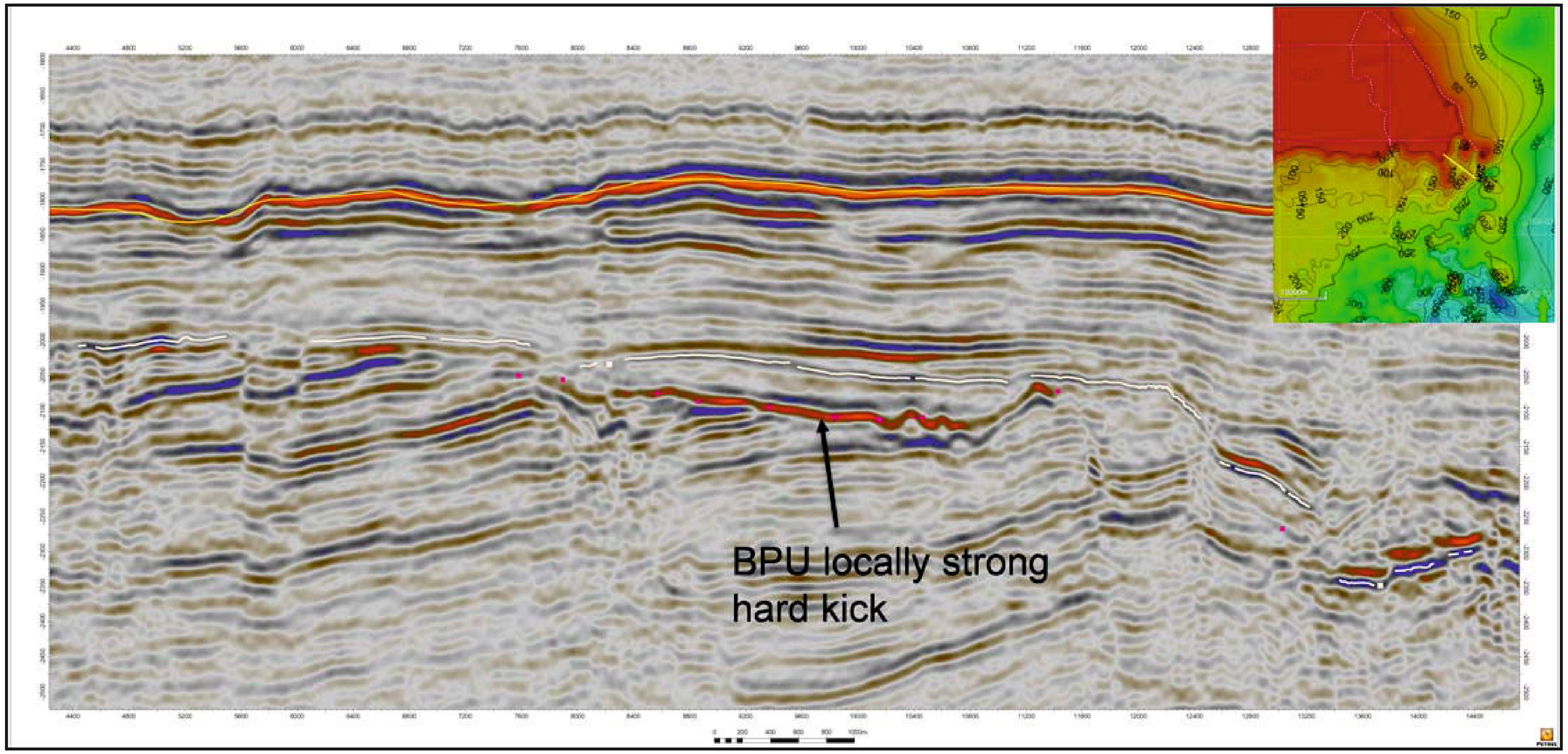


Above: Flattened composite seismic section from Tullow and DEF surveys showing thinning, onlap and pinching out of the Rotliegend interval to the North.

South of the Mid North Sea High



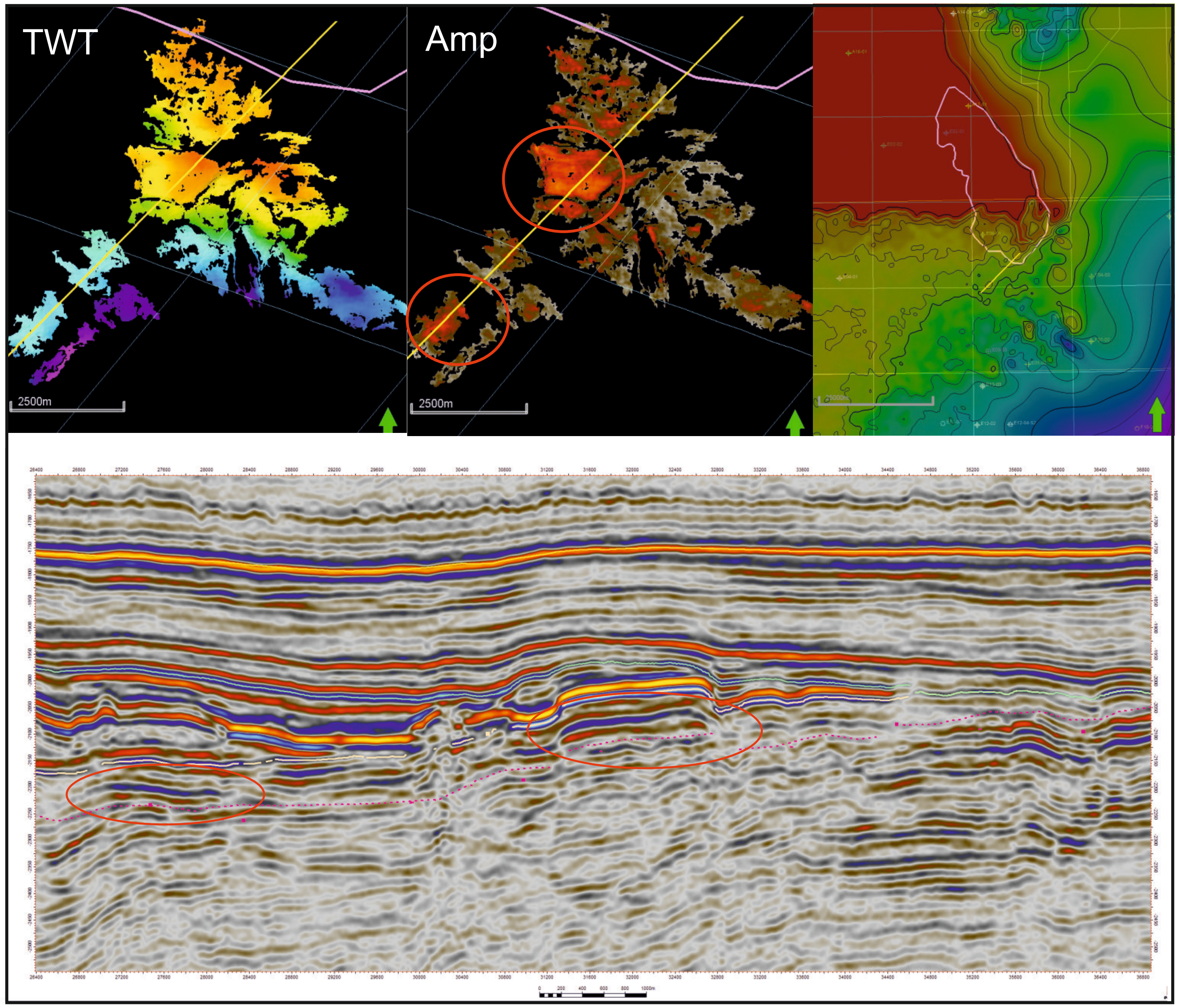
Left: NW-SE section on the SE edge of the Elbow Spit High. Here the Zechstein is absent and Chalk lies directly on top of the Rotliegend. In light yellow base Chalk (Top RO), the pink dotted line represents base Rotliegend (BPU). The reflective Carboniferous which most likely consists of Yoredale limestones has locally a rugose top probably indicating that a paleo-ridge in the landscape existed consisting of tilted limestone beds that are more resistant to weathering. Because of this the Rotliegend thickness varies considerably over short distances and has an incision-like geometry trending N-S to NNE-SSW.



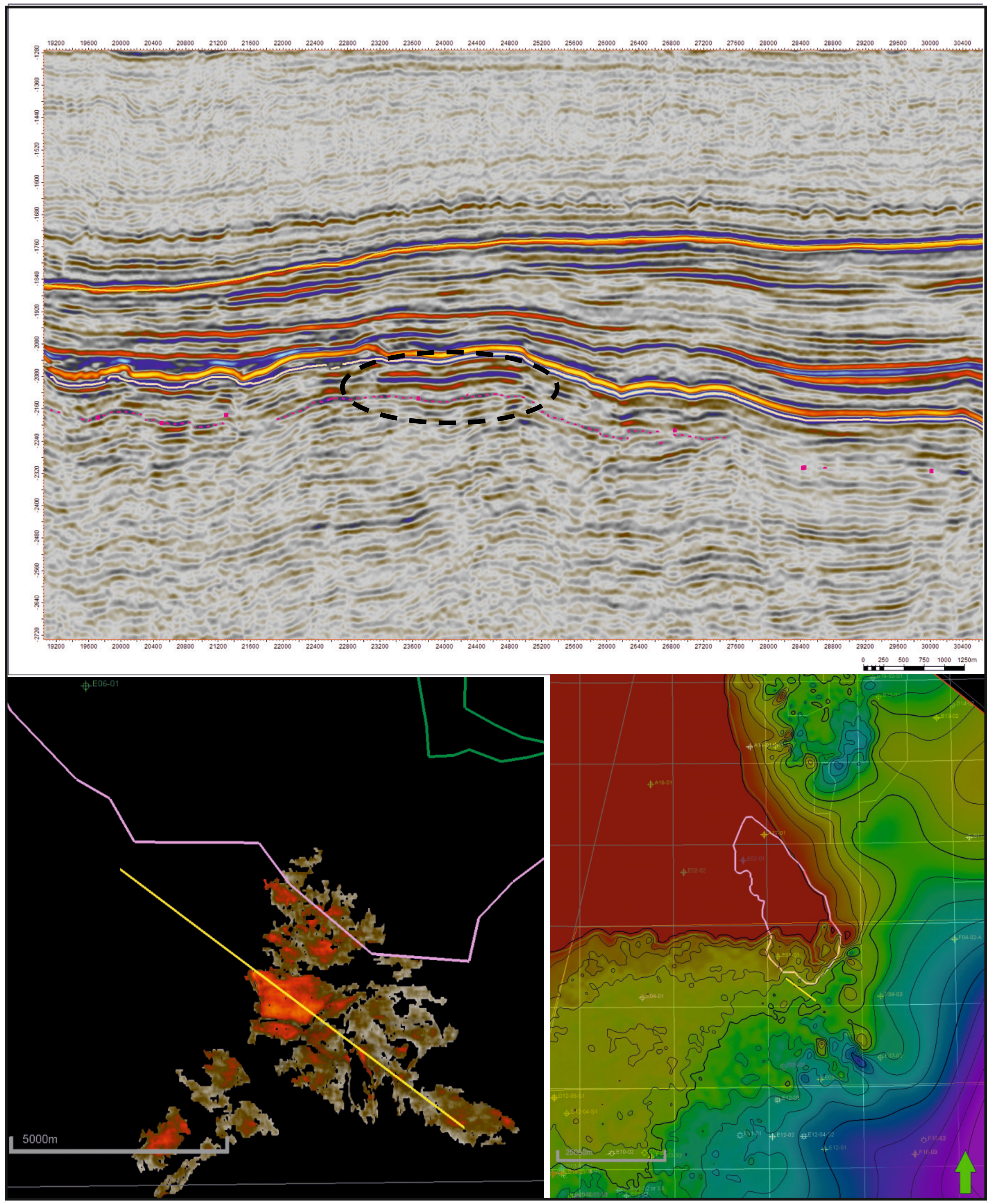
Left: NW-SE section showing a bright "hard kick" event (interface between low acoustic impedance above and higher acoustic impedance below) at the base of the incision. This event might be explained by a hard ground or volcanics forming a hard surface parallel to the Rotliegend and at an angle to Carboniferous strata. There does not seem to be much amplitude variation along the reflector although different Carboniferous beds subcrop below.

5. Seismic interpretation

South of the Mid North Sea High

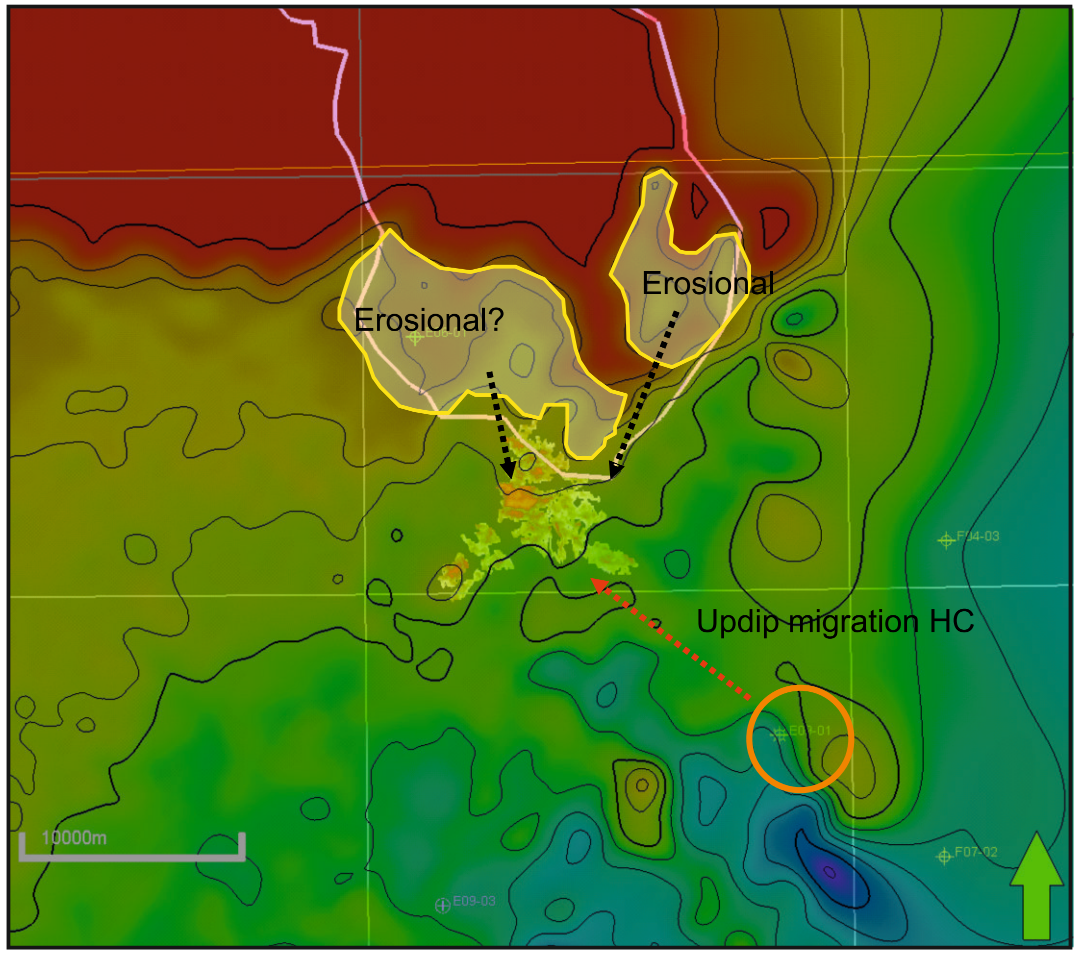


Above: Two bright amplitude events shown on SW-NE section in the lower part of the Rotliegend section (base RO dotted pink line). Above the section the TWT map is displayed (red=shallow and blue/purple = deep) and next to it the amplitude map extracted from the events. At least the northern bright event is restricted to a high block (structurally bounded), the southern is more subtle in elevation. The geometry of the bright events may indicate gas fill.

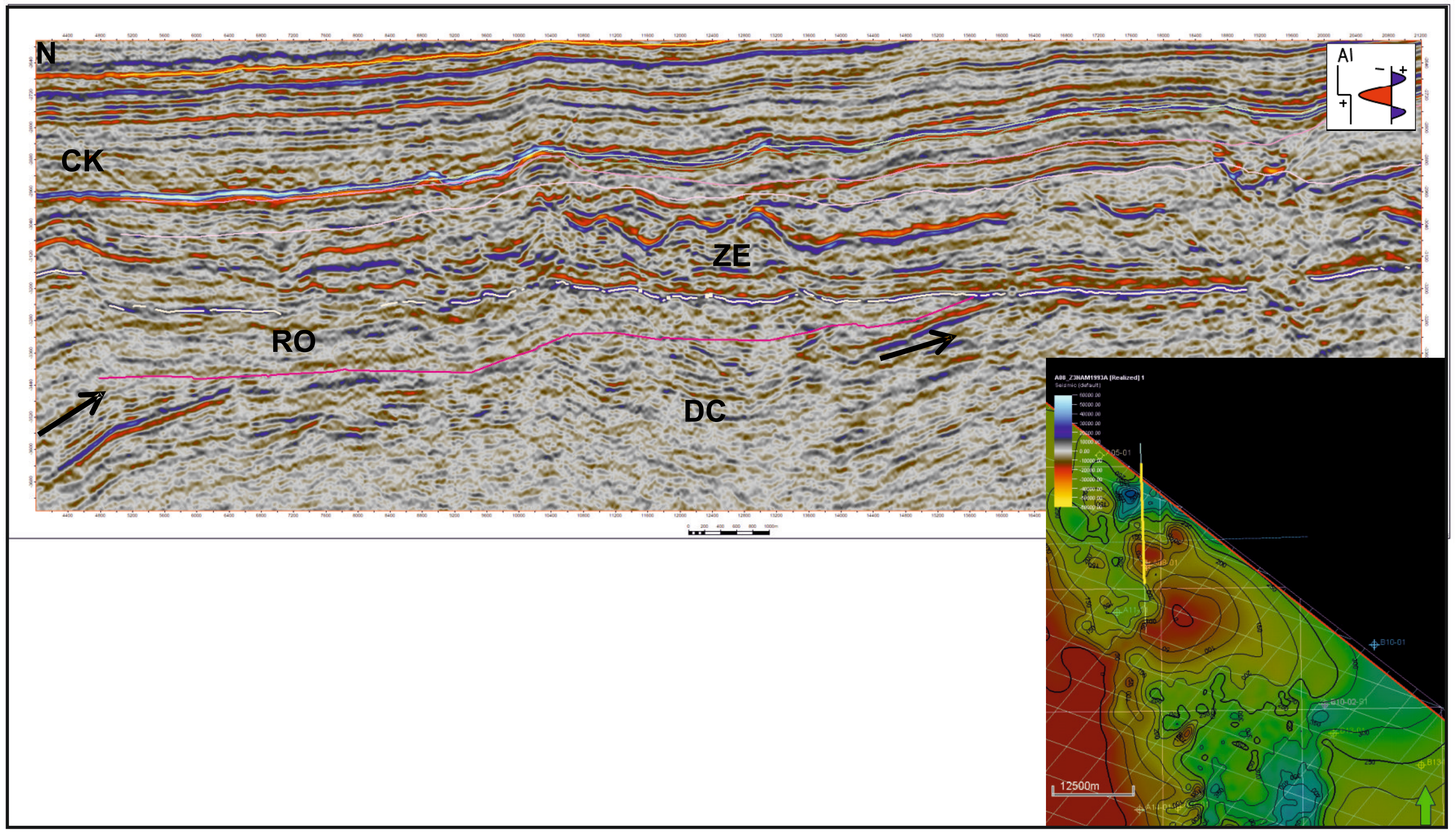


Above: NW-SE cross section showing the northern event as a bright low frequency event restricted to the shallowest part of the section.

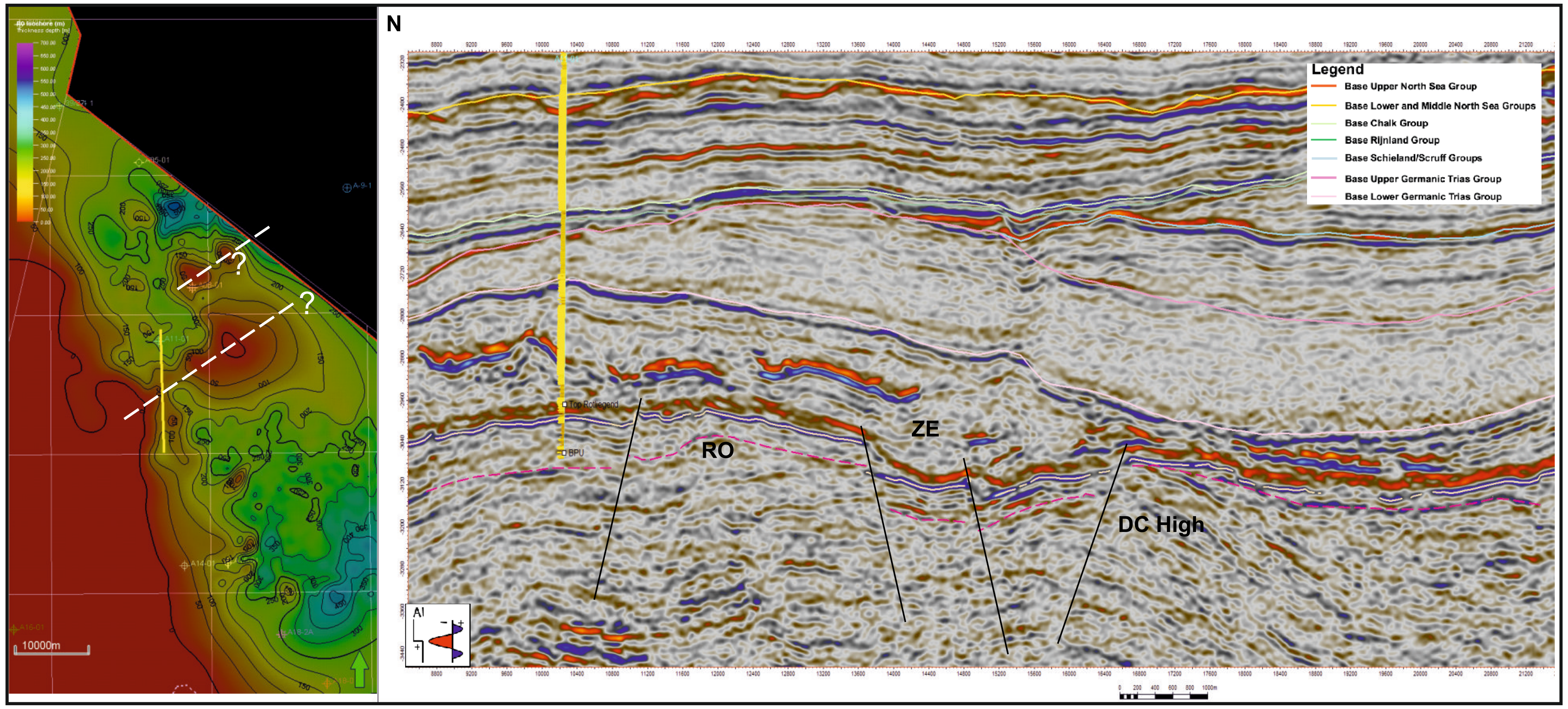
South of the Mid North Sea High



Above: Schematic map showing the position of the erosional incision areas and the bright amplitude events. In the background the Rotliegend isochore is displayed with the no Zechstein area bounded by the pink polygon. The bright amplitude events are situated downdip from the erosional events and updip from the well E09-01 where gas is proven. Black arrows indicate potential transport direction of sands, the red arrow potential migration direction of gas.



Above: N-S section south of the A08-01 well (well did not penetrate Rotliegend). In the northern part of the section an unconformity can be seen which is most likely the BPU (pink line) implying a rather thick Rotliegend. More to the south a bright dipping event is directly below the Base Zechstein (light yellow line) indicating a very thin or zero thickness Rotliegend.



Right: N-S section through the A11-01 well showing in the well thick Rotliegend. More to the south dipping Carboniferous reflectors can be seen directly beneath base Zechstein (light yellow). Base Rotliegend is the pink dotted line showing the thinning of Rotliegend onto the high.

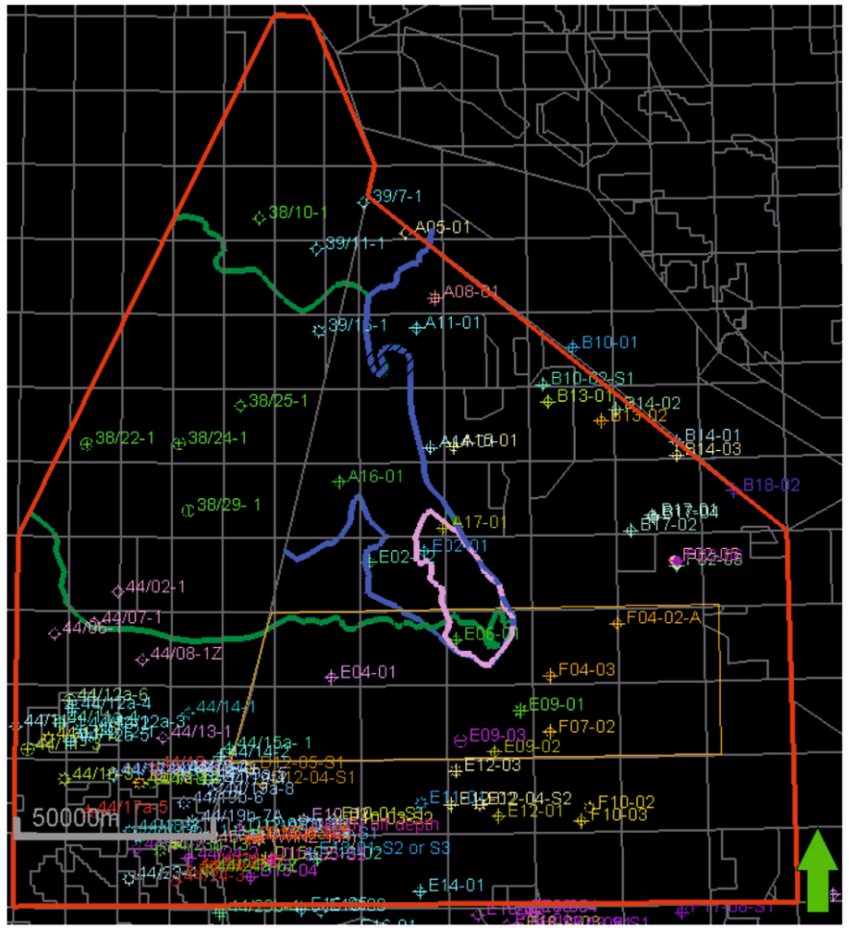
North of the Mid North Sea High

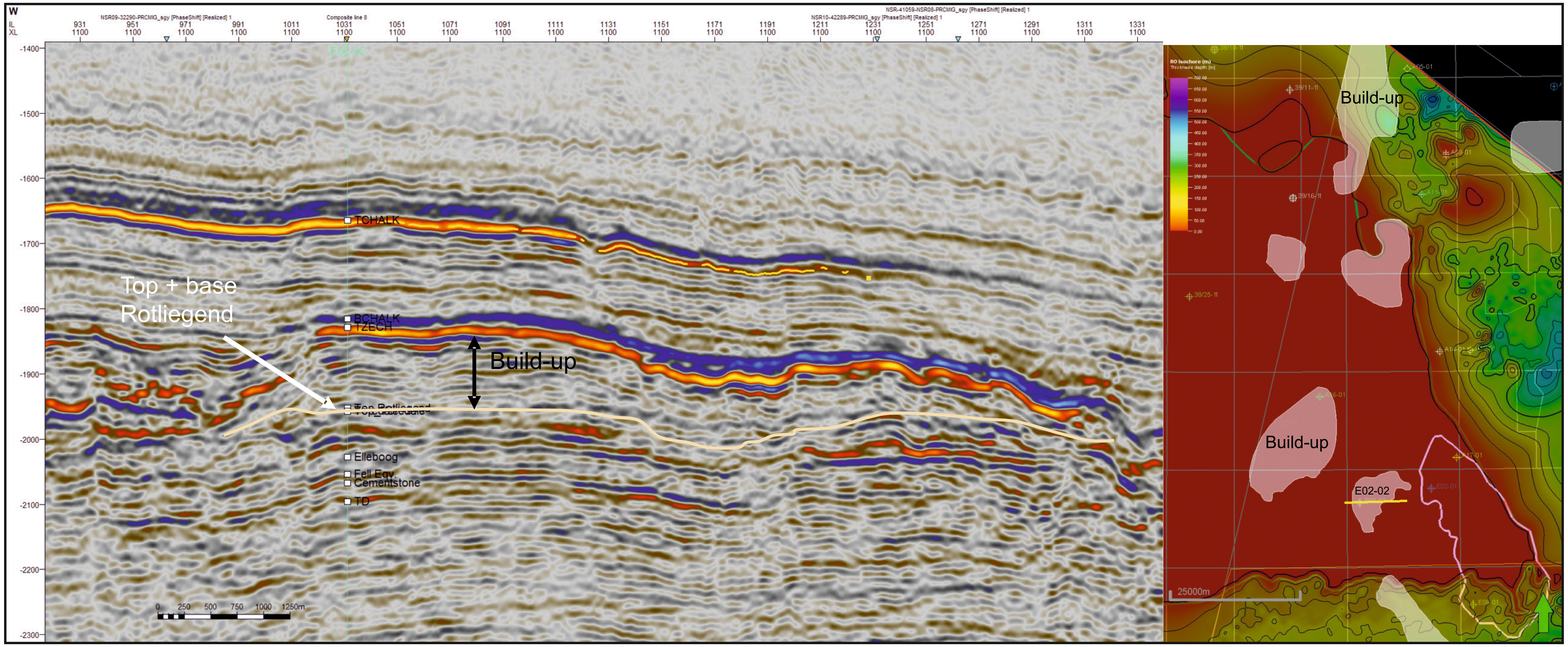
Relationship between ZE & RO thicknesses

ZE2 halites are deposited in depocentres in deepest parts of the basin. Locally basal Zechstein build-ups are present on the platforms. The deepest part of the basins during ZE times are probably also the areas which were deepest during RO deposition, as no tectonic events occurred in between.

Because the BPU is only locally visible NE of the MNSH due to reduced data quality, the presence of ZE2 halites was used as a proxy for Rotliegend deposition trends. See master PPT presentation for more detailed information

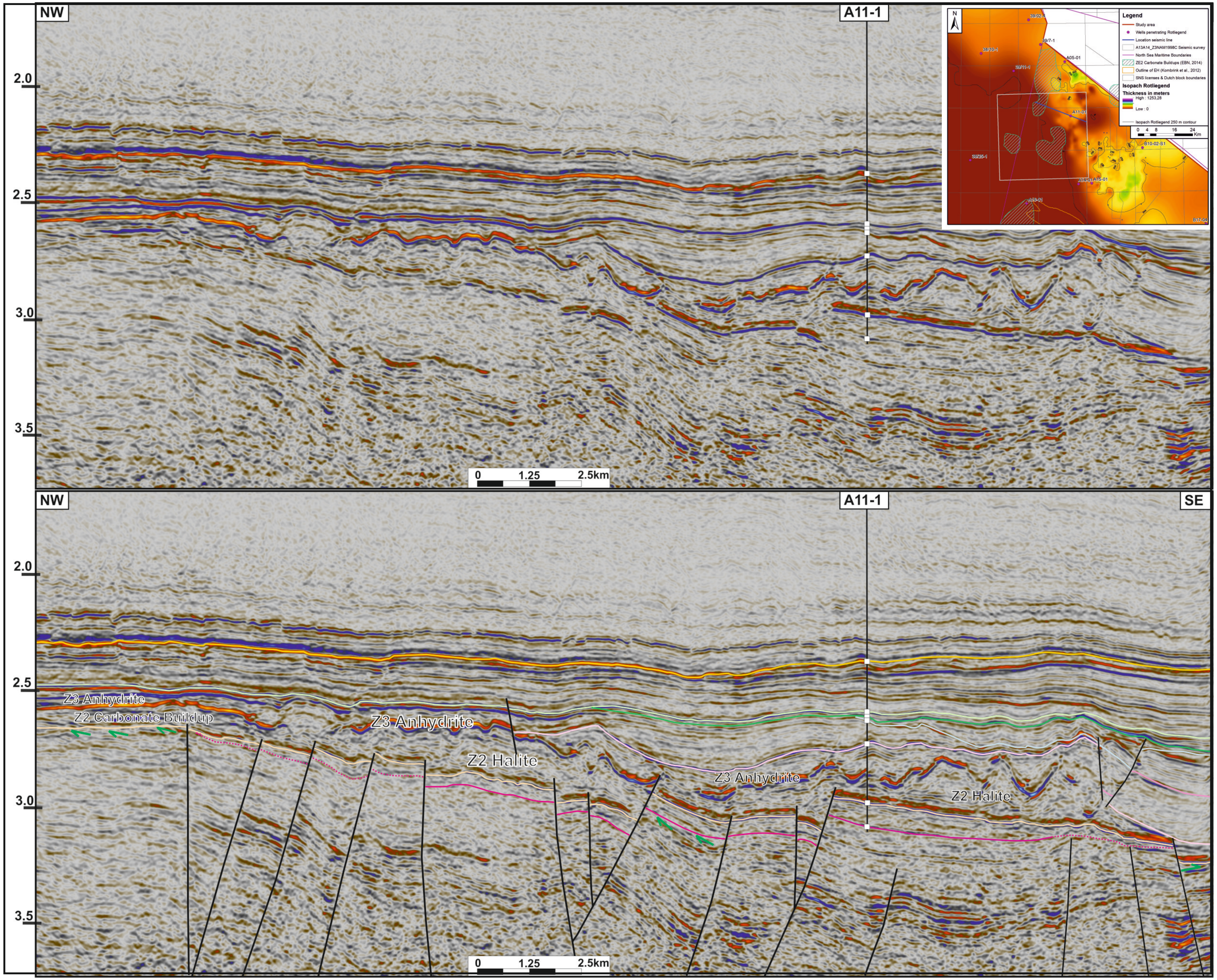
Right: Map of he ZE2 halite distribution and RO. This map was used as a guide for RO isochore mapping. ZE2 halite boundary mapped in NL (blue).This boundary merged with zero-thickness line RO Heriot Watt study (green).This combined line (green plus blue) guided RO isochore mapping. In the South zero RO thickness mapped. Here the RO pinch-out and ZE2 halite boundary do not match exactly. This indicates a SW-ward tilting during ZE deposition. Possibly ZE has not been deposited on crest ESPH (pink), evidenced by well E06-01 in which the basal ZE is thin and looks differently. Alternative explanation: ZE eroded by BCU. Weathering/subrosion/karstification of ZE remnant below BCU





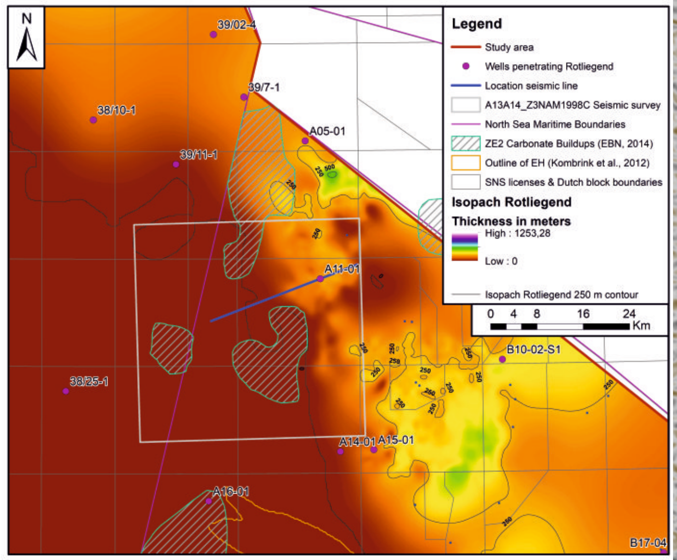
Left: W-E section through well E02-02 showing a thick Zechstein build-up also mapped by Tolsma et al. 2016 (white areas on the map at the right). The base of the Zechstein build-up is not represented by a bright reflector and difficult to pick. The Rotliegend in the well is subseismically thin and can't be picked here on seismic data.

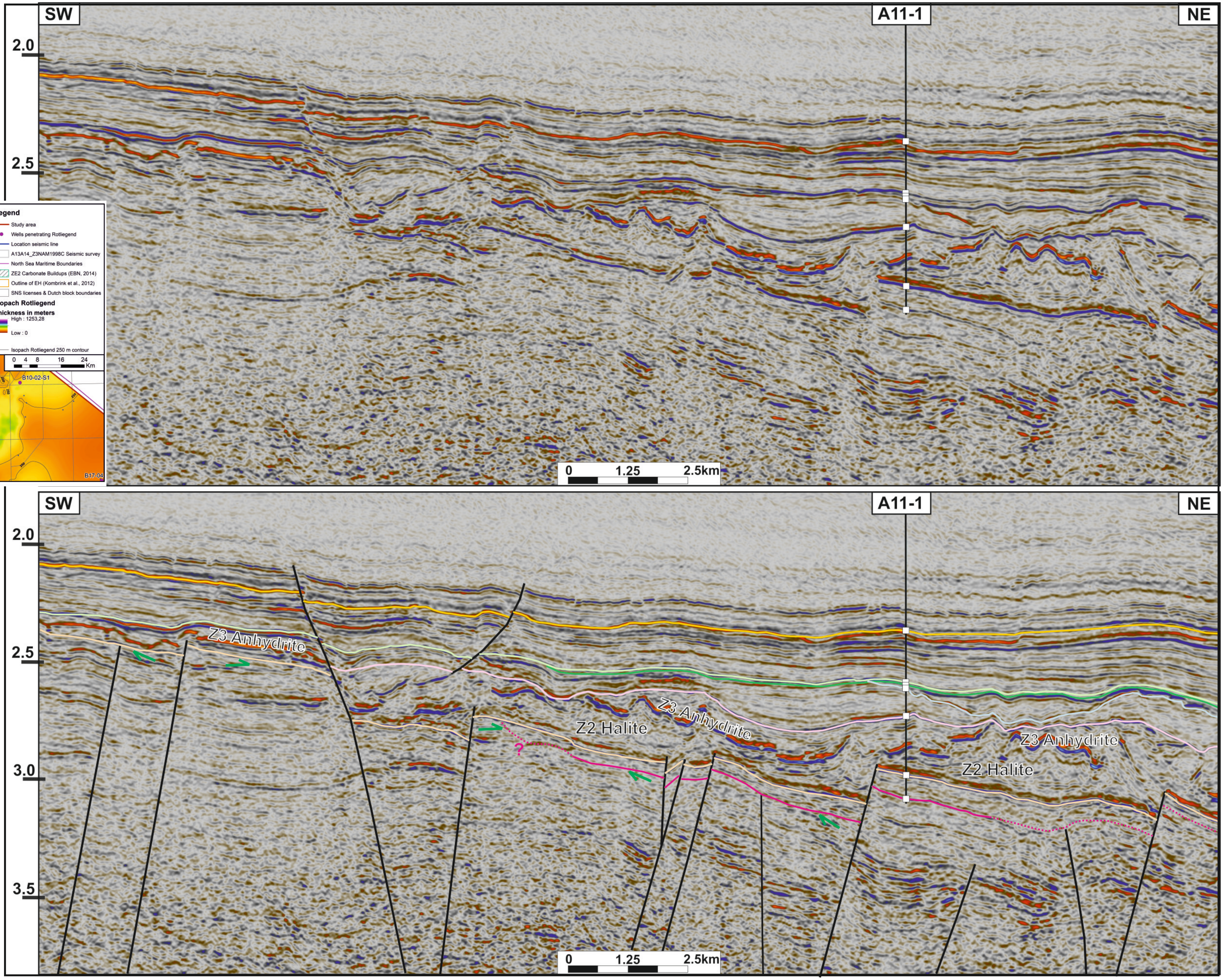
North of the Mid North Sea High



Right: Un-interpreted and interpreted SE-NW seismic line illustrating relatively thick Rotliegend strata directly around A11-1. Towards the northwest, the Rotliegend pinches out untill it is absent in the northwestern part of the section where high angle Carboniferous strata are toplapping against the base of the Zechstein. In the far southeastern part of the section, also high angle Carboniferous strata can be observed that are toplapping against the base of the Zechstein, indicating another, smaller paleo high.

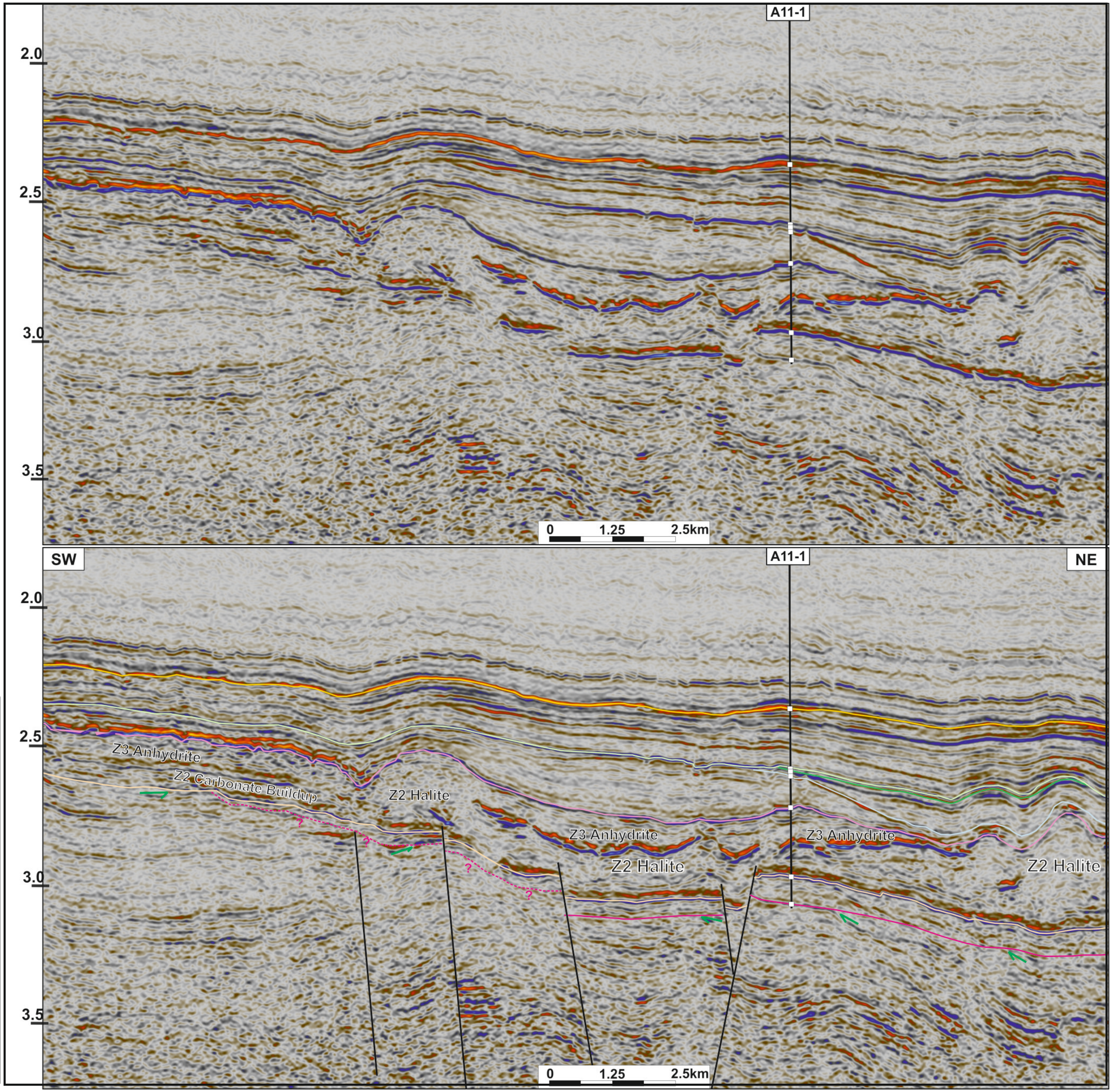
North of the Mid North Sea High



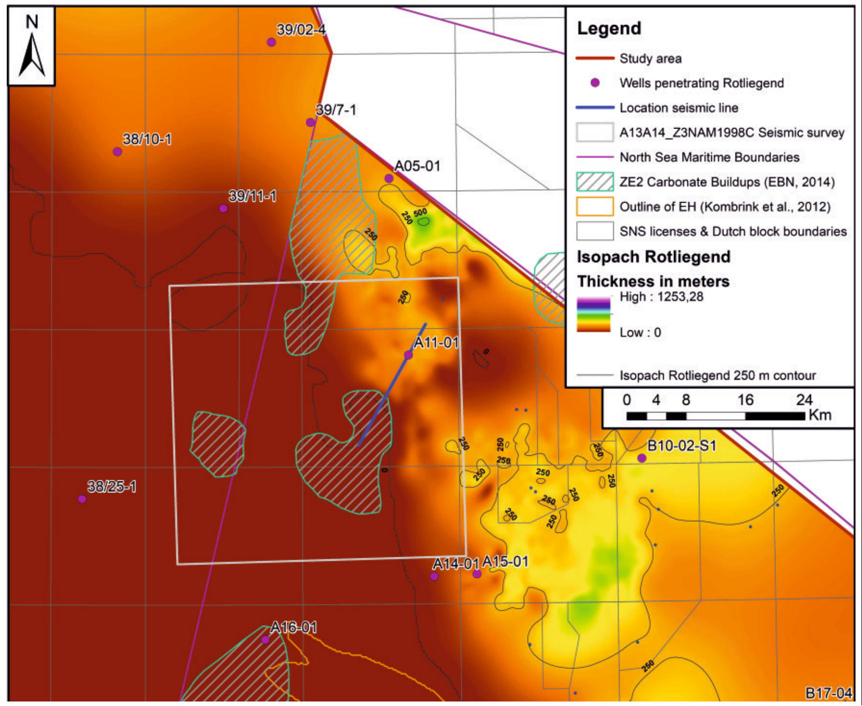


Right: Un-interpreted and interpreted ENE-WSW seismic line illustrating relatively thick Rotliegend directly around well A11-1. Towards the west-southwest, the Rotliegend pinches out until it is absent in the southwestern part of the section, where high angle Carboniferous strata can be observed that toplap against the base of the Zechstein. The exact configuration of pinch-out of the Rotliegend is unclear. Possibly relatively thick Rotliegend is present until the major boundary fault. It is noted that according to EBN (2014) no ZE2 Carbonate buildups should be present in this part (see insert map). This line however shows the possible presence of relatively thin Zechstein carbonate strata underneath the Z3 anhydrite.

North of the Mid North Sea High



Right: Un-interpreted and interpreted NE-SW seismic line illustrating relatively thick Rotliegend strata around well A11-1. Towards the southwest, the Rotliegend pinches out untill it is absent in the southwestern part of the section, where high angle Carboniferous strata can be observed that toplap against the base of the Zechstein.



Lessons learned on the use of PaleoScan for Amplitude mapping

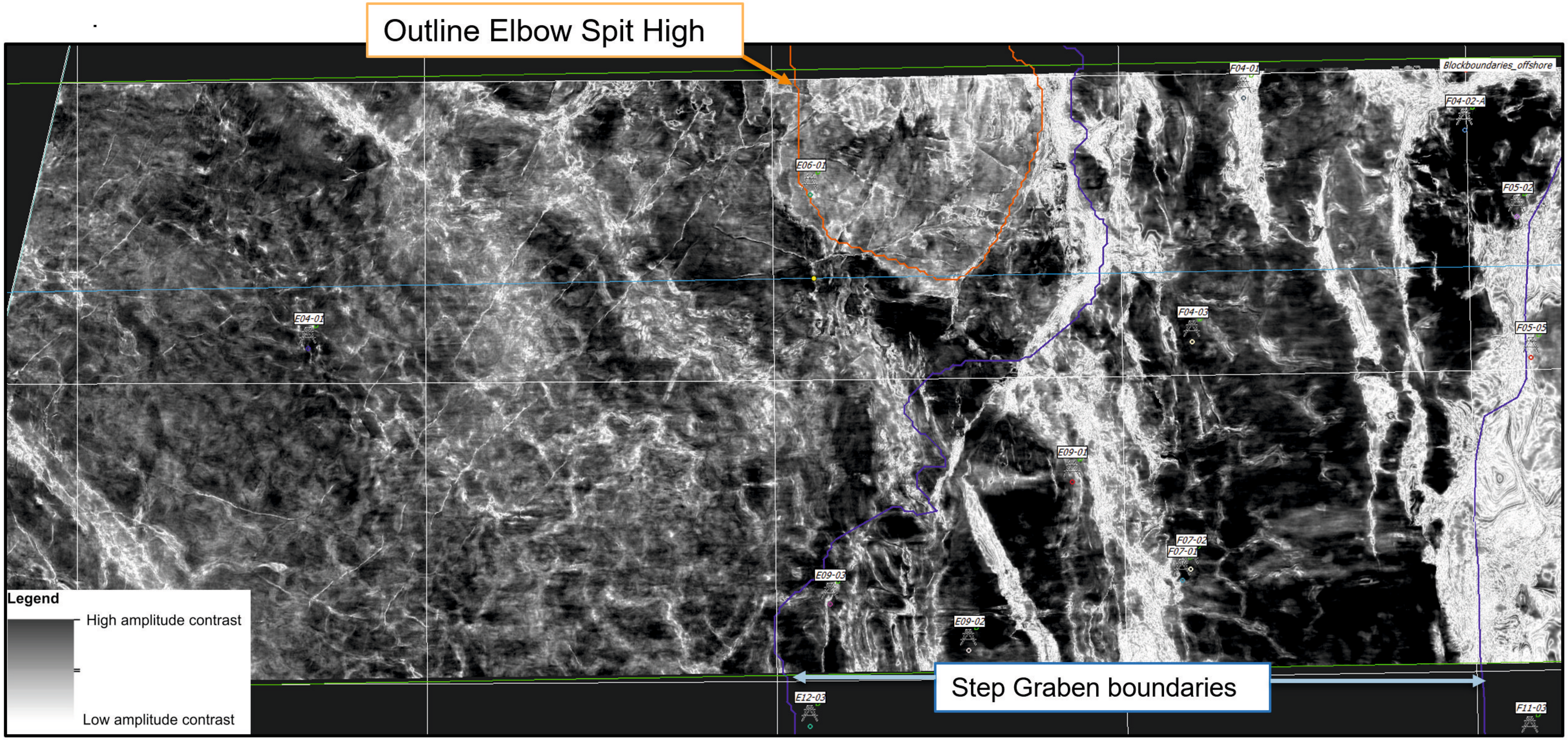
The creation of a properly constrained geomodel for the Rotliegend over a large area (such as the Tullow-survey) is obstructed by:

- The relatively thin Rotliegend in combination with limited seismic resolution;
- The seismic interference of (thinning) sub-seismic intra-Rotliegend intervals;
- Discontinuous intra-Rotliegend seismic signals due to poorly understood intra-Rotliegend complexities;
- The lack of well control.

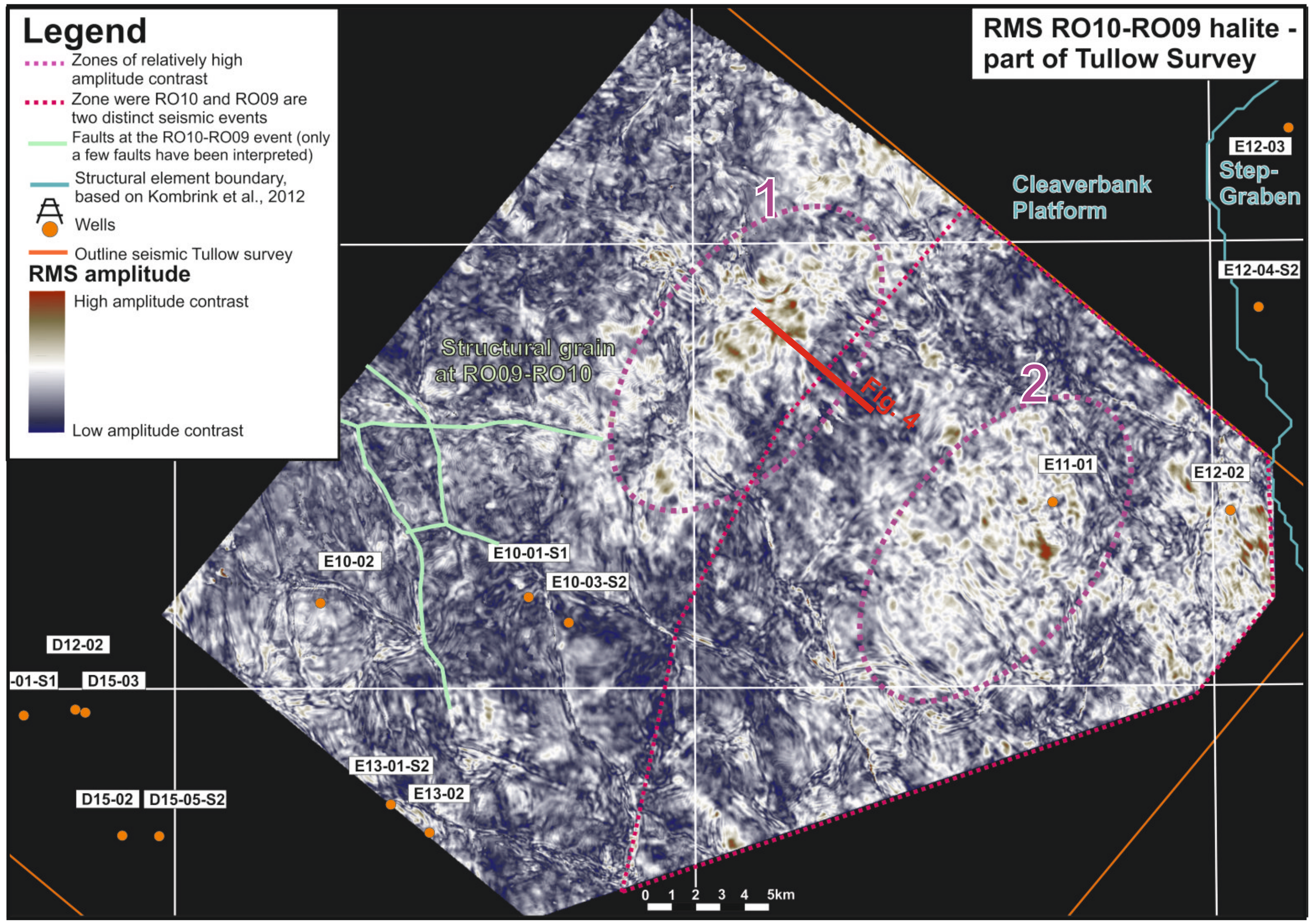
No internal Rotliegend features can be distinguished at the RMS amplitude map of base Zechstein due to the high acoustic impedance contrast at this level, which mainly arises due to the transition between the anhydrite/carbonates of the basal Zechstein and the underlying Silverpit claystones. The structural grain at the base ZE on the other hand is clearly visible.

Amplitude trends observed at the BPU are related to the seismic response of the interface between the (varying) basal Rotliegend properties and the properties of the subcropping Carboniferous. Since a detailed understanding of the subcropping Carboniferous lithology (and hence seismic response) is lacking, it is not possible to thoroughly interpret the RMS attribute map of the BPU and relate this to acoustic property changes in the basal part of the Rotliegend. Most likely most of the variations that are seen on the BPU RMS attribute map are related to variation in properties of the subcropping Carboniferous rather than to intra basal Rotliegend variations. Hence caution should be taken when relating trends seen on the BPU RMS attribute maps to basal Rotliegend architecture.

The case study in the SE part of the Tullow survey shows that it is possible to derive intra Rotliegend horizons from a properly constrained geomodel, as long as intra-Rotliegend horizons are continuous and well control is present to understand the seismic signal. Another case study could for example be performed in the area directly towards the southeast of the ESH, where the Rotliegend rapidly thickens. This area is presumed to lie close to the paleo high which might increase the change of finding paleo-depositional patterns.

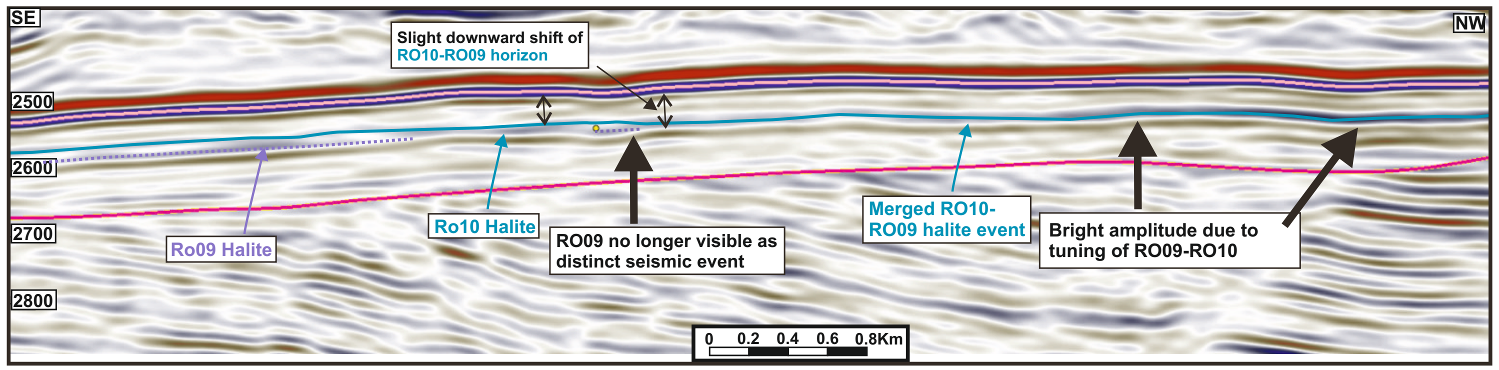


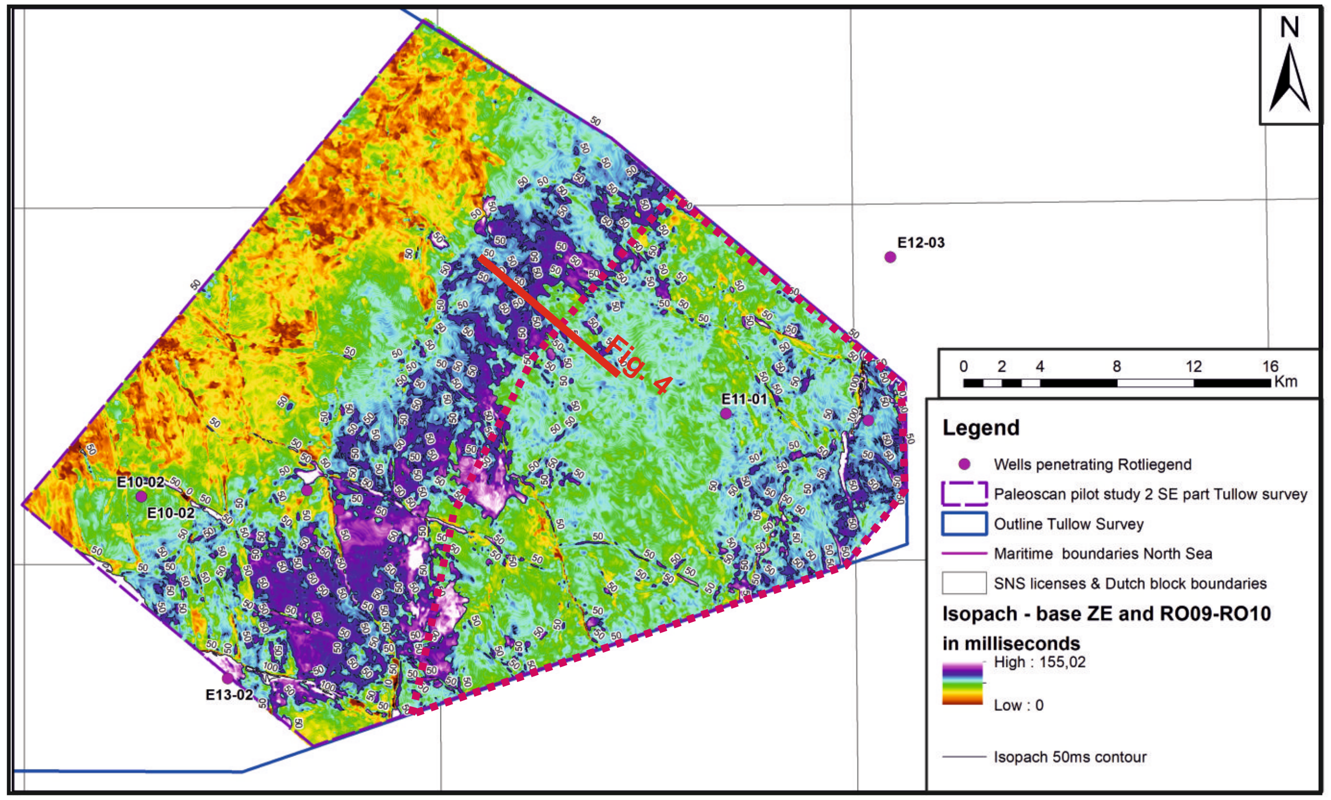
Above: RMS amplitude map of the base Zechstein for the DEF survey. A sample window of 1 was chosen, indicating that the root mean square was calculated for an interval of 4ms (1 sample = 4ms) around the base of the Zechstein. Hence; 2ms above the base ZE and 2ms below the base ZE.



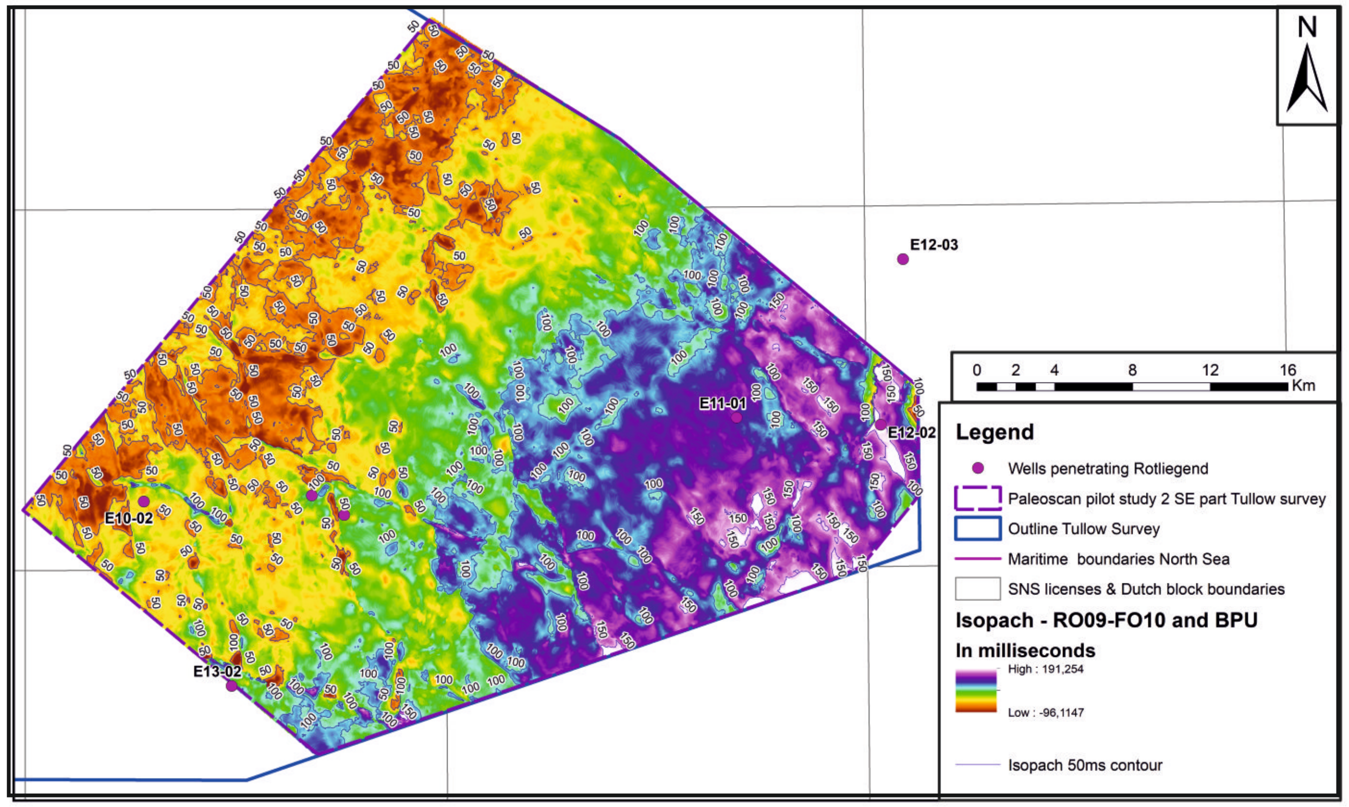
Above: RMS amplitude map of the RO10-RO09 event. In the area that is encircled by the dark dashed pink line, the RO10 and RO09 are two distinct seismic events. In this area, the horizon was picked on the RO10 event. Towards the northwest, outside of this dashed pink line, the RO10-RO09 halites show up as one event on seismic.

Besides the fault structures, which can in particularly be observed in the southwestern part of this area, the map shows two distinct NE-SW trending high amplitude zones. Zone 1 is likely a tuning event that coincides with the area where the RO10 and RO09 halites merge into one seismic event. This area can also be seen on the isopach map of the Base ZE - RO10-RO09 interval (see Figure to the upper right), where the high amplitude zone 1 coincides with a slightly thicker supra RO10-RO09 interval that is the result of a slight downward shift of the RO10 halite that merges with the RO09 halite into one seismic event (see figure below). This RMS map together with the figures on this page, illustrates how difficult it is to see genuine depositional features on the RMS maps of the Rotliegend. Even if it is possible to properly derive an internal horizon from a Paleoscan geomodel, and understand its seismic signature (as is the case for the RO10-RO09 event in this area), tuning, the imprint of overburden signals, and the generall thin Rotliegend inhibit the visualisation of genuine depositional events on the RMS maps.

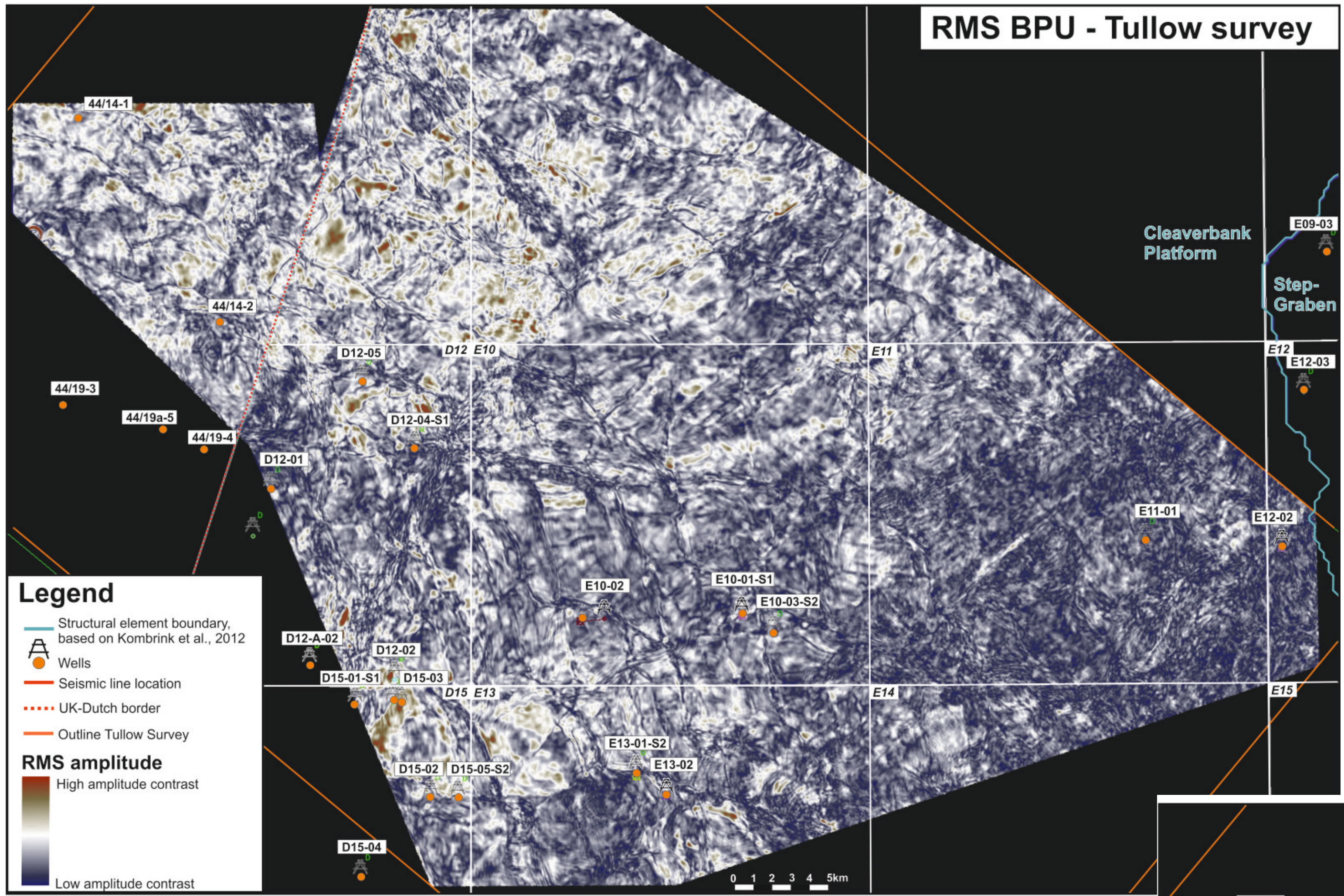




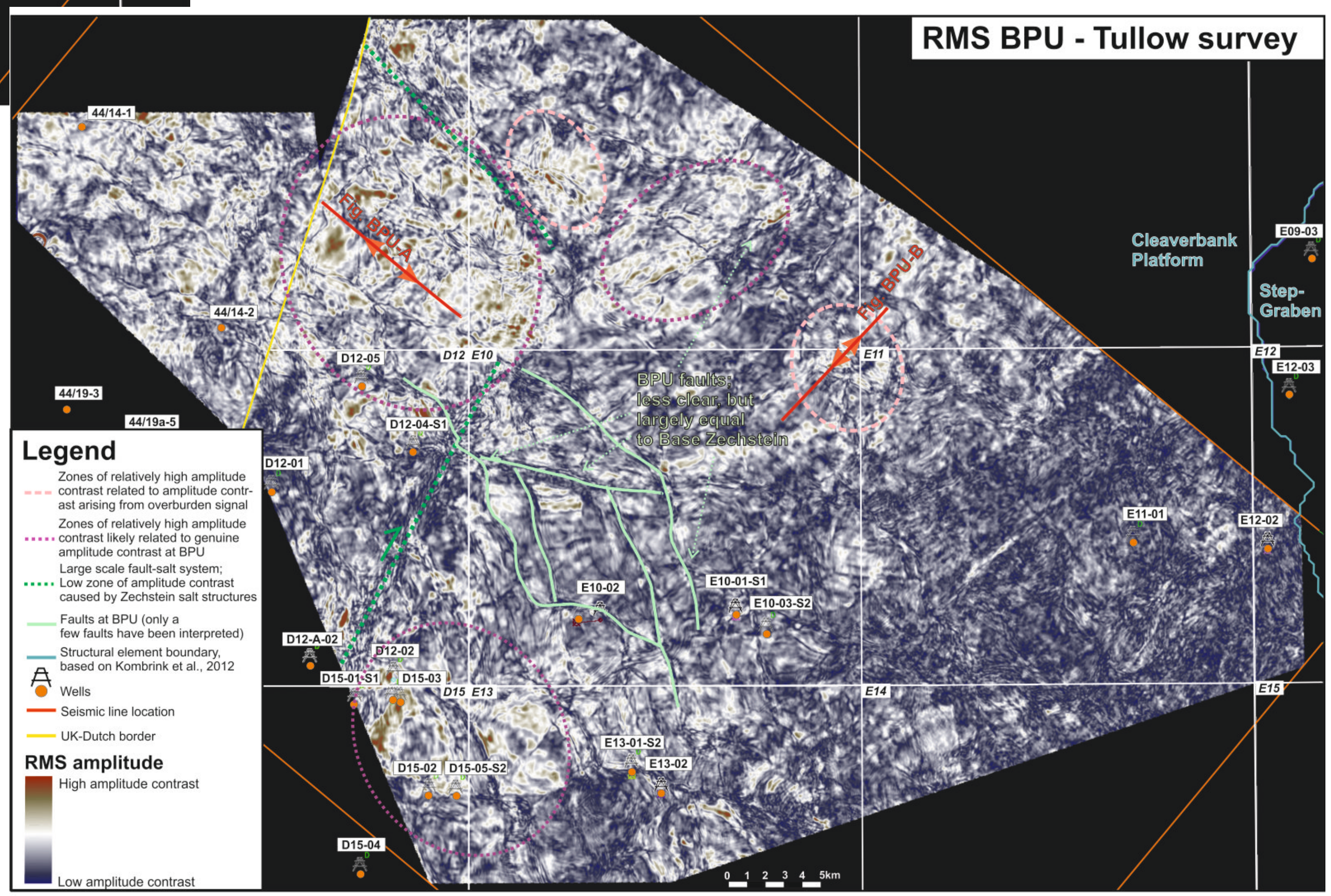
Above: Time thickness map of the interval between the base Zechstein and the RO09-RO10 event. The dashed pink area indicates the area where the RO10 and RO09 halites are visible on seismic as distinct events. Note the slightly thicker NE-SW trending zone that lies on the edge of the pink line indicating that the RO10 and RO09 halites merge into one seismic event in this zone because of generally northwestward thinning. This causes a slight downshift of the mapped horizon (see Figure to the lower left).

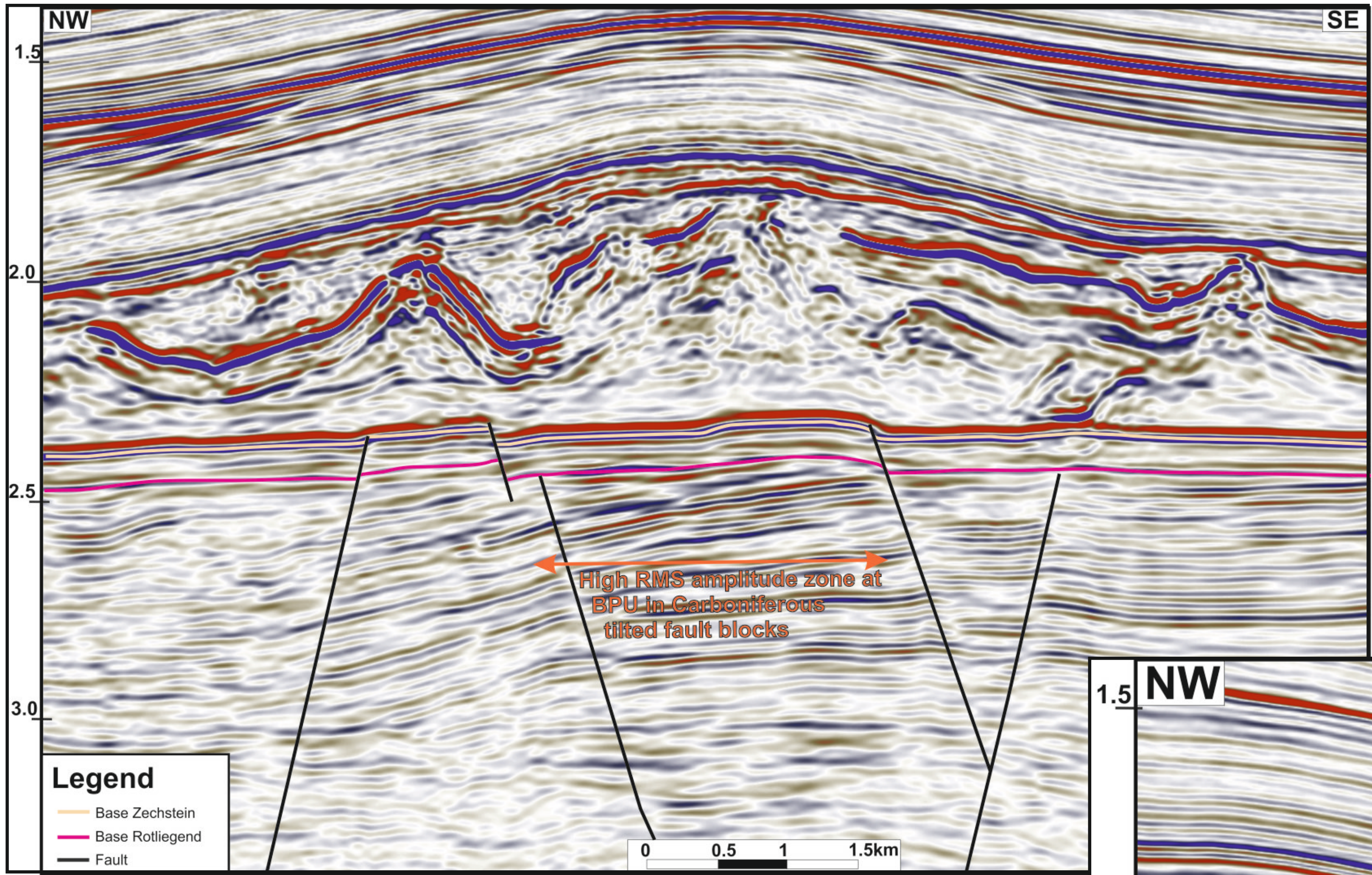


Above: Time thickness map of the interval between the RO09-RO10 event and the BPU. Note the gradual SE-NW thinning that can be observed in this area.



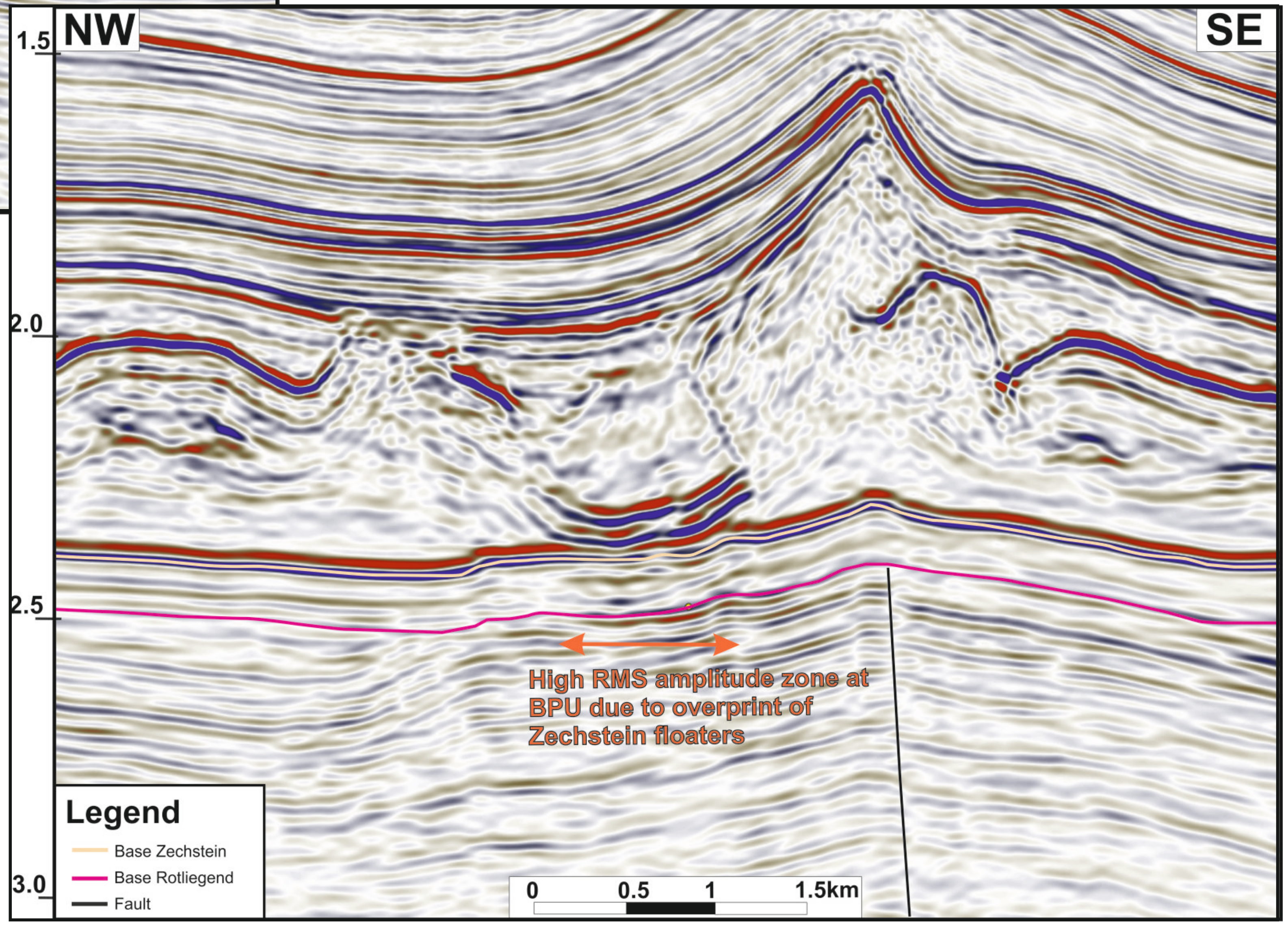
Above and to the right: Un-interpreted and interpreted amplitude maps showing the RMS amplitude at the Base Permian Unconformity (BPU). A sample window of 7 was chosen for the calculation of the RMS amplitude map, meaning: the root mean square of the amplitude was calculated over a window of 28ms around the BPU (i.e. 14ms above and 14ms below the BPU). The structural grain that can be observed largely matches the fault pattern at the base of the Zechstein, albeit the fault pattern at the BPU is less clear compared to the fault pattern that can be observed at the base of the Zechstein. A few zones of relatively high amplitude contrast can be distinguished at the BPU. These zones are indicated by the dashed purple and pink circles. The dashed dark purple circles indicate zones that likely represent a genuine high amplitude contrast within 28ms around the BPU. An example of one of these signals is illustrated by seismic line BPU-A, where tilted Carboniferous strata toplap against the base of the Rotliegend within a series of tilted fault blocks. The dashed pink circles indicate zones that likely represent a strong imprint of the overburden seismic signal, which in both pink circles means that the relatively high amplitude contrast is caused by the Zechstein floaters that have 'sanked' within the Zechstein salt towards the basal Zechstein. This is illustrated by seismic line BPU-B.

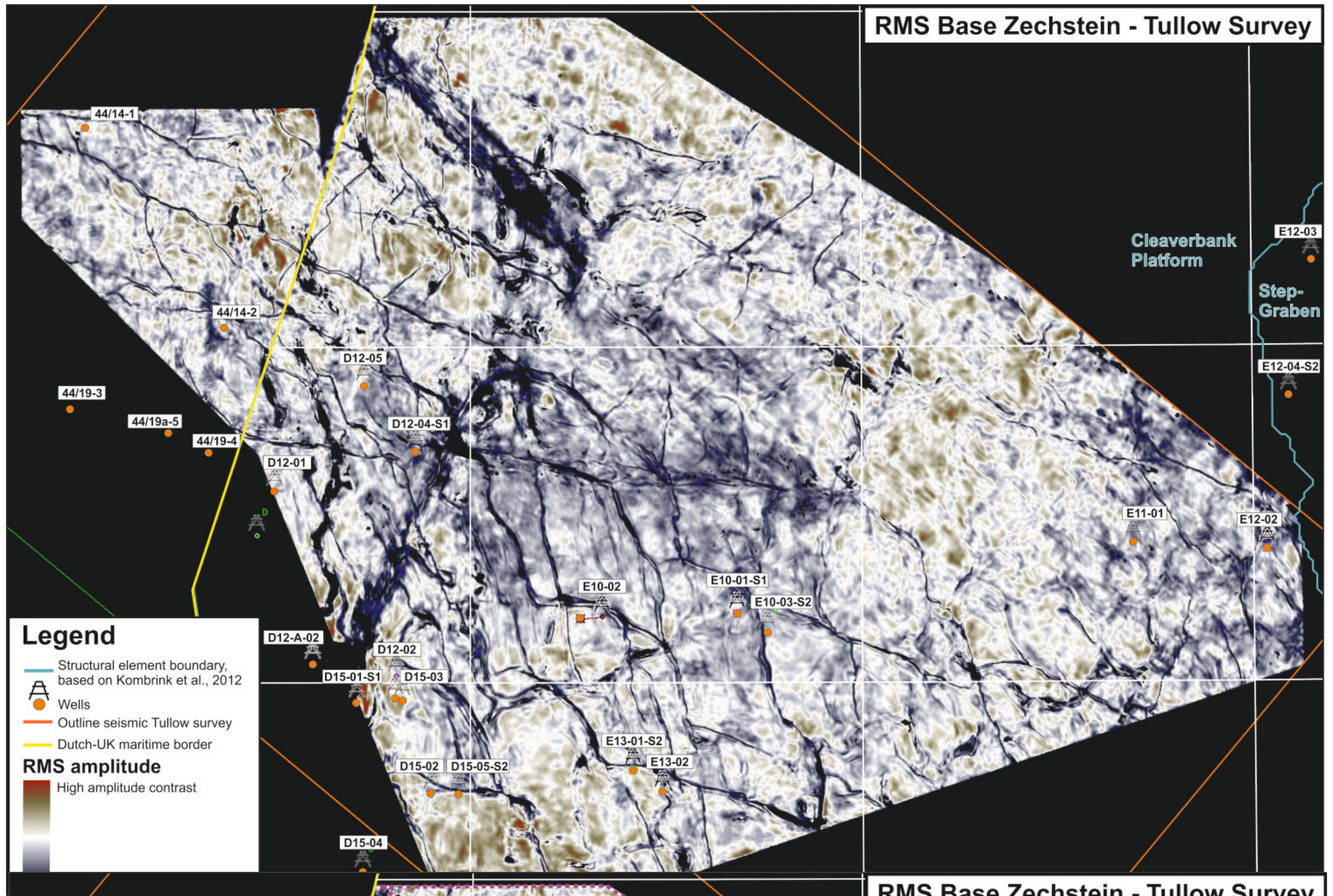


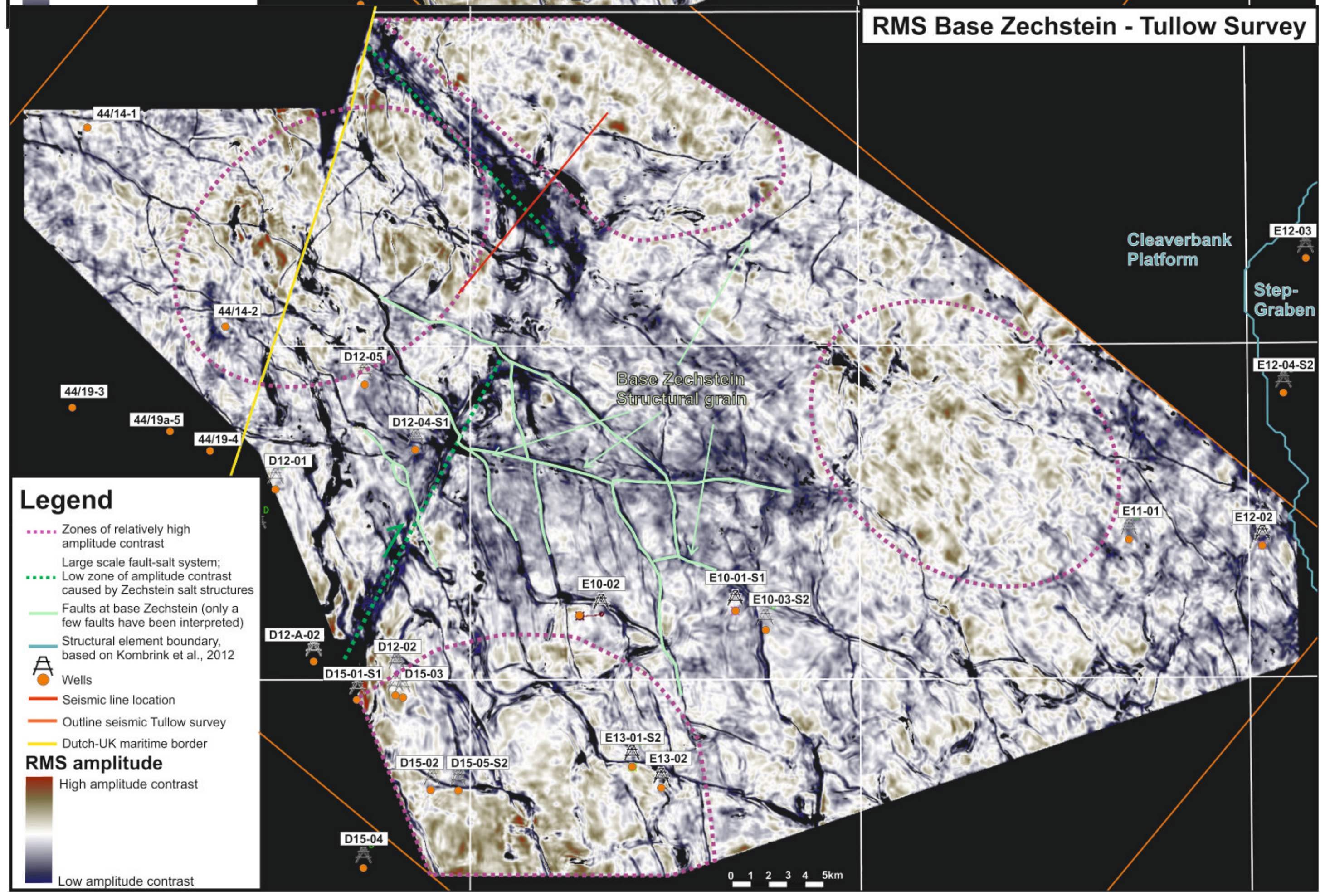


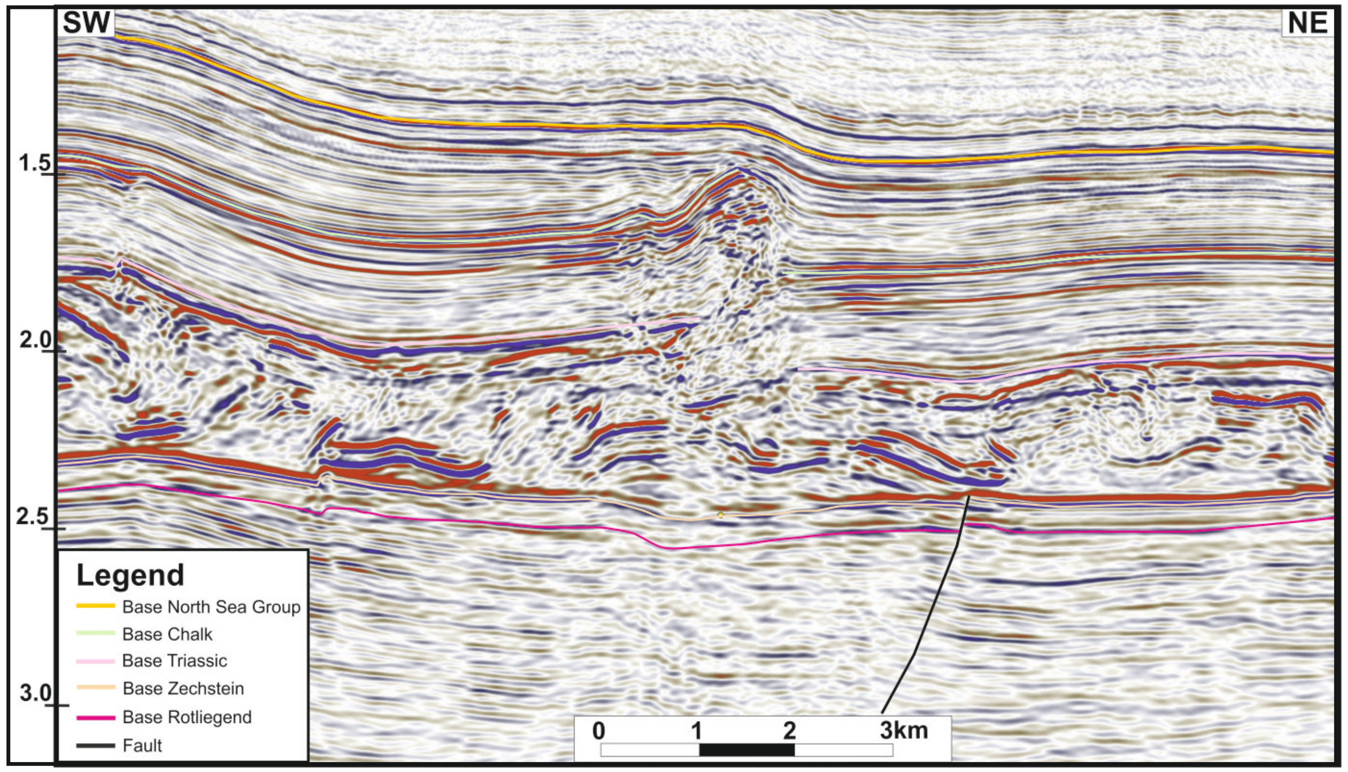
Above: NW-SE trending seismic line indicating that the high RMS amplitude contrast that can be observed at the BPU, is related to tilted high amplitude Carboniferous strata that are toplapping against the base of the Rotliegend. The location of this line is indicated as Fig. BPU-A on the RMS map on the previous page.

Below: NW-SE trending seismic line indicating that the high RMS amplitude contrast that can be observed at the BPU (fig..), is related to a strong imprint of the seismic signal of the overburden, which in this case originates from a 'sunken' Zechstein floater.The location of this line is indicated as Fig. BPU-A on the RMS map on the previous page.







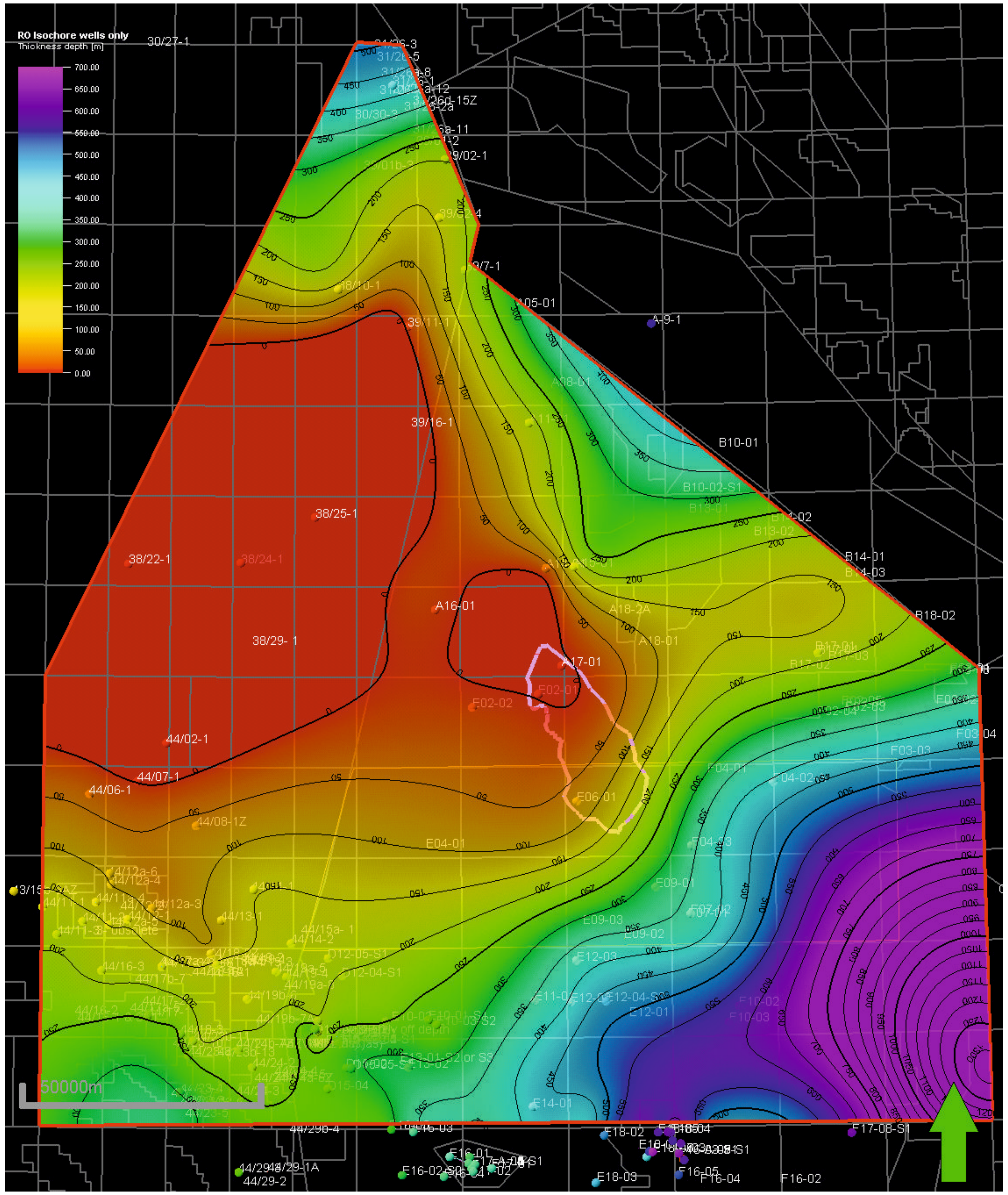


Above: SW-NE trending seismic line illustrating a zone of relatively low amplitude contrast at the base of the Zechstein which is located directly underneath a Zechstein salt structure. On either sides of this salt structure, the RMS at the base of the Zechstein shows relatively large amplitude contrasts. The salt structure itself seems to have accommodated compressional movements during the deposition of the Chalk group. This would match with a left stepping of the overall dextral fault-salt system that is visible at the RMS map of the base Zechstein (see map to te lower left).

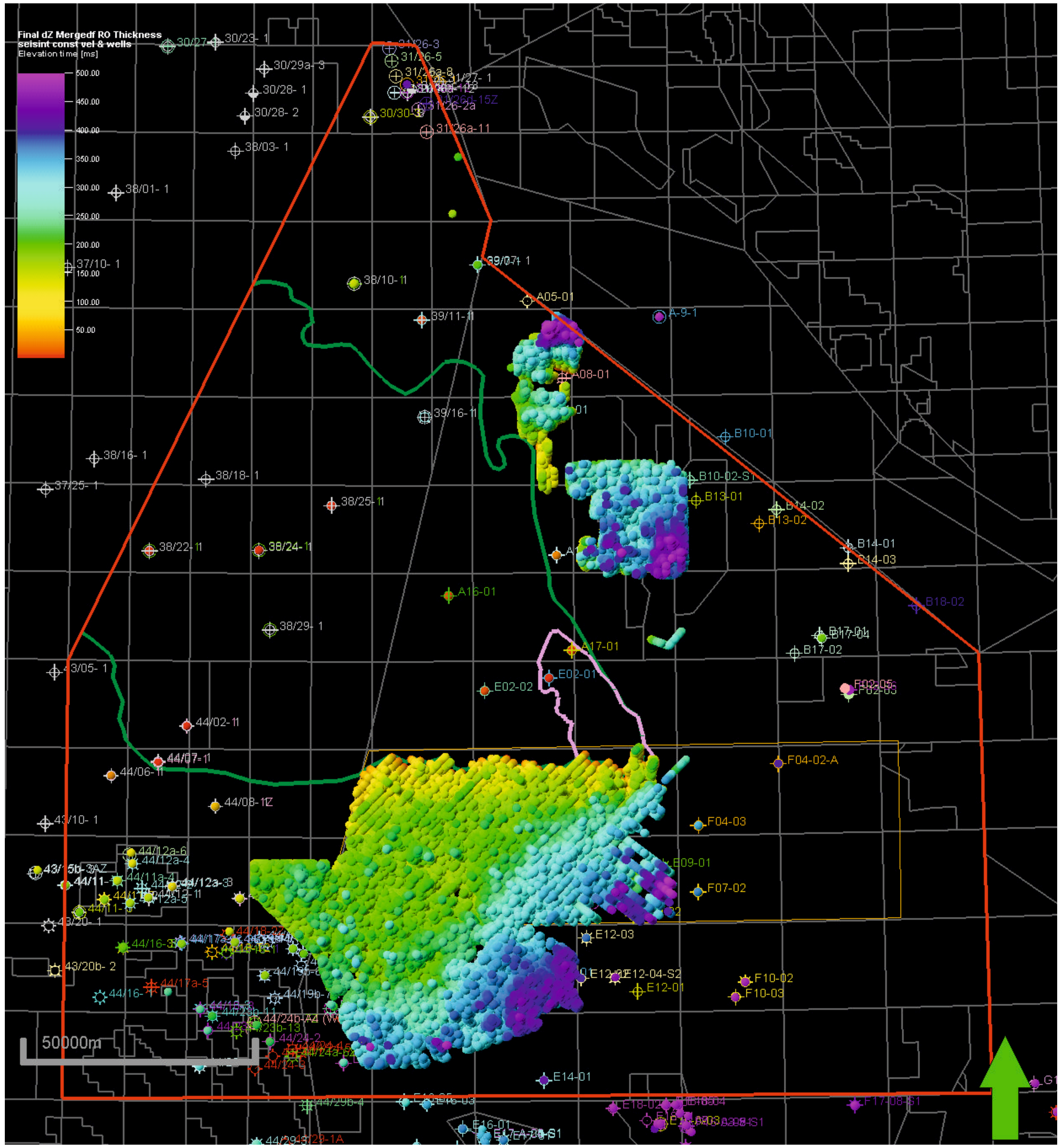
Left: Un-interpreted and interpreted amplitude maps showing the RMS amplitude at the base of the Zechstein for the Tullow survey. A sample window of 7 was chosen for the calculation of the RMS amplitude map, meaning: the root mean square of the amplitude was calculated over a window of 28ms around the base Zechstein (i.e. 14ms above and 14ms below the base Zechstein). Due to the high acoustic impedance contrast at the base of the Zechstein, which mainly arises due to the transition between the Zechstein ZE2 salt and the anhydrite/carbonates of the basal Zechstein, no internal Rotliegend structures are visible at the RMS of the base Zechstein. Clearly visible on the other hand is the structural grain at the base of the Zechstein. The relatively wide (1-3km) zone of low amplitude contrasts trending SSW-NNE, before abruptly taking a SE-NW orientation, arises due to fault-salt structures that overly the base of the Zechstein. Older faults crossing this lineament suggest a dextral sense of motion along this system (indicated by the green arrow). A left stepping of this zone further northeastwards consequently causes a zone of compression, which is mainly affecting the supra salt overburden (illustrated with the seismic line above. Over de whole Tullow survey; four zones of relatively high amplitude contrast can be distinguished (indicated by the purple circles). It is not clear what causes these zones of high amplitude contrast.

Isochore mapping workflow

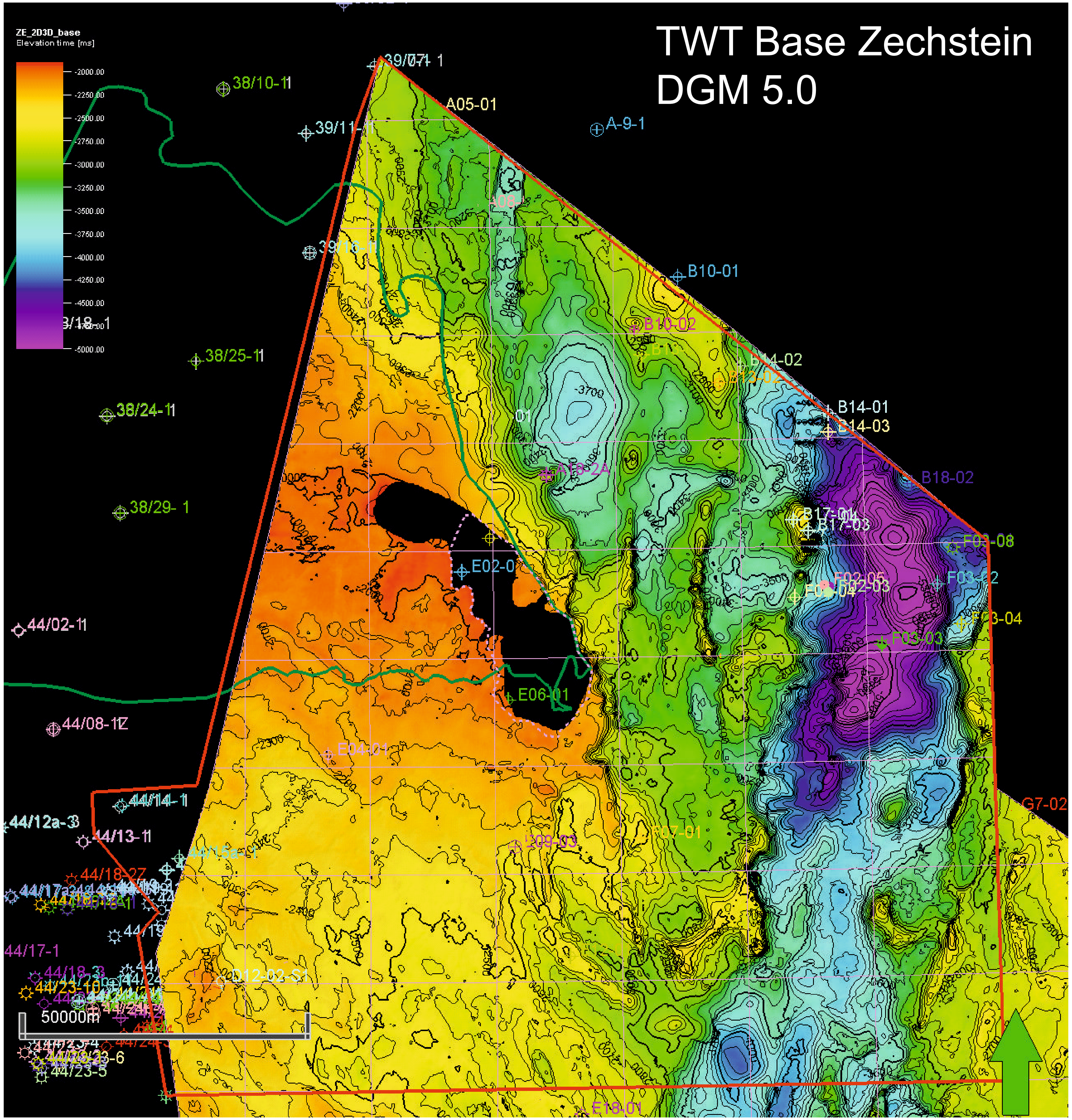
* Well isochores extracted from welltops *Neptune - TNO - NLOG merged top-base Rotliegend** saved as datapoints *Top Rotliegend – BPU**
* Wells A-9-1 and 31/26-1 added. Isochore from 31/26-1 is a minimum thickness, non of the wells in this area reached base Rotliegend. The 31/26-1 has the highest Rotliegend penetration *(Top Rotliegend - BPU (Thickness) incl A-9-1 and 31/26-1*)*
* Seismic datapoints extracted by subtracting TWT BPU from TWT Base Zechstein. This Isochron converted to isochore points by using Vint=4350/ms.
* Seismic isochore points and well isochore points merged *(Final dZ Merged RO Thickness seisint const vel & wells*)*
* Sub-seismic thickness bounded by Green polyline. Inside polygon zero thickness assumed. Polygon used as secondary input for gridding the isochore.
* Isochore map is not tied to wells. If seismic interpretation is present around well there could be a (small) misstie.



Above: Rotliegend Isochore (m) map based on wells only. Well thickness represented by colour of the point.

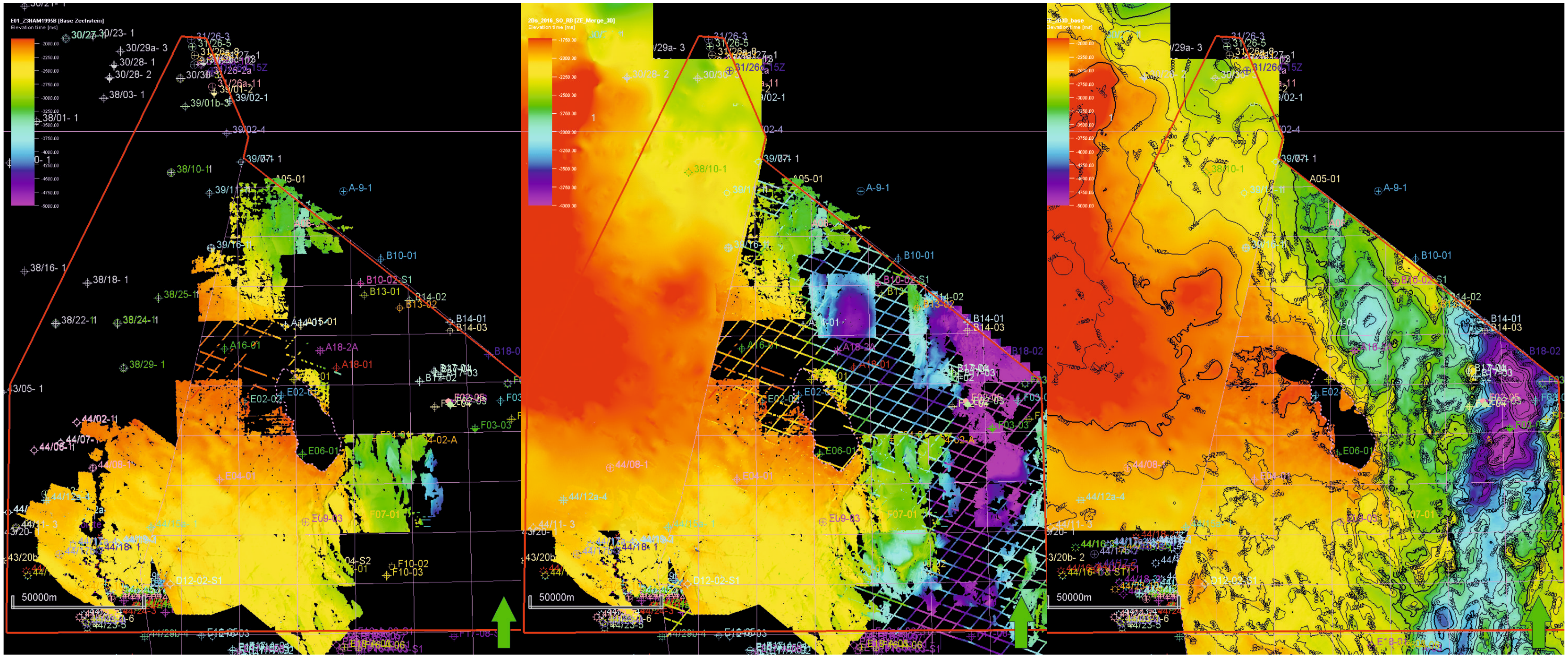


Above: Rotliegend isochore points from wells and seismic, well isochore values are shown as single points. The red polygon is the study area, the green polygon is the area in which Rotliegend thickness is zero or subseismically thin. The pink polygon bounds the area in which the Zechstein is absent.

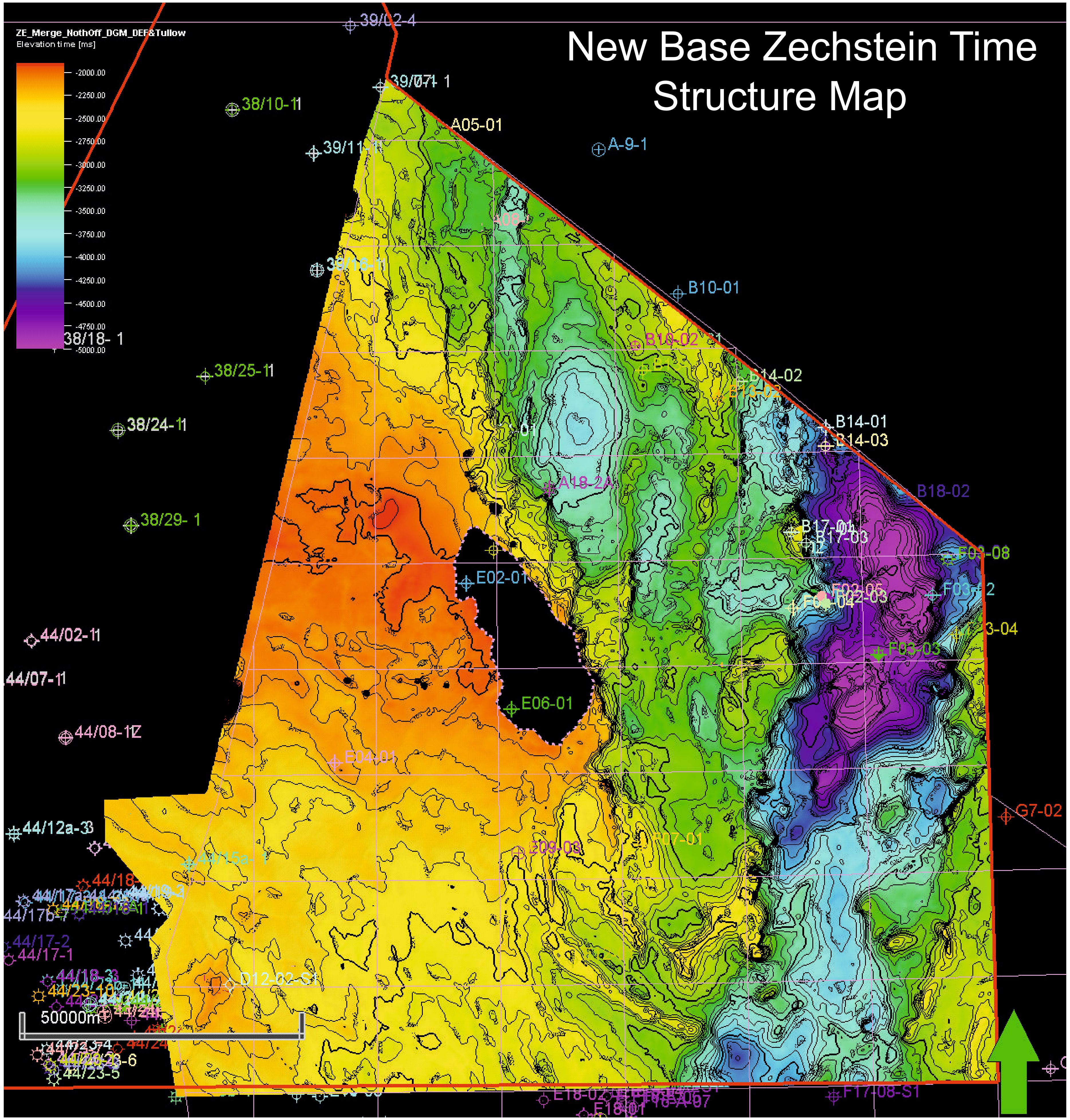


Right: Time structure map of the Base Zechstein (top Rotliegend) as mapped in the DGM 5.0 model of the Geological Survey of the Netherlands.

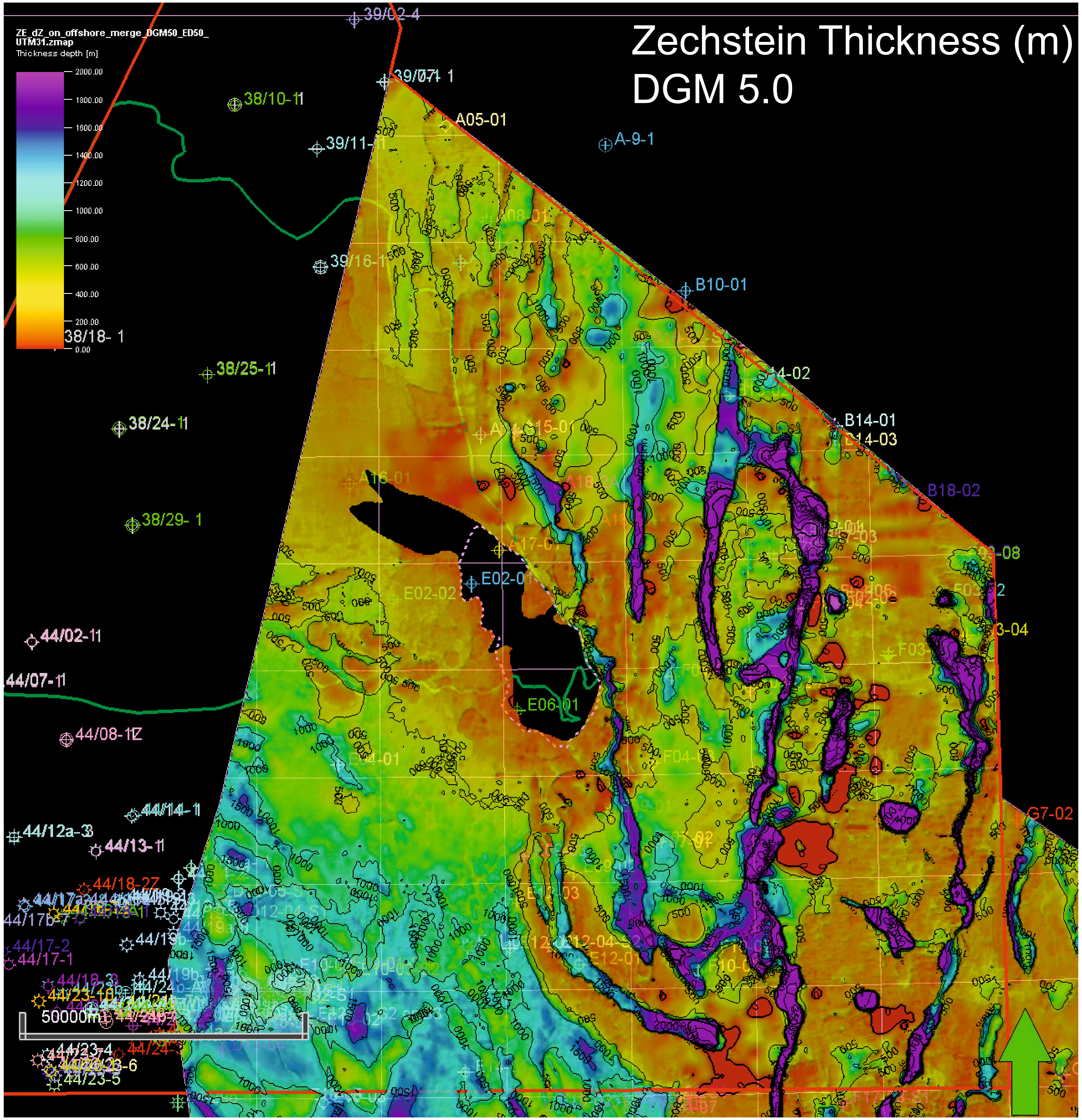
Autotrack this project | Available interpretation | DGM5 and MNSH Heriot Watt



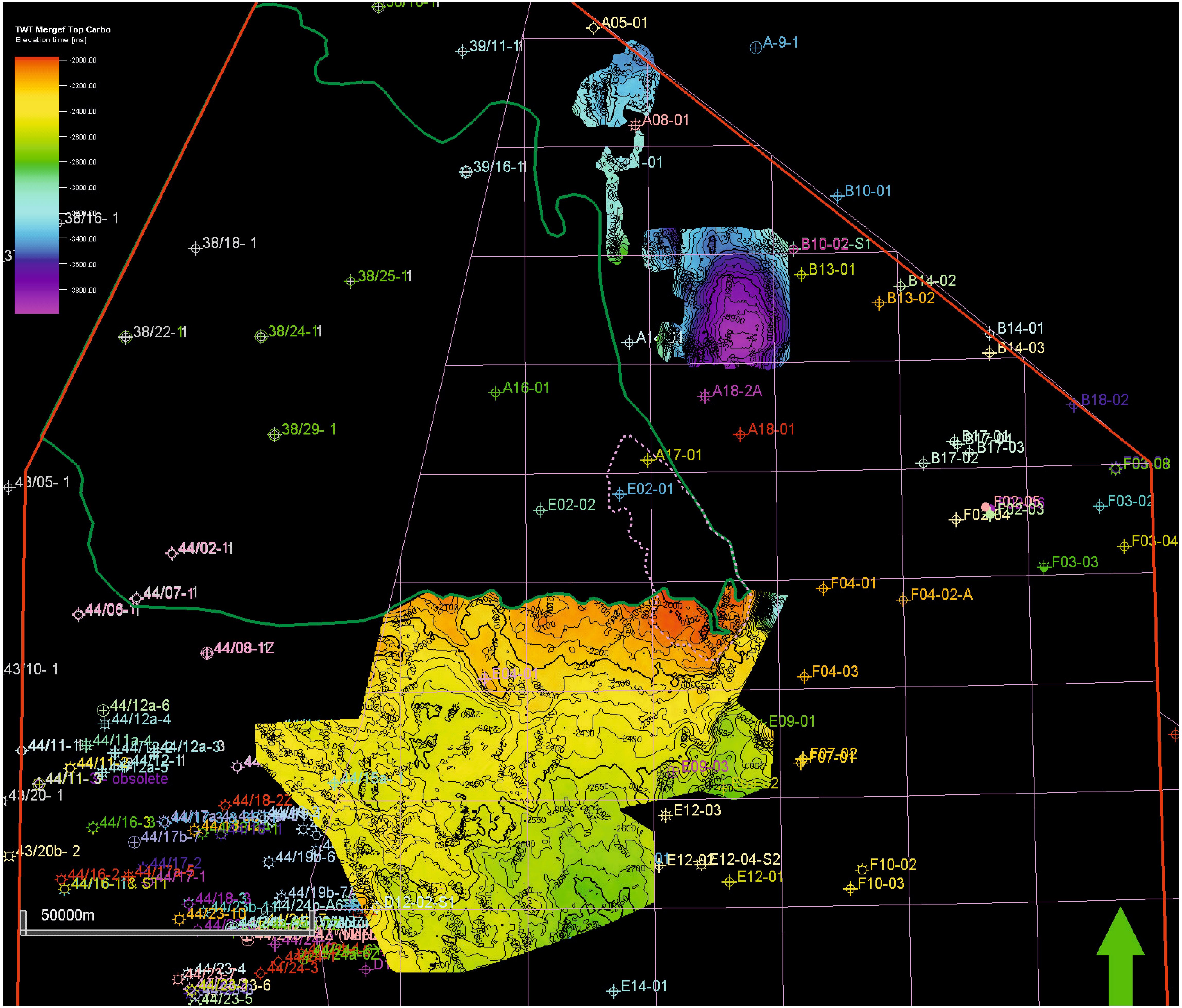
Above: Time depth maps of the Base Zechstein. Left map is the autotracked base Zechstein in this study. The middle map shows the available Base Zechstein interpretation at TNO combined with the TWT map by Heriot Watt university at the UK side. For the map to the the right, the TNO DGM 5.0 model TWT and the Heriot Watt Base Zechstein TWT are combined.



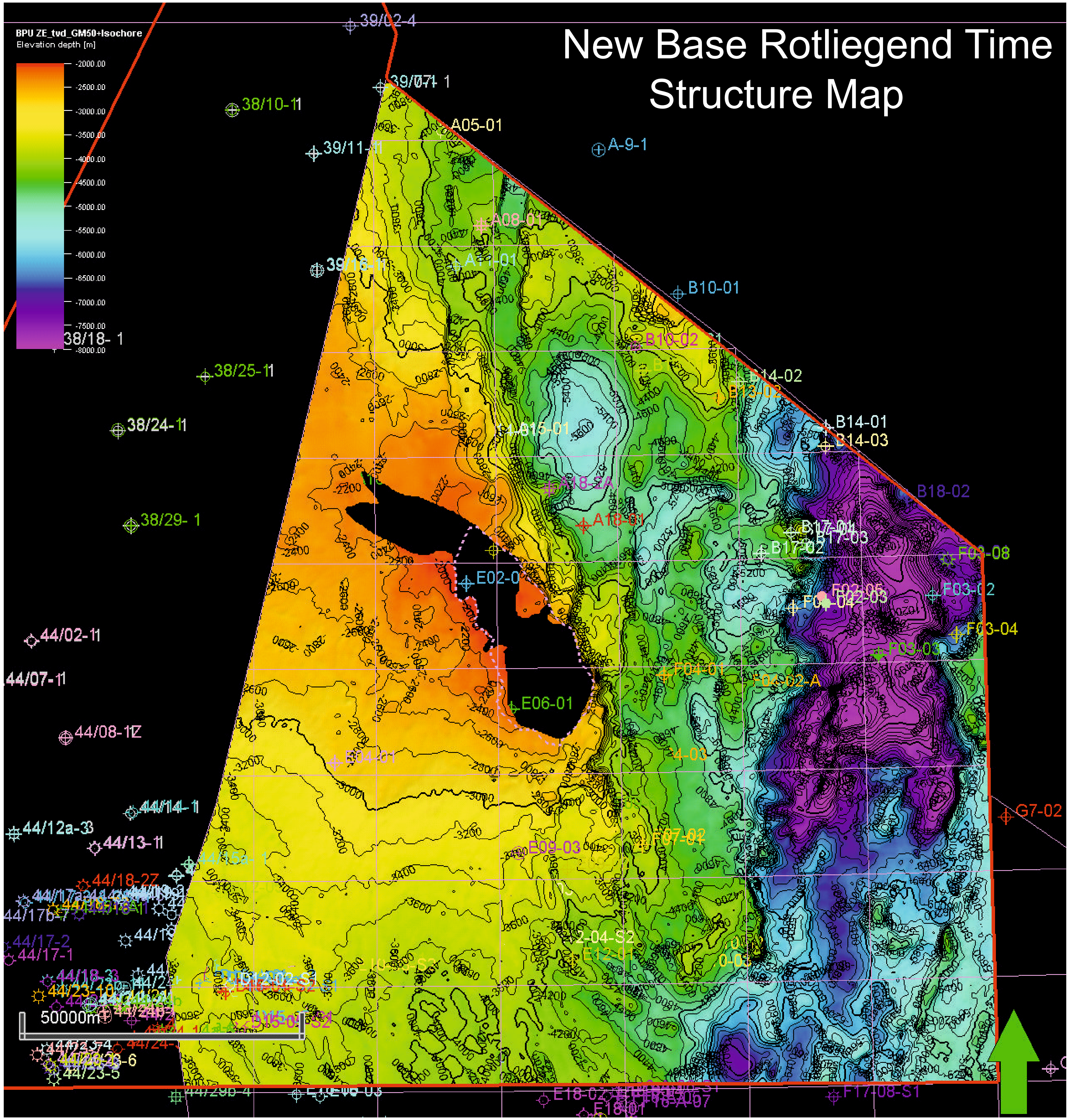
Right: Time structure map of the Base Zechstein (top Rotliegend) using the Base Zechstein autotracked data of the DEF and Tullow surveys complemented by base Zechstein from the DGM 5.0 model on the Mid North Sea High and interpretation of the Northern Offshore project (3D and 2D autotrack and manual interpretation) elsewhere.



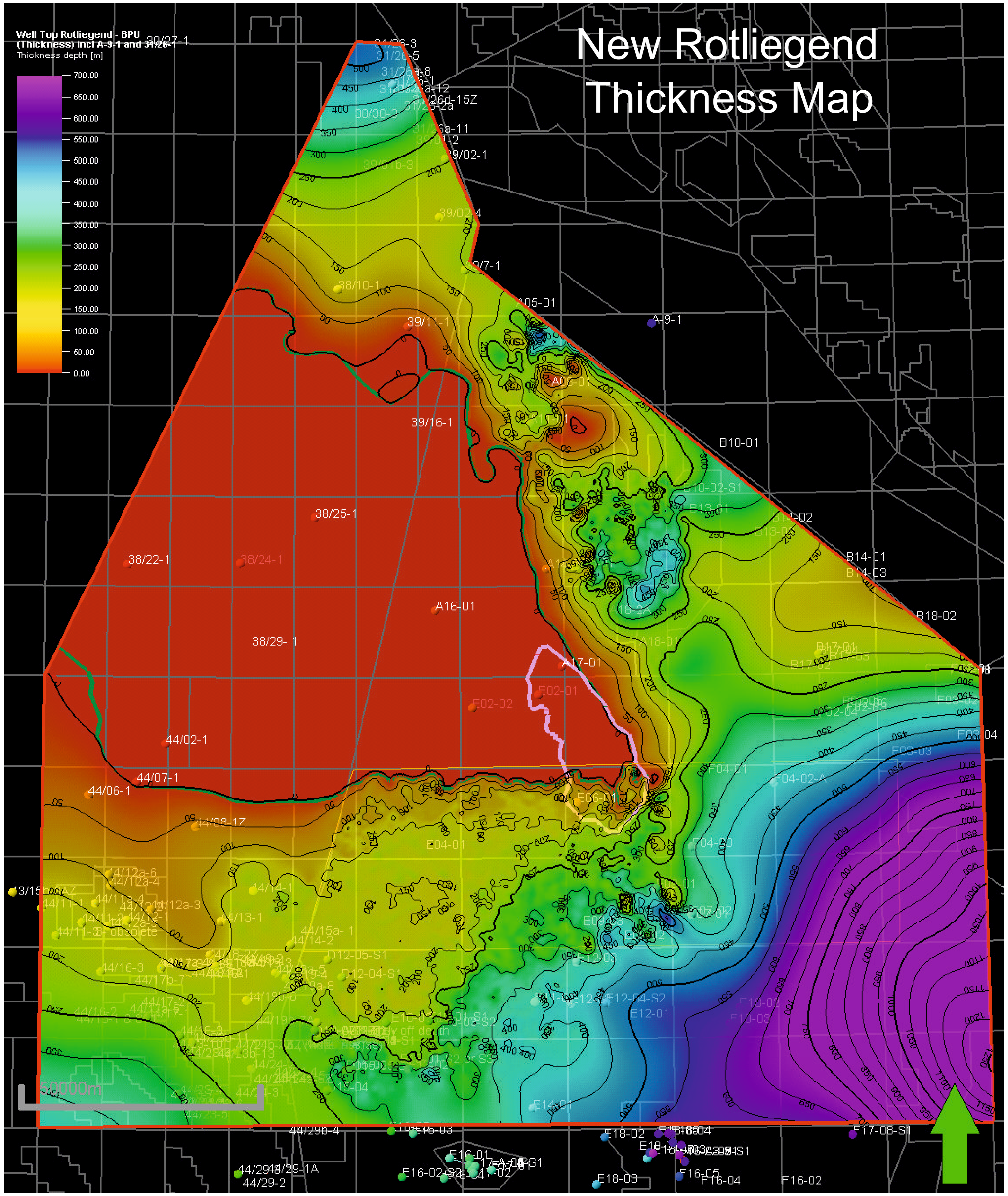
Right: Isochore of the Zechstein Group mapped in the DGM 5.0 model of the Geological Survey of the Netherlands. On the Mid North Sea High the thickness is reduced with Zechstein being absent in the eastern part of the High. Large areas on the Mid North Sea High lack Zechstein Halite and locally Carbonate/Anhydrite build-ups are observed. In the Step- and Central Graben the thickness of the Zechstein is dominated by halokineses resulting in areas where the Zechstein salt has withdrawn and areas where salt has accumulated in salt walls and domes.



Right: Time structure map of the base Rotliegend (BPU). The DEF and Tullow surveys were of sufficient quality to interpret this horizon while in the northern area the horizon could be tracked only locally.

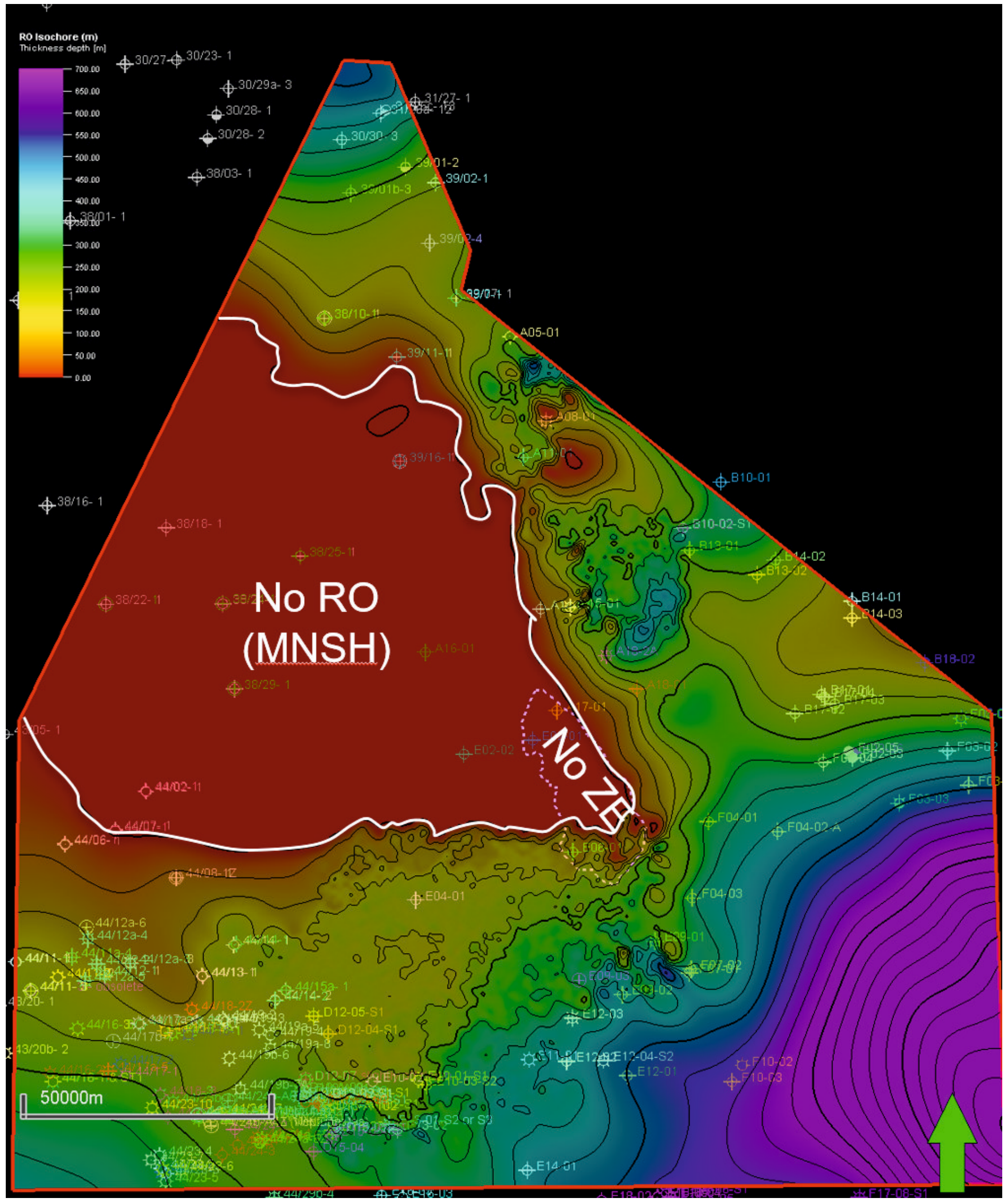


Right: Depth map (m) of the Base Rotliegend (BPU) constructed by adding the Rotliegend Isochore to the depth of the Base Zechstein taken from the DGM 5.0 model of the Geological Survey of the Netherlands



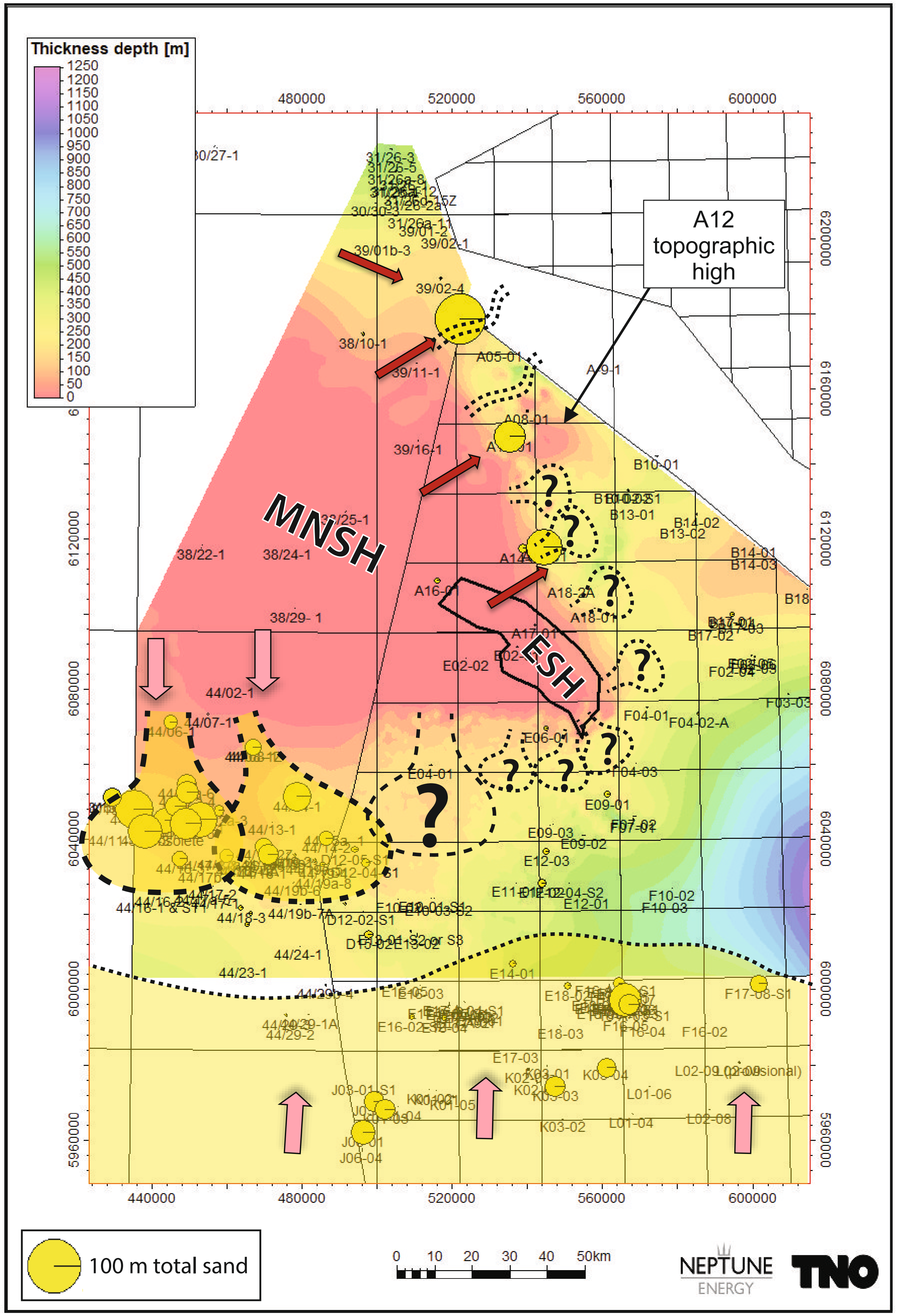
Input for the isochore mapping:

- All RO thicknesses from wells in the study area are used.
- Seismic interpretation in areas where the base RO was interpreted (NL side only).
- ZE2 halite boundary used in the north as RO zero-thickness boundary. This boundary is connected to the UK zero thickness line (from Heriot Watt's recent study). In the south the mapped RO pinch-out line is used.
- Vast area with no (or below seismic resolution) RO extends from NL to UK (Mid North Sea High, MNSH).
- RO gradually thinning northward along the south side the MNSH.
- Gradient of thinning on the east side of MNSH is higher.

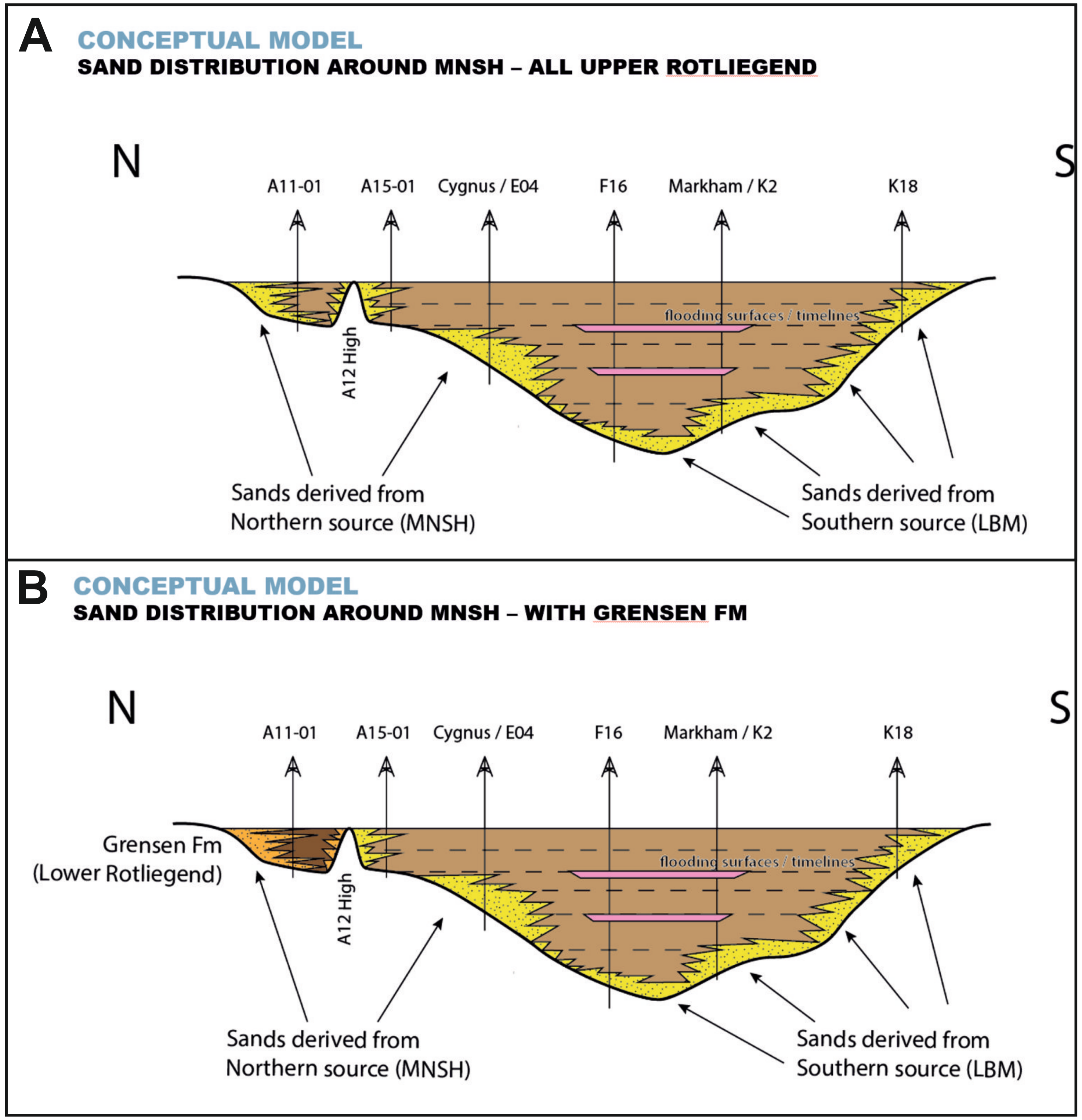


Above: Rotliegend Isochore map (m) based on wells and seismic data, showing the depositional limit of the Rotliegend on the Mid Nort Sea High (that includes the Elbow Spit High)

Left: Rotliegend Isochore map (m) based on wells and seismic data. The seismic TWT thickness is converted to isochore values by using a constant velocity of 4350 m/s.



Left: Conceptual sediment pathway map overlay on the Rot;iegend thickness map



Above: Conceptual models of the Rotlegend in the Dutch offshore. A) In this model the northern part of the Northern Dutch Offshore is composed of Upper Roteligened strat (e.g. A11-01). B) In this model, the nothern part of the Northern Dutch Ofsshore os composed of Lower Rotliegend ((or Gresen Formation, as it is referred in UK). Note that in both models, sandy fringes are likely present around the A12 topographic high.

7. Conclusions and recommendations

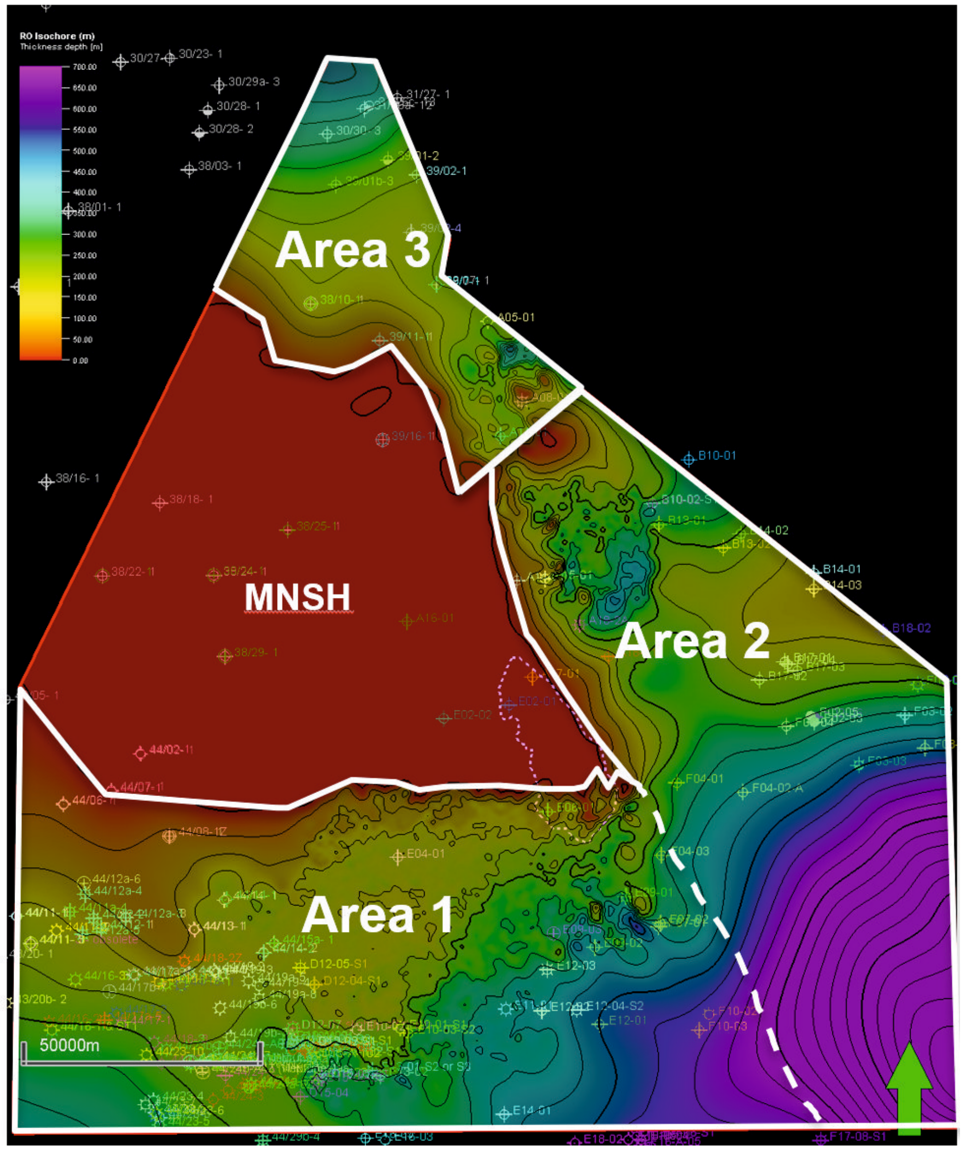
Conclusions

Geographic relationship between presence of ZE2 halite and the distribution of RO is observed, indicating that the paleohighs devoid of RO deposition were later the focus of ZE carbonate build-ups. This result shows that detailed mapping of the Zechstein Group can be used as proxy for RO distribution trends.

Three distinctive areas are defined:

- **Area 1:** South of the MNSH, resembles the Cygnus configuration with RO thinning and onlapping gently northward onto an E-W oriented basin margin. Some incisions in the SE corner of the MNSH indicate confined settings and possible sediment pathways through canyons/incised valley systems.
- **Area 2:** East of the MNSH, RO thins rapidly onto the western basin margin. Sand distribution is likely narrow, yet possibly thick, along the western basin margin.
- **Area 3:** Northeast of the MNSH, connecting with the UK, NO sectors, the Rotliegend is likely older, overall sandier and genetically related to the Grensen Formation (Pre-Saalian unconformity, Lower Rotliegend). This fluvial sequence contains good sands and is considered the primary reservoir sand in this region.
- Areas 2 and 3 separated by a paleo high located in Blocks A08/A11.

The presence of sandy strata around the MNSH was not directly demonstrated due to limitations in seismic response. Yet, RO thickness trends and deduced paleotopographic features identified around the MNSH (onlap, gentle vs rapid thinning and local conduits) indicate probable sandy inputs around the MNSH.



Recommendations for future work

1) Well-based approaches

Have a new look at the volcanic rocks (cuttings, cores) around the Elbow Spit High by volcanic experts to determine

- Whether they are intrusive or extrusive;
- Their age;
- Their composition (for provenance and / or age)

A more extensive petrophysical study aimed at the lithological composition of the Rotliegend sands around the ESH might provide the answer as to whether they are Lower or Upper Rotliegend in age

Provenance studies on cores and cuttings to, potentially, obtain more criteria for distinguishing RV from RO
Add more information from the German Sector (e.g. A5) to better understand the relationship between RV and RO regionally.

2) Seismic-based approaches

Reprocessing of the existing 3D (and 2D) surveys in the NE part of the study area making use of recent multiple and noise elimination and imaging techniques to achieve more reliable, and extensive seismic interpretation of the BPU. Ultimately new seismic data acquisition could be necessary to achieve data quality good enough to image (gas filled) sandy units, like in the Cygnus field.

To interpret intra-Carboniferous intervals on the DEF and Tullow surveys. Data quality of these surveys is sufficient to distinguish between high reflective intervals and low reflective intervals. Subcrop mapping will help to understand the seismic signal of the BPU and understand which amplitude trends at BPU level are coinciding with changing subcrop. For example, what is the exact relationship between the location of subcropping Carbonate intervals of the Yoredale Formation and the local depo-thicks of the Rotliegend? In the other 3D datasets seismic imaging is probably not good enough to achieve a reliable intra-Carboniferous interpretation. Here reprocessing should be attempted first.

Map out the incisional features in the E06 block in more detail (preferably each line) and extract and analyse amplitudes along the BPU to get a better grip on the exact geometry of these features and their origin. Underlying Carboniferous faults should also be mapped to study a potential relation to tectonic structures.

Make a synthetic seismic model of a 2D section, filling the Carboniferous and Rotliegend with properties making use of the properties measured in (a) well(s) that lie on the section. Study the amplitude behavior along BPU by varying the properties in the lower part of the Rotliegend (lithology, porosity, fluid fill, layer thickness).

7. References

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