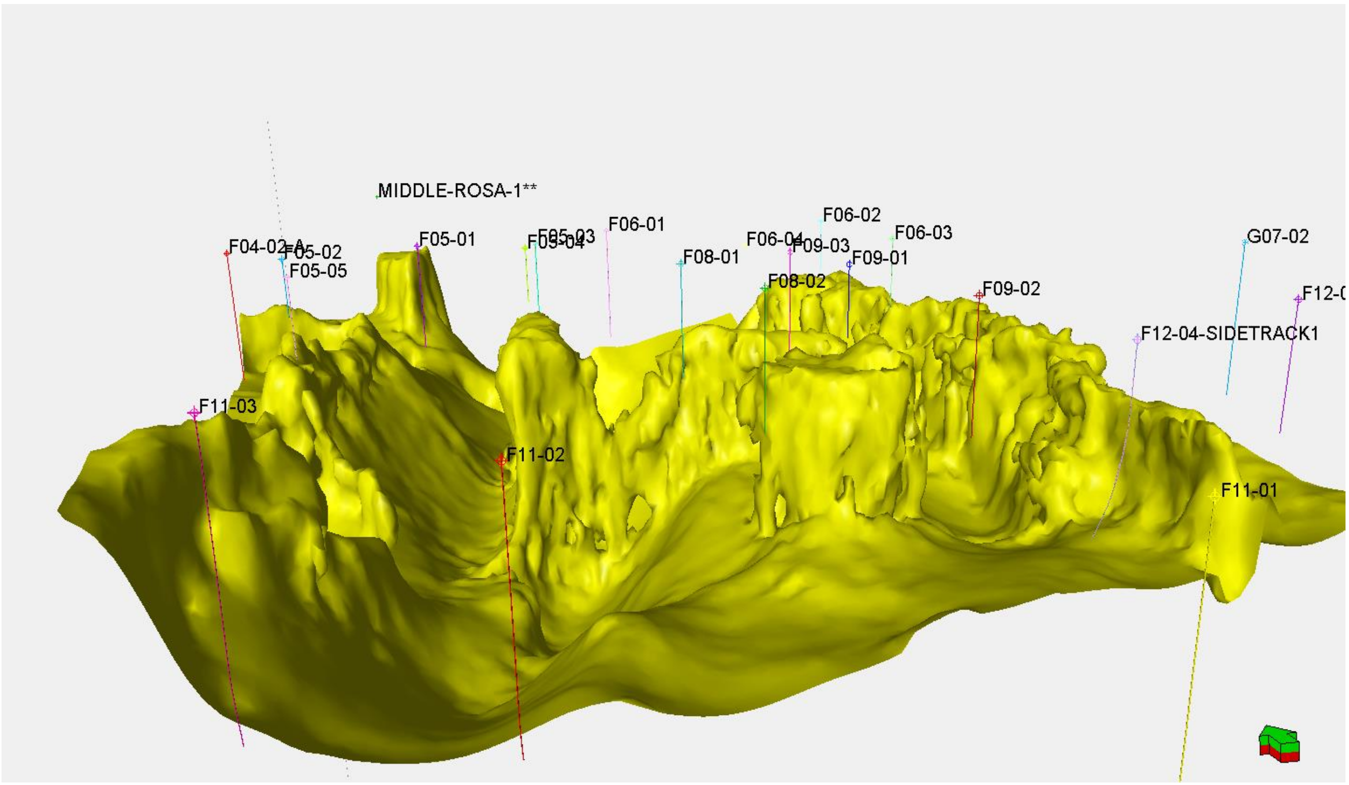
3-D restoration of the Dutch Central Graben

Predicting prospects in the Chalk plays



Universiteit Utrecht

Folkert van Straaten

Supervisors: Bastiaan Jaarsma (EBN)

Hans de Bresser (UU)

1-4-2016

Contents

Abstract

Chalk structures in the Central Graben of the North Sea Basin were deformed by halokinesis. Halokinesis in the North Sea Basin has been studied over decades, but remains poorly understood. Halokinesis is known to have affected several aspects of hydrocarbon plays in the Central Graben: by affecting the maturity of the source rock, influencing the migration paths of hydrocarbons, and affecting trap formation. Therefore, a detailed understanding of how the salt flow has affected its overburden is crucial for successful hydrocarbon exploration and a better understanding of the halokinesis, can potentially result in an increase in success rate of the exploration of the petroleum plays in this part of the world.

Structural restoration is a technique that provides inside in the deformation history of an area. Already many 2-D sections across the North Sea Basin were restored to give inside in the deformation history. However, an area affected by halokinesis and also having a complex structural character, cannot be restored in two dimensions without violating the main assumption; that is no volume is moving in and out of the plane of section. Therefore in this study a 3-D restoration is made, so volume is preserved while restoring the area.

In this study the area is restored till the Early-Cretaceous because of two reasons: first more details (more horizons, smaller geological events) can be included in the restoration, second the most important plays in this area are the Chalk plays which were formed during the Late Cretaceous. By restoring the area till the Cretaceous, the deformation of several horizons through time was visualized. Based on these results, an analysis of the hydrocarbon generation, migration and trapping was performed. It was assumed that the Posidonia Shale is the source rock for the hydrocarbons in the area. The hydrocarbons migrated, through the Middle Graben formation, until they spilled into the Chalk members (Maastrichtian and Danian). In these members the hydrocarbons were trapped. Using this model an analysis was made where the hydrocarbons could possibly be trapped. This was tested against well data.

1. Introduction

Chalk structures in the F-blocks in the Dutch Central Graben drilled so far were formed by Zechstein salt halokinesis. Drilling results varied ranging from dry wells to wells with oil shows, to gas shows (F09-01) to oil discoveries. The impact of burial and (salt) tectonics might explain the differences in drilling results. Also, shallow gas is found at some locations above the salt diapirs. This might indicate relative recent leakage to the surface, as a result of recent salt tectonics. However, halokinesis in the North Sea Basin is relatively poorly understood. In this study a 3-D structural restoration of the F5, F6, F8, and F9 blocks in the Dutch Central Graben will be presented. By restoring this area till the Cretaceous times, a better and more detailed understanding of the tectonic history will be provided. As will be shown afterwards, the restoration will provide a powerful tool to understand migration of hydrocarbons and trap formation of the Chalk plays in this area.

Section balancing is a powerful method to understand the evolution of salt structures and their interplay with surrounding sediments through time. Already a 2-D structural restoration is made by Van Winden, 2015. In his regional study many salt structures were identified and mapped using new 3D seismic data. By afterwards restoring a 2-D section he showed a general tectonic evolution, and the importance of halokinesis in this area from Triassic till Present. It is however, well known that halokinesis is a 3-D process, and in this area faults are orientated in practically every direction. So the key assumption of 2-D restoration (no volume moves in and out of plane) does not hold in a tectonically complex area like the Dutch Central Graben. Therefore, in this study a 3-D restoration will be presented. Since the main objectives are to understand the occurrence of shallow gas, and the prospectivity of the Chalk plays, the restoration will focus on post-Jurassic deformation. By focusing on the Cenozoic-Late Mesozoic history, smaller geological events can be incorporated in the restoration model, to get an accurate result of the tectonic history in the area. In this study Pleistocene glaciation, the prograding Eridanos Delta, several Cenozoic and Mesozoic erosion events are all incorporated in the restoration. Also, a detailed rock property model and relative sea-level changes are included in the model.

Two restorations were made, one with minimum erosion, another with maximum erosion. The restorations included 22 time frames of all horizons used in the model. So at every time step, the exact restored geometry of a layer could be investigated. This provided a powerful tool to understand hydrocarbon maturity and migration and trap formation.

2. Previous research

2.1 Geologic Setting

Rifting of the Dutch Central Graben was initiated in the Late Carboniferous (Cartwright, 1989). In the Middle to Late Permian, Zechstein salt was deposited that would later act as a decollement layer in the basin. During the Permo-Triassic times, moderate rifting was initiated whereby sedimentation matched the subsidence rates. Rapid subsidence started in the middle-late Jurassic, resulting in rotation of half-grabens along WNW- and NE-trending faults. During this phase up to 5000m of shale was deposited (Wijhe, 1986). This phase ended at the start of the Cretaceous. The rifting did not entirely cease, but continued at a slower pace (smaller offset of faults) and had a more regional character. During the Middle-Late Cretaceous Chalk was deposited. Short episodes of inversion affected the region, whereby salt halokinesis became (re)active and older Jurassic faults were inverted. Shortening in the area was limited ~1km and minor NW-SE oriented folds developed. The thickness of the Chalk is therefore not heterogeneous (Van der Voet, 2015), but affected by patterns in regional subsidence, sin-depositional deformation and redistribution of allochthonous Chalks (by slumping).
During the Paleogene pulses of inversion occurred (De Jager, 2003; De Lugt et al., 2003). The siliciclastic input increased and the area became a shallow marine environment (Benvenutti et al., 2012). A shelf delta system developed, prograding towards the SW. During the mid-Miocene, a pulse of uplift resulted in an unconformity called the MMU. The amount of erosion during this event is still debated (Huuse et al., 2001). After the mid-Miocene a delta system developed called the Eridanos Delta, draining the Fennoscandian and Baltic areas. In this study area the Eridanos delta prograded towards the S-SW

2.2 Previous restorations in the North Sea Area

Salt has a lower density than other rock formations in the North Sea, therefore it has the tendency to migrate to the surface (so called halokinesis). Besides salt is a very ductile rock type, therefore (small) tectonic stresses will result in salt flow to places with the least resistance (Harding and Huuse, 2015). There is still debate about the exact mechanism which triggers halokinesis. Halokinesis can be triggered in two ways either by differential loading, or by reduced overburden.

The Zechstein salt migrated upwards in several pulses (Harding and Huuse, 2015). An early phase occurred during the Triassic, where salt migrated upwards and formed non-piercing pillows. The diapirism was probably reactive, in response to Triassic faulting. Active diapirism started in the late Jurassic, when salt diapirs pierced the Jurassic strata and no or less sediments were deposited on top of the diapirs. The active diapirism probably started as a result of differential loading by extensional faulting. In the Early Cretaceous the diapirism ceased and sediments filled the rim-synclines (Wijhe, 1986). In the Late Cretaceous diapirism became active again, as indicated by slumps in the Chalk groups (Van der Voet, 2015) and thickening in the rim-synclines (Van Winden, 2015). This new stage of halokinesis is related to inversion events, reducing the overburden. Since salt related (conical) faults almost reach the surface, halokinesis has not ceased in the Tertiary, but continued until present (Harding and Huuse, 2015; Wijhe, 1986).

Previous restorations of areas in the North Sea Basin were made by other researchers. Most of these restorations were 2-D restorations of sections (e.g. Buchanan et al., 1996; Cartwright et al., 2001). Buchanan et al., 1996 made a restoration of a section through the Central Graben, north of the area in this study. In his restoration, the Zechstein salt did not increase in thickness, nor changed much in shape until Jurassic. The restoration of Buchanan et al., 1996 also shows that salt did not reach the surface at any point in time. They therefore assumed that no salt was dissolved, although as stated, it is not possible to determine if salt has dissolved in the Jurassic-Triassic. Instead, they propose a model where salt diapirs on the platforms were not formed by vertical movement of salt, but rather by lateral stretching and thinning of salt, creating “pseudo” diapirs.

Cartwright et al., 2001 made a restoration of the Forth Approaches Basin in the North Sea. In that area it appears that salt had dissolved from the top of the diapirs. Rather than the classical Trusheim’s Model for halokinesis, they favor a model where salt dissolves from the top of the diapirs and is replenished by salt in the mini basins. In this model it is not the diapir that rises to the surface, but the space in between the diapirs subsides due to salt withdrawal towards the dissolving diapirs. Cartwright et al., 2001 estimated that up to 40% volume of salt may have been dissolved in the Forth Approaches Basin. Also Hossack, 1995 found very high (50%) salt dissolution volumes in the Gulf of Mexico, indicating that salt dissolution is a global phenomenon. These two papers address the problem of the precise dating of salt dissolution. Both however, state that it seems most likely that salt dissolves when the diapir is close to the surface and comes into contact with ground water (e.g. Late Cretaceous).

To determine the dissolution of salt in diapirs, present day analogue examples can be used. It appears that estimated dissolution rates of salt diapirs vary widely worldwide. Faster dissolution rates of diapirs can be expected, if the salt extrudes to the surface where it comes into contact with meteoric water. Also a compressional stress regime increases the dissolution rate. A compressional stress regime, pushes the salt upwards, so it comes into contact with meteoric water. Only for a few diapirs the dissolution has been determined. The bedded Salado Salt in Texas dissolves with a rate of 1mm/KY (Anderson, 1981). The salt diapir in the Orca Basin dissolves with 10m/KY (Pilcher & Blumstein, 2007), whereas the Hormuz glacier in Iran dissolves with 46m per 1000 years (Talbot and Jarvis, 1984).
Geluk & Wildenborg, 1988 estimate the Quaternary dissolution of salt diapirs in the Netherlands to be 0.15mm/y, which is quite low compared to the worldwide values of salt dissolution.

Van Winden, 2015 made 2-D cross sections in the A,B,F,G blocks, focusing on salt structures in the Dutch Central Graben, Step Graben and the adjacent highs. His study provided a detailed understanding of the different phases of diapirism in this area, by analyzing ~30 salt structures and restoring a regional section till Early Triassic. He also made a first step in analyzing the impact of halokinesis on the overburden. However, since his work covered a large area, his 2-D restorations included only major geological events, and smaller events were neglected.

2.3 The effect of glaciations on substrata

Glaciations might have an effect on halokinesis in the North Sea area (Lang et al., 2014). The ice caps would have resulted in increased burial of their substrata and created differential loading. This might have resulted in reactivating halokinesis. Lang et al., 2014 modelled the effect of an advancing ice sheet over a salt diapir in northern Germany. They modeled the vertical displacement directly above a diapir. In this finite element model parameters such as the thickness of the ice sheets, the viscosity, thickness of the salt layer, the height of the diapir and duration of the glaciation were varied to investigate their effect on the vertical movement of a diapir. Their models showed that a diapir rises once an ice cap is approaching (salt is pushed away under the ice cap into the diapir). However, if an ice cap covers a diapir salt will be pushed out of the diapir again. The most sensitive parameter for this effect is the ice cap thickness. An ice cap of 1000 meters thick will push the diapir down as much as 35 meters. After the glaciation, the salt moves back into the diapir so that the net displacement is ~ -4m. Lang et al., 2004 therefore concluded that the effect of ice caps on halokinesis is overestimated. A larger effect can be expected from the prograding Eridanos delta during the Tertiary (Cohen and Hardy, 1996; Gemmer et al., 2004, 2005; Albertz et al., 2010), because the additional overburden of an ice sheet is short lived, compared to a sedimentary wedge. In the model of Lang et al., 2014 however, no compaction is taken into account. Therefore it remains unclear, how the shape of the diapir will change due to overlying ice caps, or how the overlying strata will deform during glaciations.
Another study (Grondboor en Hamer, 2010) has quantified the vertical displacement of the overlying strata during the Quaternary. It appeared that in the Netherlands the vertical movement above salt diapirs as a result of ice sheet loading was roughly 0.2mm/y, and in Germany it was 0.3 mm/y. This means that during the Ice Ages which lasted ~100.000 years, the surface was potentially uplifted by 20-30 meters.

The study area (F5, 6, 8, and 9) was covered by an ice cap during only one glaciation called the Elsterian which lasted from 478,000- 424,000 y.a. (De Gans, 2007), see also Fig. 1. The thickness of the ice caps covering the study area during this time remains uncertain. The best estimate of the ice thickness is to use modern-day ice cap profiles (Jan Piotrowski, personal correspondence). Since the outer extent of the Elsterian ice cap is known (De Gans, 2007), the thickness of the ice can be calculated. The profile of an ice cap is captured in the following formula (Nye, 1952):

$$h = \sqrt{2} h_0 s$$

$$h_0 = \frac{\tau}{\rho g}$$

Value of basal shear stress (τ) is between 50-150 kPa (also for Pleistocene glaciers (Clark, 1967; Mathews, 1967). The density of ice (ρ) is 917kg/m3. The gravitational constant (g) is 9.81, so H0 ~11m (between 5.6m-16.7m). The distance from the ice cap boundary (S) is ~150km in Elsterian (De Gans, 2007).
So the thickness of the ice sheet is between 1296-2238 meters thick at the location where the restoration is made. Since topographic relief decreases the expected thickness of an ice-sheet due to reduced basal shear (Nye, 1952), 1500m is taken as an estimate of the ice sheet thickness in the study are during the Elsterian.

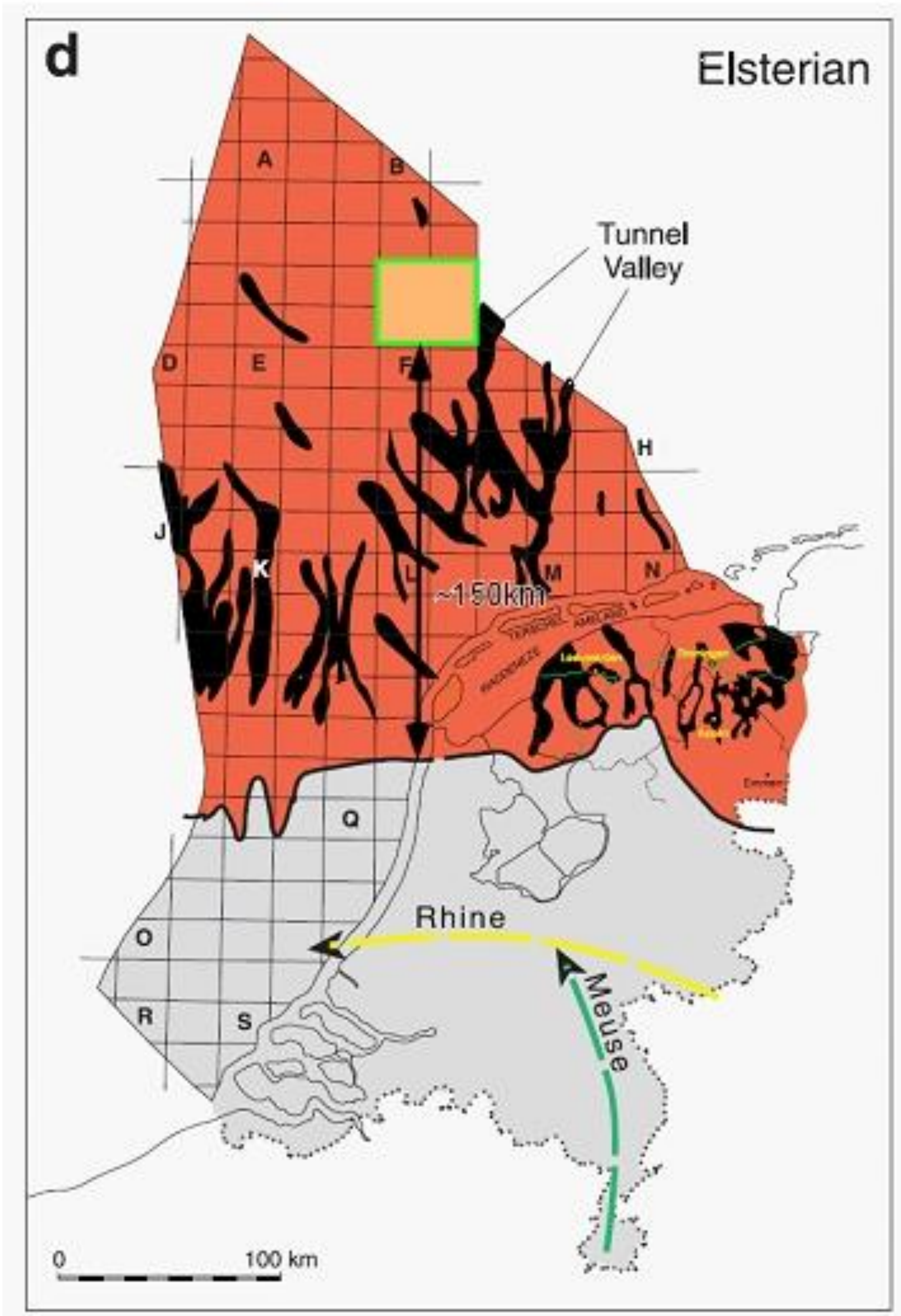


Figure 1: Extent of the ice sheet during the Elsterian. In red is the extent of the ice sheet covering the present day Dutch on- and offshore areas, in green the outline of the study area is shown. As can be seen in this picture, the study area (F-blocks) are entirely covered by ice during the Elsterian. Picture modified from de Gans, 2007

3. Methods

3.1 Interpretation of Horizons & Faults

Top Zechstein interpreted in Multi-Z

Previous interpretations of salt domes were available at EBN as “normal, single-z grids”. Typically however, salt structures broaden at their top, when they grow vertically and therefore have multiple points in depth at each location, the so called multi-z character. Therefore, it is chosen to re-interpret the salt structures, using the multi-z tool in Petrel (see also Appendix 1). The interpreted density varies, ranging from 5-15 increments. At locations where no salt structures exist and the salt lies horizontal, an already existing and accurate single-z interpretation is used for these areas and no new interpretation is made there.

The two interpretations need to be joined together to make one horizon. To make sure that no overlap exists in the joined interpretation, polygons are drawn around the salt structures. By eliminating the multi-z interpretation outside the polygons and eliminating the single-z interpretation inside the horizons, no overlaps exists in the two interpretations. Next the old single-z interpretation is appended to the multi-z interpretation, so that one joined interpretation is created. When appending surfaces to multi-z, it is possible that some of the “normals” point in the wrong direction. Therefore “QC-normals” was performed to see if all the normals had the right orientation. The multi-z interpretation was then converted to depth using an existing velocity model (Eikelenboom, summer 2015, modified from Velmod2 (Dalfsen et al., 2007)). Next, the seismic cube needed to be depth converted, before a triangle mesh could be generated. The depth converted seismic cube was used as an input in the Triangle mesh. The triangular mesh is created in a mixed mode, with a coarsening factor of 8. The mixed mode is essential since the appended surface are densely interpreted, but the salt structures are coarsely interpreted. The result is shown below. Finally, the triangular mesh was simplified using the beautification tool in Petrel (z=1), and smoothed afterwards. The result is shown below.

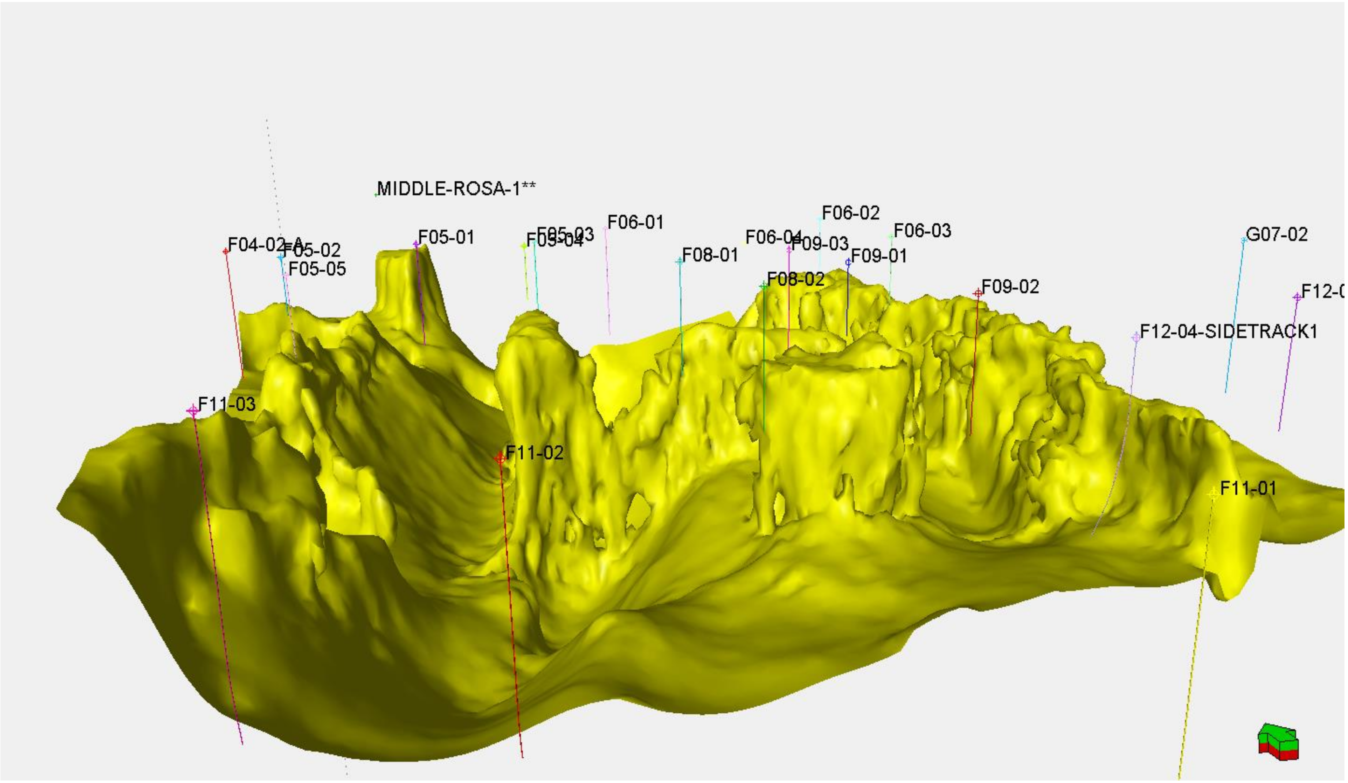


Figure 2: 3-D view of top Zechstein as mapped in the study area. Also indicated are the wells.

Chalk Horizons

Three boundaries in the Chalk were used: the Top Camanian was used for the oldest Chalk units (Campanian, Santonian, Coniacian, and Turonian), the top Maastrichtian was used to separate the Maastrichtian into one single unit, and the Danian forms the third unit, where the Base Lower North Sea Group forms the Top Danian. These boundaries were chosen based on erosion events (Van der Voet & Heijnen, personal correspondence). The interpretations of Van Der Voet, 2015 of these horizons were checked. In her interpretation, the horizon separating the Maastrichtian and Danian (Top Maastrichtian), is often absent, indicating that no Danian Chalk is present at these locations. Since in MOVE this will be interpreted as a very thick Danian succession, the Top Maastrichtian needed to be extended parallel and slightly below the Base Lower North Sea.

In the north-eastern corner, Maastrichtian was interpreted in the study of Van Der Voet, 2015. Since these strata were southward continuous, without unconformities or faults, the interpretation of Van der Voet was extended southward (roughly till the boundary between the F6 and F9 block). The same method was used to extend the top Campanian. Top Campanian was interpreted by Van Der Voet in the south-eastern corner of the study area. Since the horizons are continuous towards the north and west, the interpretation was extended.

Eridanos Delta

A study of TNO (Verweij et al., 2012), showed the system tracts of the Eridanos Delta; high stands, low stands, transgressive and falling systems tracts. In their study, they used the nomenclature of Kuhlmann and Wong, 2006, to differentiate between the system tracts. In this study not all systems tracts from the TNO study are used; only the thicker units which are also present in the DCG will be included. The systems tracts that are used, are summarized below including their ages. The ages of TST4 and S11 are unknown therefore the average ages of the underlying and overlying strata were as ages for these systems tracts. The systems tracts were not edited, but were directly incorporated as surfaces in the model.

Name	TNO nomenclature	Age (Ma)
TST 3	S4	2.58
TST4	S5I	*2.51*
HST4	S5K	2.44
HST5	S6	2.16
S11	S11	*1.98*
S13	S13	1.8

Table 1: System Tracts and their ages. The ages of TST4 and S11 are unknown.

Additional Horizons

The amount of compaction that can occur in a certain time frame, depends among other aspects on the lithologies of the (overlying) strata. To model this accurate, extra horizons were incorporated in the model. These include: Mid Miocene unconformity (MMU), Base North Sea Group, Base Chalk, Base Cretaceous, Base Schieland, Base Jurassic, and Base Zechstein. These horizons were not interpreted in this study, but were copied from the EBN database. Some of these horizons were not continuous. E.g. the Base Cretaceous had not been interpreted if the Lower Cretaceous was absent. In MOVE, this would result in a too thick Lower Cretaceous layer (the Schieland Group would be absent as Move would recognize it as Lower Cretaceous). To prevent this, the horizons were therefore extended a bit, so that they were continuous through my study area. This resulted in stratigraphic layer that are present over the entire area, but at some locations had a zero thickness.

Ice Caps

The ice sheet is assumed to be 1500 meters thick, which is the average of the determined ice thickness (between 775m and 2335 meters). The compaction of strata is time dependent, this is included in the model. The ice sheets are assumed to have been overlying the strata for 10-20 ky. The ice sheets are moving slowly from the north to the south (75-150 m/a), therefore it lasted ~400 year to cover the 30 km long section. To include this in the model, an extra horizon was made extending only halfway to the section. The underlying strata were first compacted using the half extended ice sheet and afterwards compacted using the fully extended ice sheet, implying that the retreat of the ice sheet lasted long and the approach lasted neglectable short. The snout of the ice sheet was incorporated (the ice sheet does decrease in thickness towards the south). A random N-S section of the model with all the horizons as modelled in MOVE is shown in Fig. 4.

Faults

Multiple faults offset the strata in the DCG. Faults with an offset larger than 50m and a length larger than 1 km were interpreted. These faults were divided by their age (i.e. the youngest horizon they off-set). The interpreted faults were converted in a structural framework, so that they could be exported into move. The results are shown in Fig. 3.

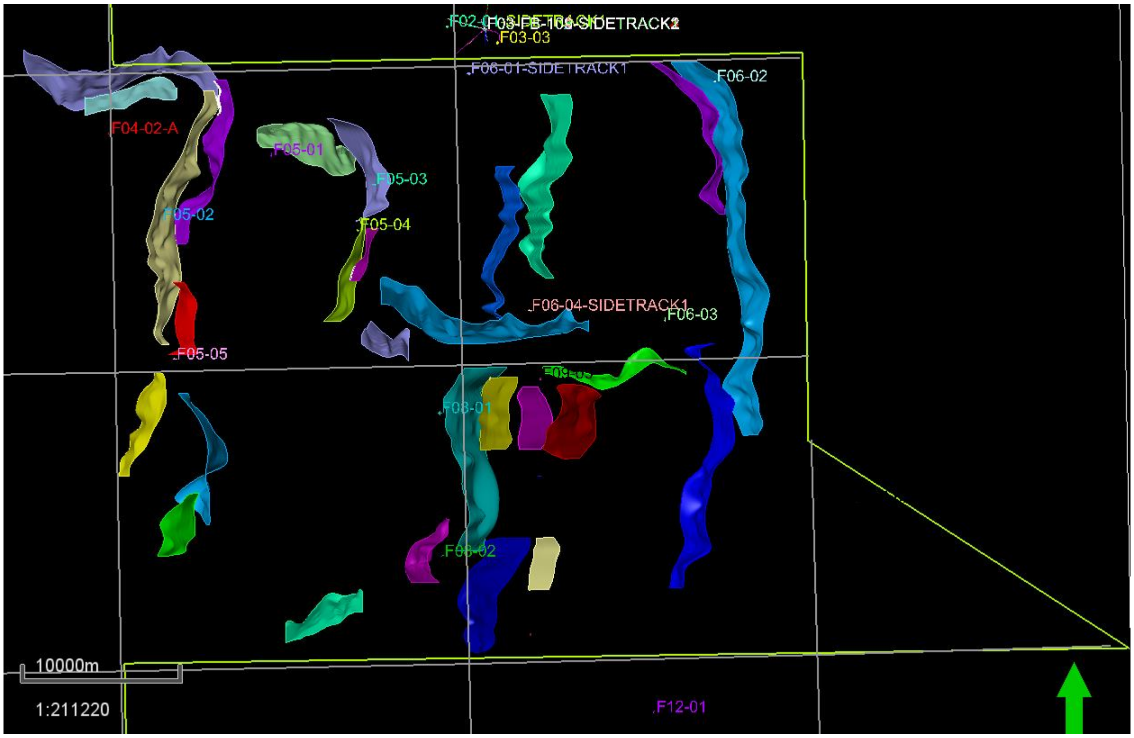


Figure 3: Showing the faults that were mapped in the area. Only larger faults with on offset of 50m and longer than 1 km were mapped. Also the wells are indicated in the figure.

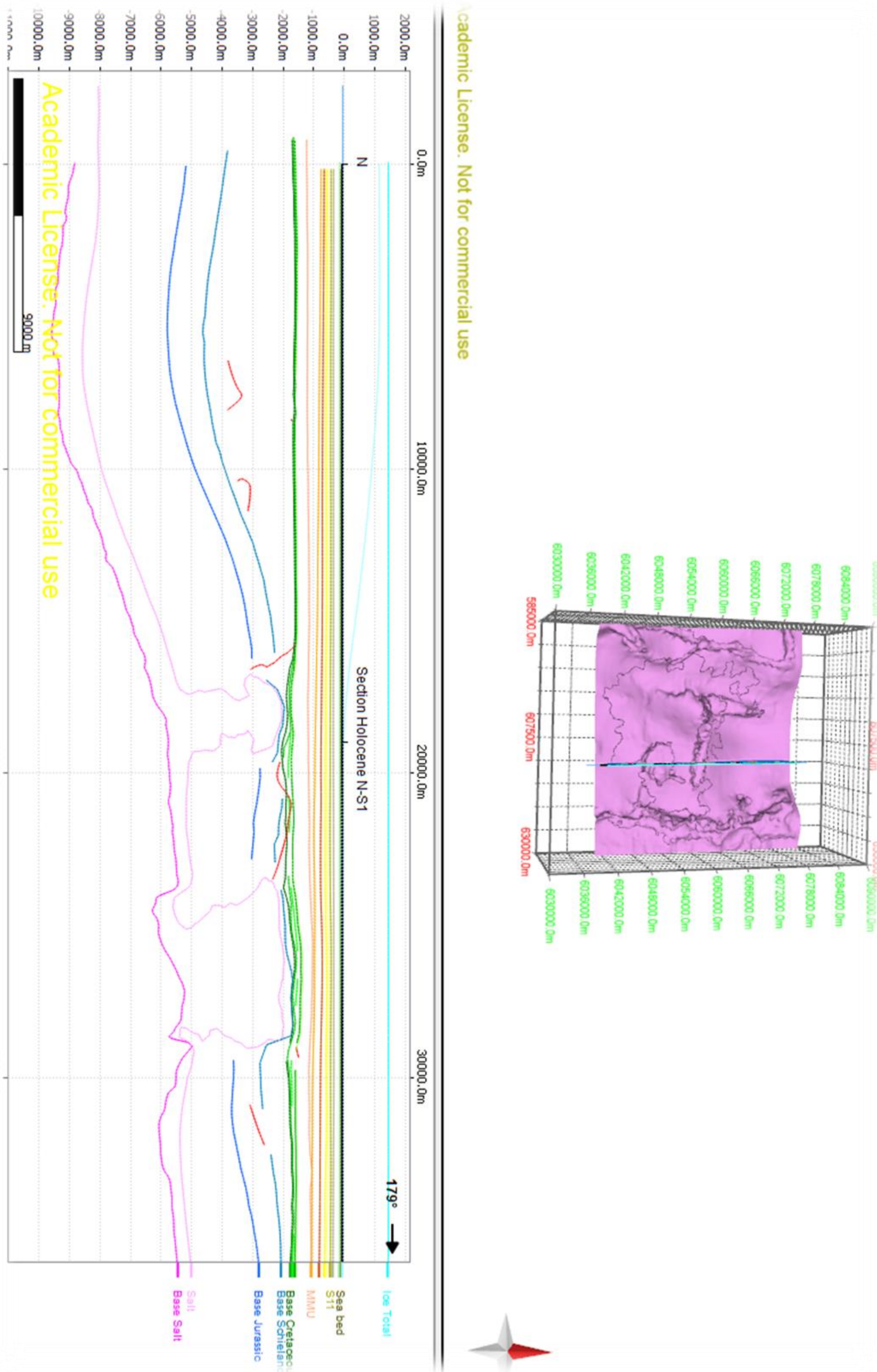


Figure 4: Showing a random N-S section in MOVE. Location of the section is shown above, where the top Zechstein is also shown. Also indicated is the Pleistocene ice sheet as modeled. In red are the faults offsetting the horizons. These faults sometimes appear to have a strange orientation, since they are not orientated perpendicular to the section.

3.2 Workflow

The work flow in structural restoration of a subsiding basin consists out of the sequential steps: decompact top layer, move on faults (if necessary), and unfold to datum (if necessary). If there was erosion during a certain time frame, then the workflow is different: add eroded material, compact, move on faults (see Appendix 1). The parameters required in each step are mentioned in this setting. The restoration was performed with 22 time steps. In each time step several horizons are restored. The number of horizons in each time step varies between 18 and 4 horizons, depending on the time interval on which the restoration is performed (older time intervals have fewer horizons).

Decompaction top layer

To decompact underlying strata through time, the strata are assumed to follow compaction behavior as described by the empirical Sclater-Christie curve. Sclater & Christie, 1980 state that all functions for lithologies like sandstone, shale and chalk are exponential. Therefore the compaction behavior of these lithologies can be described by the following relationship. In this relationship f is the porosity at depth, f_0 is the initial porosity at the surface, c is the compaction coefficient (km^{-1}) and z is the depth:

$$f = f_0 e^{-cz}$$

It is assumed that the area is isostatically adjusted after the top layer is removed. The isostatic relief is described by Airy Isostacy, where the mantle bulk density is assumed to be 3300 kg/m3. If the area was below the sea level, as the North Sea Basin was during most of the restored period, the load was sub-marine.

Fault restoration

Fault blocks are restored in 3-D using simple shear algorithm in MOVE (Appendix 1). Simple shear assumes volume and area balance, but does not preserve line length. It assumes that in the hanging wall, the deformation is diffuse, rather than discrete slip between beds. This makes it a good algorithm to use in extensional regimes, where growth faults have developed. Using simple shear fault restoration, the heaves of faults have to be determined. The heaves of the faults are variable and therefore an estimate of the heave at the center of the fault, as well as at the edges of the fault should be determined.

Unfolding

When unfolding beds, simple shear was used as the unfolding algorithm (Appendix 1). Using this algorithm, area and volume are preserved. Line length, however, is not preserved using this algorithm. This algorithm is typically used in extensional regimes, or areas with salt tectonics. The bed are unfolded to a target. The target is the paleo-bathymetry.

3.3 Input variables in MOVE

Compaction

It is well known that compaction factors vary locally (Sclater and Christie, 1980; Scholle, 1977), depending on the influences of the following aspects: overpressure, pressure solution, stylolitisation, and cementation. Therefore it is chosen to determine the compaction factor for this area, using porosity data from certain wells in the study area. Using porosity data to estimate compaction, it is assumed that compaction is caused only by burial, and that porosity changes with depth are only caused by compaction. Other processes that prohibit compaction (e.g. secondary precipitation of salt) are assumed to be not present.

Porosity depth data from the following wells are used: F05-04, F06-03, F08-01, F08-02, F09,-01, F05-01. The log porosity data is plotted against depth as shown in Appendix 2, Fig.11 , also indicated are the lithostratigraphic units. The Sclater and Christie porosity-depth relationship derived for each unit is shown in the graph, where y is the porosity (%) and x is depth (m). As can be seen from the graphs, the porosity sometimes increases with depth for certain stratigraphic units. This can be explained, by changes in lithology with depth. Often, the depth at which a certain unit is situated changes per location, so at different wells, a unit can be found at different depth. By assuming that the units do not change in lithology laterally, the porosity depth relationship can be determined, by plotting the wells together (Fig. 12- 18). This however, only worked for units that were present at different depths in different wells. The Lower North Sea Group does not vary in depth across the region, therefore its porosity depth trend is still positive. To “solve the decrease in compaction with depth” the regression was forced to go through an initial porosity that makes sense (30%). By doing this a negative porosity depth coefficient was obtained.

No porosity data was available for the units below the Base Cretaceous (Schieland Group, Jurassic, and Triassic). Therefore for these stratigraphic units, the compaction coefficients from Sclater and Christie, 1980 were used. Zechstein salt is assumed to be incompressible (compaction coefficient of 0). Also ice sheets are assumed to be incompressible. The compaction coefficients and initial porosities used as input in MOVE are shown in Table 2.

Density

The density of each of the stratigraphic units as defined in this study, is determined using well-log data. Wells F05-04, F06-03, F08-01, F08-02, F09-01, and F05-01 are used to determine the average density for each of the stratigraphic units in the area. Not all wells have density data measured along the entire borehole. Only in F05-04, the density is measured for the entire depth. Therefore the densities of some stratigraphic units are based only on the measurements of one well (Pleistocene, Post MMU), others are based on multiple wells (Danian, Maastrichtian, Campanian, Lower Cretaceous). The density of the Lower North Sea Group has been measured for all wells. The average densities per well are summarized in Appendix 4, the input as in Move is summarized in Table 2 below.

Horizon	Name rock type	Porosity (%)	Depth Coefficient	Density
Ice Total Ice Half	Ice Sheet	0	0	850
Sea Bed Pre-Elsterian S11, S13 HST4, HST5	Pleistocene	0.3839	1.19	2077
TST3, TST4	Pliocene-MMU	0.1880	0.87	2125
MMU	Lower North Sea Group	0.3000	0.29	2065
Base North Sea	Danian	0.2300	0.08	2274
Maastrichtian	Maastrichtian	0.5100	0.53	2283
Campanian	Campanian	0.6680	0.86	2389
Base Chalk	Lower Cretaceous	0.1550	1.24	2345
Base Cretaceous Base Schieland Base Jurassic	Pre-Cretaceous	0.5600	0.39	2680
Top Zechstein	Zechstein salt	0	0	2200

Table 2: showing the input parameters in MOVE for the horizons used. No distinction was made for all the horizons in the Eridanos Delta, nor for the pre-Cretaceous strata

Fault offset

To restore the movement of fault blocks in MOVE, the heave of the fault needs to be given as input (Fig.5). The heave for each fault was measured at two locations: at the centre of the fault and at the edges. Most faults in the North Sea Basin are growth faults and therefore vary in their heave. The heaves were therefore measured multiple times if required. The results are shown in Appendix 3. The heaves in the table can be sometimes less than the actual heave as seen on the seismics. Especially the system tracts of the Eridanos Delta were interpreted in older seismics. Therefore, faults were ignored and the horizons were smoothed, giving them a zero heave across faults. Therefore the heaves in the table should be considered as the heaves of the horizons in the restoration model.

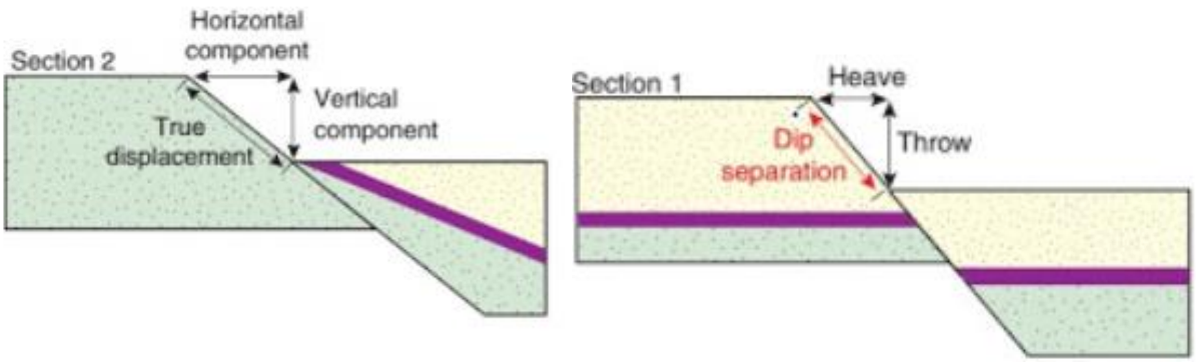


Figure 5: Figure showing schematically the relationship between fault displacement, heave and throw. Figure from Khattak, 2015 *http://geologylearn.blogspot.nl/2015/08/fault-terminology.html* .

Paleo-water depth

In a restoration it is important to have a basic understanding of the paleo-water depth through time. Changes in the water depth, results in additional or reduced overburden, which results in a respectively increase or decrease in compaction. The paleo-water depth in the North Sea basin has been well studied. The paleo-water depth for the central North Sea area is determined by Gradstien and Bergren, 1980. Amoco 2/8-1 is relatively close to the study area, so these paleo-water depths can be used. Also other researchers determined the paleo-water depth for the Mesozoic, Gemmer et al., 2002; Barton and Wood, 1983; Overeen et al., 2001 for various areas and time spans. The combined results of the paleo-water depth is shown in the Table 3.

Erosion Events

During the Late Cretaceous, Early Tertiary time, the subsidence in the Dutch Central Graben ceased and multiple invesrion events started. De Jager, 2003 regognised 4 pulses of inversion based on analysis of vitrinite reflectance data, fission track and fluid incusion data. The four pulses are:

- Sub-Hercynian phase, which started in the Turonian, but peaked in Campanian.
- Laramide phase, which occurred in the mid-late Paleocene.
- Pyrenean pulse, which occurred at the end of the Eocene.
- Savian phase that occurred at the end of the Oligocene.

De Jager, 2003, determined the amount of erosion at the Dutch Central Graben during each of these events. It appeared that only the sub-Hercynian and Laramide phases resulted in erosion. All other events resulted only in non-deposition of sediments, but no erosion occurred. The amount of erosion was 600-700 meters during the two phases (De Jager, 2003). This amount is in line with the results from others 500m (Huyghe & Mugnier, 1994), 750m (Heybroek, 1975).

According to TNO, 2015 (New Petroleum Plays in the Dutch Northern Offshore), another inversion event occurred during the Tertiary. This event occurred in the Oligocene and resulted in erosion of 200 meters of the Rupel formation.

Japsen, 1998 determined the amount of erosion in the North-Sea Basin based on sonic logs. Sonic logs give an indication of over compaction, by an increased seismic velocity. In his method, sonic data from Chalk sections were used to determine the velocity anomaly in these strata compared to a region without erosion. The velocity anomaly is captured by the following formula:

$$dV = k\Delta z\,(e^{k\Delta T/2} - 1)^{-1} - V_0 - kz_t$$

In this formula dV is the velocity anomaly, k is the velocity-depth gradient, Δz is the thickness of the layer, T/2 is the one-way travel time, V_0 is the velocity at the surface and z_t is the depth of the top of the layer. The reference velocity model is used from Japsen, whereby k is 2 and V0 is 500. The erosion would have resulted in over compacted strata at a certain depth compared to a region without erosion. The relation between velocity anomaly and burial anomaly is given by:

$$dZ_B = - dV/k$$

Any later burial will partly mask the increased compaction due to erosion. Therefore it is needed to understand the timing of erosion, so that later burial can be taken into account. In the North Sea Basin, the erosion was of Neogene age (probably related to the mid-Miocene unconformity). To determine the amount of erosion, the post Miocene burial should be added to the negative burial anomaly to get the amount of erosion:

$$\Delta z_{miss} = - dZ_B + B_E$$

The amount of erosion was estimated in this study area, using four wells (F05-01, F06-03, F05-02, F09-01, and F05-04). These wells were selected based on their presence in this study area. Two of these wells are located above salt diapirs (F09-01, F05-04), whereas the three others are located above the rim-synclines. The amount of erosion, varies per well:
F05-01: 280m, F06-03: 540m, F05-02: 340m, F09-01: 700m, F05-04: 900m. The uncertainty range in the amount of erosion is ~100m according to Japsen, 1998. It appears that the amount of erosion is the highest above the salt diapirs.

Finally a third estimate of the amount of erosion was used based on comparison with well data in the G-block. In this approach, it was assumed that no erosion occurred in the G-Block (Heijnen, personal correspondence). The thickness of the chalk units found in this block can therefore be used as an estimate of the original thicknesses (without erosion) of the chalk units in the F blocks.

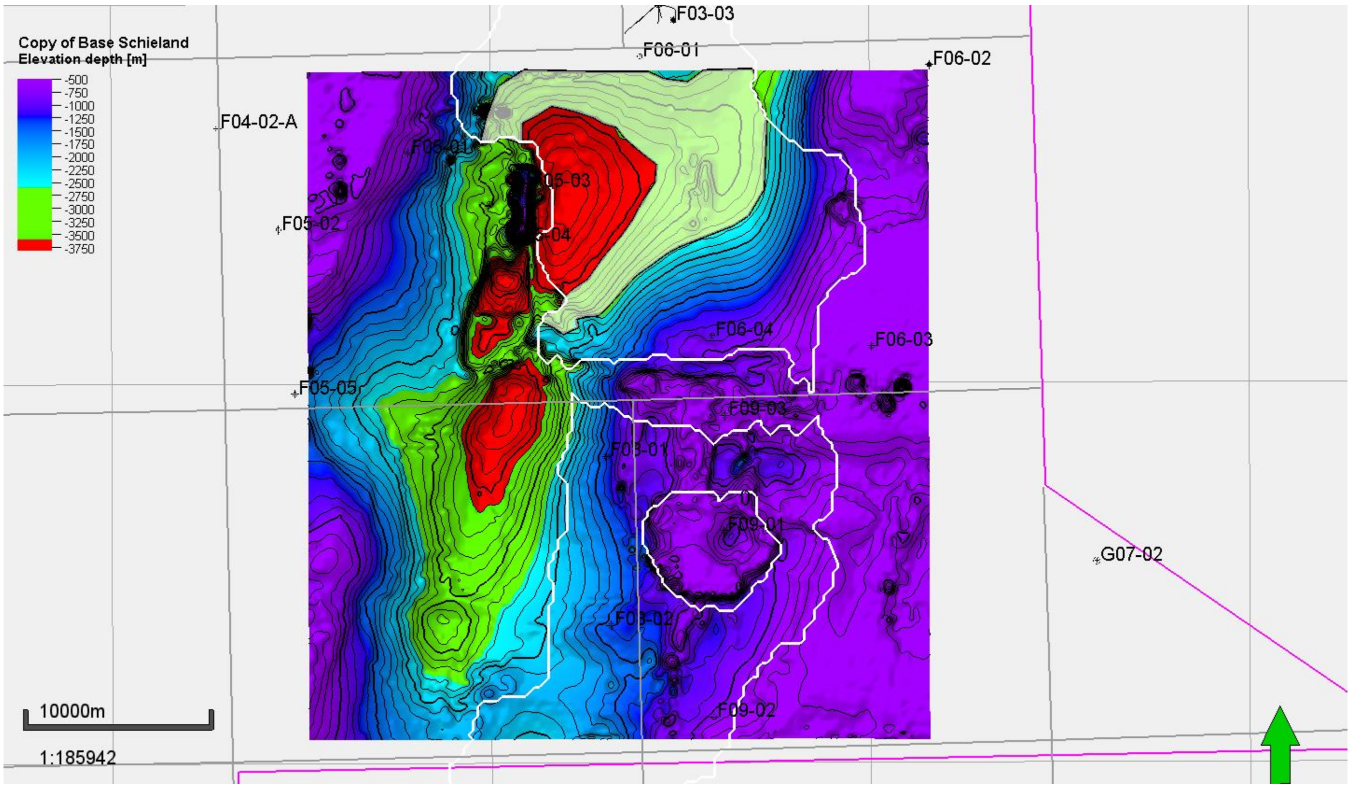
horizon	age (M.y.a.)	paleo-depth(m)	Erosion(m)	Comments on erosion
Sea Bed	0,0	N/A		
Pre-Elsterian	0,4	-100		
S13	1,8	-150		
S11	2,0	-150		
HST5	2,2	-200		
HST4	2,4	-300		
TST4	2,5	-300		
TST3	2,6	-300		
MMU	16,0	-200	50/200	Based on TNO 2015, own analisis compaction chalk
Base North Sea	62,0	-50	0/50	Based on TNO 2015, Comparison G-block
Maastrichtian	66,0	-100	50/200	Based on comparison G block, De Jager, 2003
Campanian	72,0	-100	100/200/500	Based on Panterra 2012, comparison G-block, De Jager, 2003
Base Chalk	100,0	-200		
Base Cretaceous	145,0	-50		
Base Schieland	164,0	N/A		
Base Jurassic	201,0	N/A		
Top Zechstein	260,0	N/A		
Base Zechstein	272,0	N/A		

Table 3: All horizons used in the restoration with their (average) paleo-bathymetry depth (if applicable), and amount of erosion.

4. Results

4.1 Impact of Erosion

Two 3-D structural restorations were made. One restoration was made using the maximum amount of erosion for all time intervals with erosion as shown in Table 3, the other restoration uses the minimum values of erosion (also Table 3). Because of the large amount of data, only the horizons of the Base Schieland, and top Maastrichtian and Danian are shown here. These horizons are the most important in predicting the Chalk prospectivity. First a comparison between the two models maturity will be shown. As can be seen in Fig. 6 the boundaries where the Posidonia is mature in the early Cretaceous is barely different (<1km) in the two models. Also other horizons were compared to see whether those had large differences between the two models. The horizons for the base Cretaceous at Campanian times are shown below in Fig. 7, as well as the horizons for the Maastrichtian during the Mid Miocene times in Fig. 8. As can be seen the two models result in different depth at which the horizons are at a certain time. Also, the dip angle differs at certain locations. However, the overall trends do not differ between the two models. Therefore, it is expected that the migration paths do not depend on the amount of erosion used in a model.



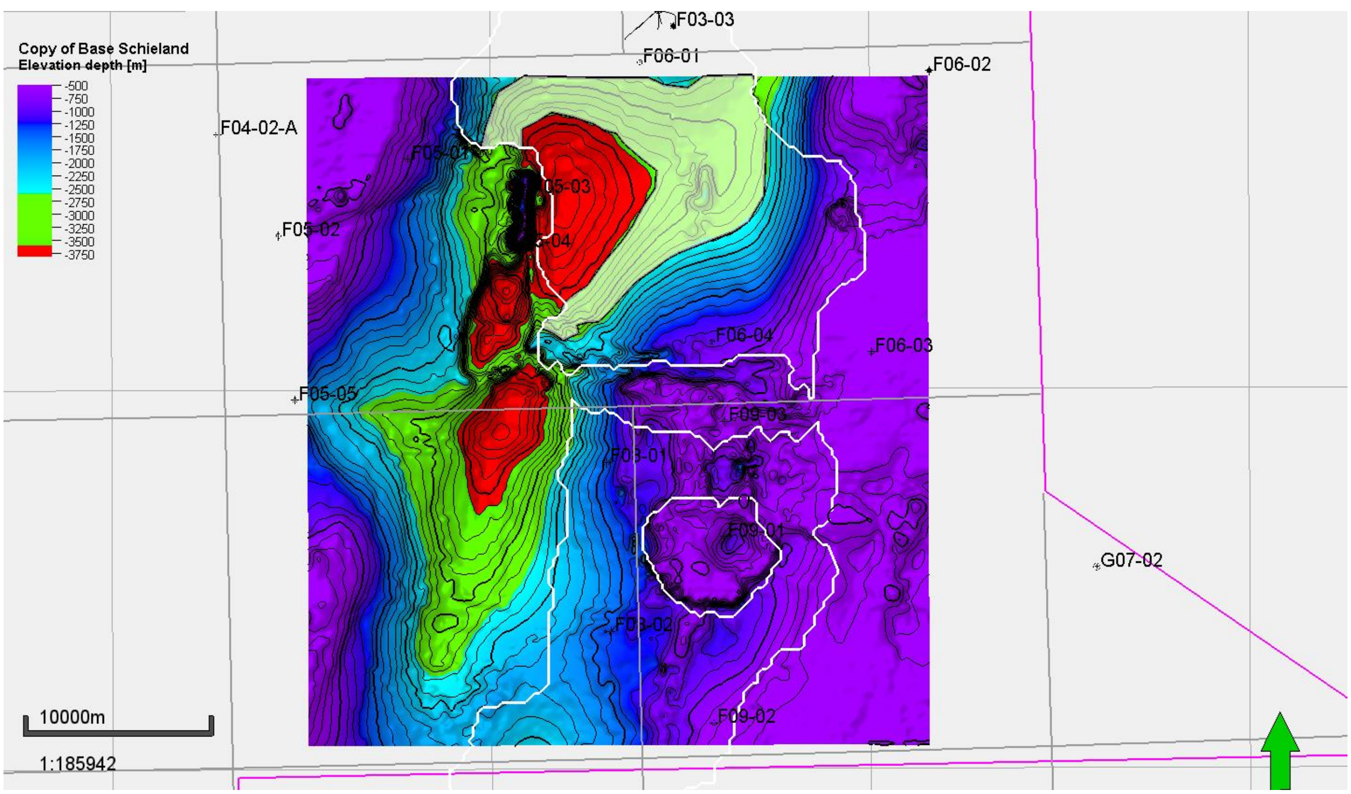


Figure 6: Showing the maturity of the Posidonia shale during the start of the Cretaceous in the maximum erosion model (upper figure) and the minimum erosion model lower figure. In green is the area where Posidonia is present and mature. In white is the outline of the Posidonia. As can be seen in the lower figure the two models barely have any difference (as can be seen by looking at the outline of the polygon).

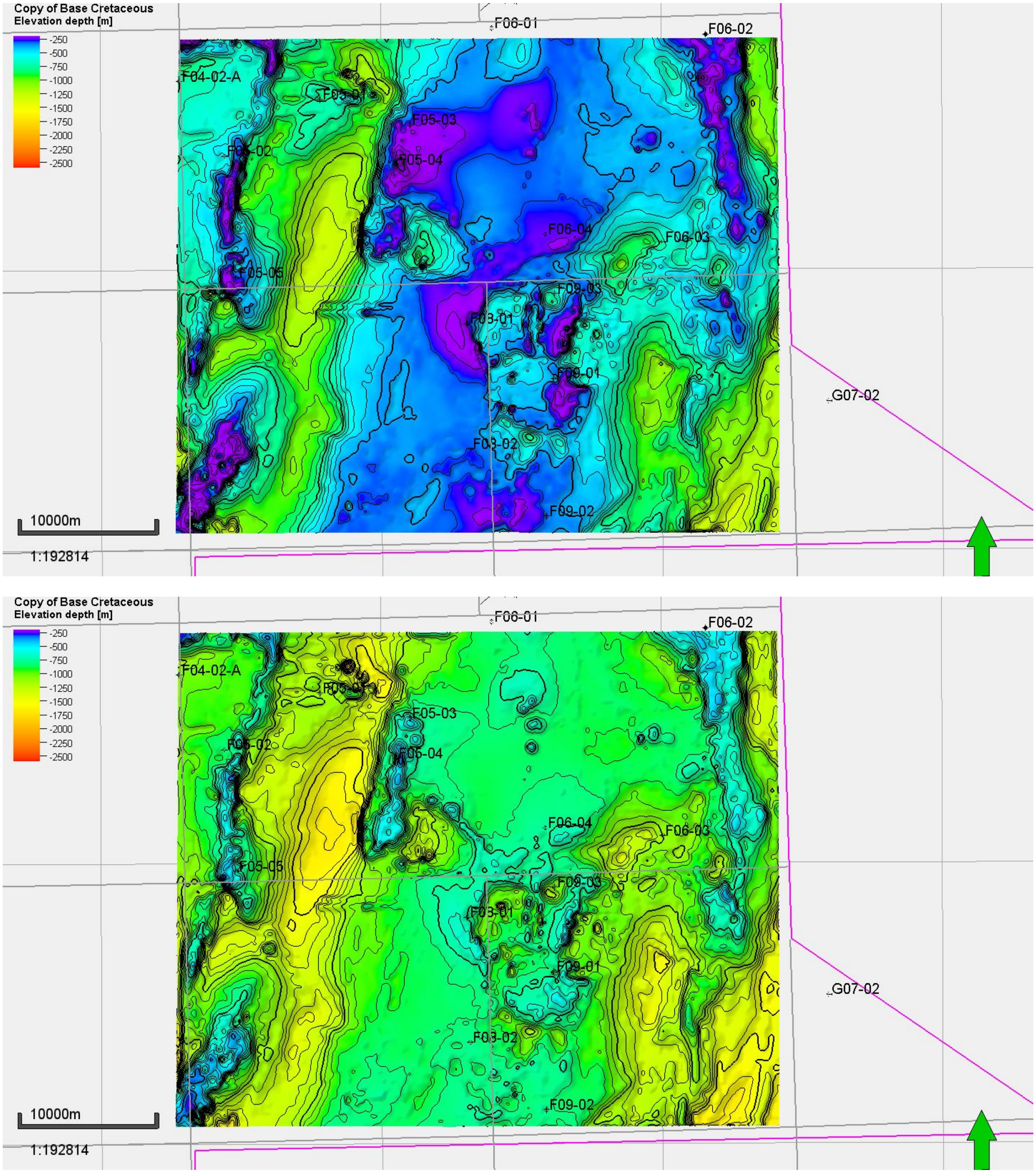


Figure 7: paleo-depth of the base Cretaceous during the Campanian time. Above in the minimum erosion model, below in the maximum erosion model.

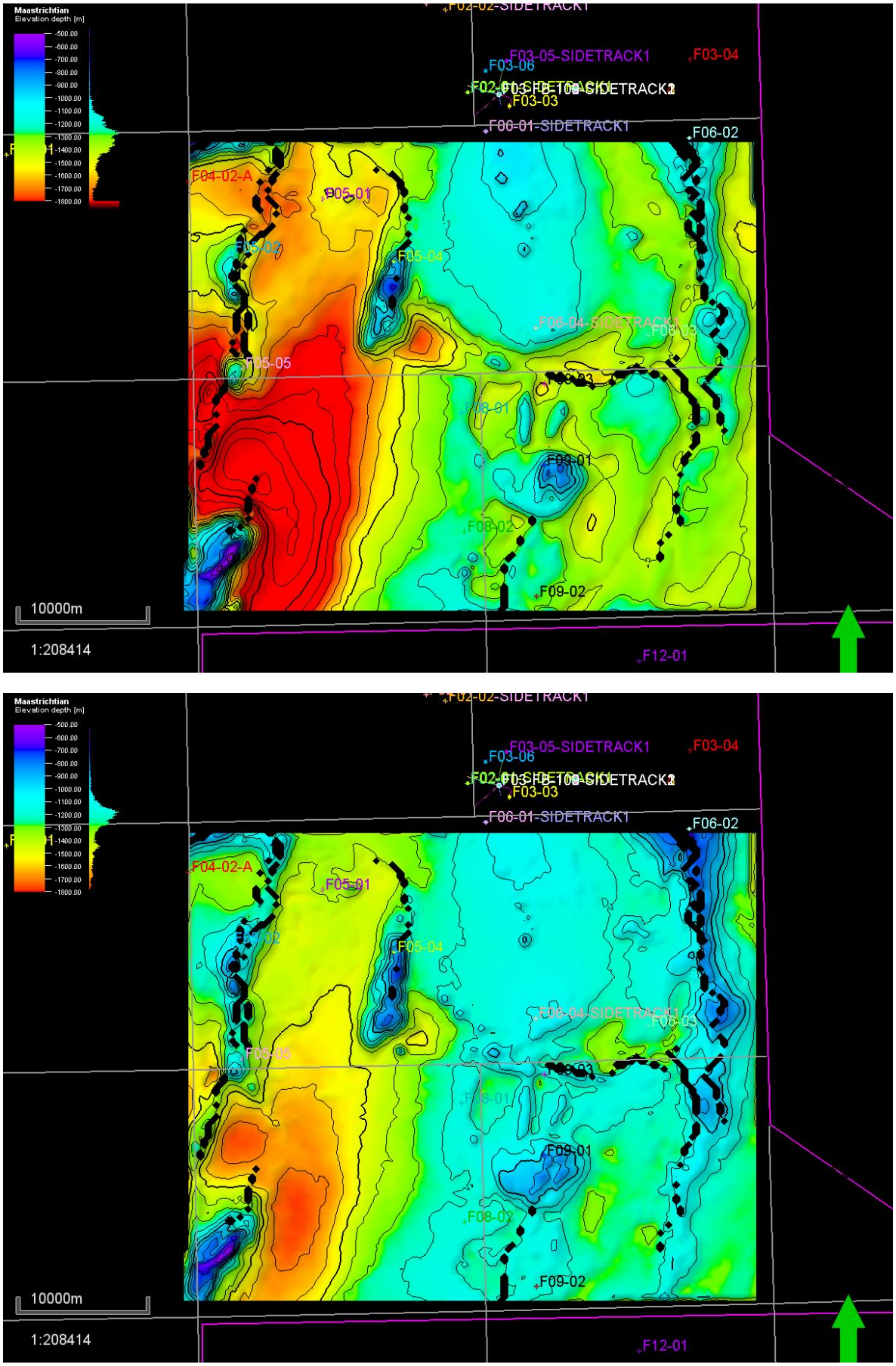


Figure 8: paleo-depth of the Top Maastrichtian during the Mid Miocene (before erosion). Above in the minimum erosion model, below in the maximum erosion model.

4.2 2-D cross sections.

To show the impact of each restoration step in detail, 2-D section were created through the study area. The sections run N-S and E-W. The locations are indicated in Appendix 5 (Fig. 19). In Appendix 5 (Fig. 20-31) the results are shown. As can be seen in the appendix, the Pleistocene ice sheet significantly impacts the compaction of the upper strata. The lower strata however, are not much effected by compaction (probably because they were already compacted). These strata however, show the impact of isostacy of the ice sheets. As can be seen in the 2-D sections some layers increase in their thickness significantly, when the overburden is removed. As can be seen in the cross-sections, the salt diapirs remain far below the surface during most of the time. Only during the late Danian and Early-Mid Cretaceous the salt diapirs appear to be very close to the surface. Furthermore the cross-sections show that minor changes in dip in the Cretaceous-present horizons have much larger impact than on pre-Cretaceous strata. Pre-Cretaceous strata are more heavily folded, so that small changes do not have a large impact on their overall dip direction. The Cretaceous-Present strata, are lying almost horizontally, therefore a subtle change in dip can change the dip orientation significantly. This observation will later be used when maturity and migration will be discussed.

4.3 Analysis

The model is tested for petroleum plays. The model can predict whether there will be a mature source rock and whether the migration of hydrocarbons will result in dry wells or hydrocarbon shows in wells. In some of the wells located in the study area, hydrocarbons were found. A summary of the wells and their hydrocarbon shows are given below. These wells are used for comparison to test the model against. The wells summarized below show a geographically pattern: no wells in the F8 block have hydrocarbons shows, in the F9 block only F09-01 has gas shows, almost all wells in the F6 block have hydrocarbon shows (gas or oil), and in the F5 block the hydrocarbon shows are only present in the eastern part of the block.

F05-01	TD in Lower Jurassic Aalburg shale. U. and L. Graben Sst. Found water-wet. Oil shows (35 m column) in Chalk, structure not salt induced. Tertiary shallow gas shows. P&A dry.
F05-02	TD in Triassic Lower Bunter. Middle Bunter water-wet. No shows in Chalk. Structure presumed bypassed by migration fairway due to fault along Central Graben edge. P&A dry.
F05-03	TD in Permian Zechstein. Upper and Lower Graben in salt edge play found water-wet. Top and lateral seal failed due to inversion related fault. P&A dry.
F05-04	TD in Permian Zechstein. Overpressured Chalk, good oil shows (but no gas), some H_2S (up to 360 ppm). DST (no acid wash) had water influx. Sampled 6-8 l of 18-19 °API biodegraded oil out of appr. 10,000 l fluids. Seal assumed to have failed due to 'pressure cooker' effect. Chalk ϕ 25 - 30%, k 1 - 10 mD. P&A oil shows.
F05-05	TD in Jurassic Upper Graben. Chalk (oil) target.
F06-01	Gas
F06-02	TD in Permian Zechstein caprock. Chalk porosity 33%, overpressure 50 bar. Tested small oil accumulation with 50 m column. Waste zone in Danian with RFT gives a FWL of 1431m TVMSL.
F06-03	TD in Jurassic. Well to Chalk Ekofisk prospect. Good porosity. No shows.
F06-04	TD in Jurassic. Prospect for Central Graben oil, water wet. Sand (5 m) in Werkendam oilbearing, not tested.
F08-01	TD in Lower Jurassic Aalburg shale. (dry well)
F08-02	TD in Lower Jurassic Aalburg shale.
F09-01	TD in Permian Zechstein. Well tested water bearing Chalk and Zechstein. Gas shows in the North Sea. P&A dry.
F09-02	TD in Lower Jurassic Aalburg shale. Jurassic target. P&A dry
F09-03	TD in Triassic Bunter Volpriehausen. In Chalk 50 bar overpressure. Carboniferous and Bunter targets. P&A dry.

Table 4: Summary of the hydrocarbons found in the wells located in the study area. Summary from EBN Basis Registratie

Maturity

The only source rock considered in this study is the Jurassic Posidonia Shale. Posidonia Shale reaches early maturity at ~2600m, its conversion to gas generation is at ~3600m depth (Verweij et al., 2012). The Posidonia is lying almost directly below the Base Schieland Horizon. Therefore the depth of the Base Schieland is used as a proxy for the depth of the Posidonia shale. The Posidonia is present in the areas as indicated by the white outline (Appendix 6). The maps show that the Posidonia reaches oil maturity at certain locations (boundary purple-blue), and is gas mature at deeper locations (red). These areas also change in location through time. Since only one well F09-01 contains gas shows, the focus of the migration lies on oil. The change in oil maturity (green polygon) in time is shown In Appendix 6. As can be seen in Appendix 6 the Posidonia is not mature in the F8, F9 blocks until Tertiary times, only in the F5, F6 it is mature since the start of the Cretaceous. From the late Danian till present, it becomes mature also in the F8 block. The Posidonia in the F9 block is only mature from the deposition of S11 till present (~2my). The Posidonia in the F5 block is completely in the gas window during the Elsterian. Furthermore, it is interesting to observe that in the F8, F9 blocks no gas is generated, - the Posidonia never enters the gas window in these blocks (with exception during the Elsterian in the F8 block). The maturity maps show that the maturity can be separated in a situation before the Mid Miocene (where the Posidonia is only mature in F5, F6) and situation after the Mid Miocene (where the Posidonia is also mature in F8, F9). This observation will later be used in determination of the migration paths.

Migration

Above the base Schieland Horizon is the Middle Graben Formation which consists mostly out of sandstone (Abbink et al., 2006). This lithostratigraphic unit is assumed to be the layer through which the hydrocarbons can migrate laterally. Especially oil migration needs a highly permeable rock unit, to migrate through, gas can also migrate through less permeable stratigraphic units. The Middle Graben Formation is lying conformably above the Base Schieland. The migration is assumed to have happened as follows: hydrocarbons are assumed to have migrated upwards vertically from the source rock. When entering the Middle Graben Formation, they followed the up-dip path. The migration is assumed to be unaffected by faults, nor by facies changes in the Middle Graben Formation, that are known to be present (Jaarsma and Rosendaal, personal correspondence). When the hydrocarbons reached the unconformity between the Middle Graben formation and the base Cretaceous, they are assumed to migrate out of the Middle Graben formation and move vertically up, through the Lower Cretaceous into the Chalk. Once they are in the Chalk they migrate up dip again until they reach a trap.

The Middle Graben Formation is not present everywhere. Since the Middle Graben Formation is not restored separately in this study, the Base Schieland is used as a proxy of how the Middle Graben sandstone deforms. Subsequently, this proxy horizon is deleted everywhere where the Middle Graben Sandstone is absent. At certain locations the Middle Graben sandstone forms an unconformity with the base Cretaceous. By looking at the deformation of the Middle Graben Sandstone, an understanding of the migration of hydrocarbons (and especially oil) is obtained. It can be shown how the hydrocarbons migrate up-dip and where the entry point to the base Cretaceous could be.

From the results in Appendix 6, we conclude that the first migration occurred during the end of the Early Cretaceous, the second pulse was after the Mid Miocene. Therefore, before the Mid Miocene times the maturity is outlined as it was during the start of the Cretaceous, after the Mid Miocene the maturity is outlined as it was during the Mid Miocene. The migration is shown in maps in Appendix 6. The migration is assumed to follow the following path: From the source rock it migrates in an up-dip direction to the entry point (the unconformity between Base Cretaceous and Middle Graben Formation). The migration is indicated as follows: in black arrows the primary migration is outlined as it occurs during each time span directly from the source rock (as outlined in green). In colored arrows is outlined how secondary migration can occur (migration from a point where in in an earlier time span hydrocarbons had migrated to). As can be seen in Appendix X the migration paths do not change much through time. Most of the times the highs remain highs and lows remain lows. Therefore, secondary migration is rare through time. Also the entry points do not change through time since the dip orientation of the Middle Graben formation does not change (already discussed in Chapter 4.2). An extra entry point however is created in block F09 due to changes in maturity outlines.

Trap

The reservoirs in the study area are located in the Chalk units. Therefore to have some understanding of trap formation, the evolution of the deformation of the Chalk units is analyzed. It is unknown when the hydrocarbons migrated from the Middle Graben Sandstone into the Chalk units. Therefore, in this approach time frames will be shown with arrows. The arrows start above the point where the unconformity exists between the base Cretaceous and the underlying Middle Graben Sandstone (indicated by grey polygons, which have the same location as the end points of the arrows in the maps of the Middle Graben formation). The arrows end at a point that can form a trap in the Chalk units. Again in black is primary migration (from the grey areas to an up-dip point), in red/purple is indicated the secondary migration. The hydrocarbons are assumed to always migrate towards the trap in an up-dip manner. Also indicated are the hydrocarbon shows (red = gas, green = oil, grey = no show), for wells which had been released the 1st of April 2016. The red outline indicates where the chalk is absent (has zero thickness), against this outline stratigraphic traps can be formed.

4.4 Testing the Model

The restoration model was tested using the hydrocarbon shows (or lack thereof) of the wells in the study area. Especially if well data showed hydrocarbons the model has to predict that hydrocarbons can migrate to that area. In the case of no hydrocarbon shows, the sealing capacity of the cap-rock might have resulted in leakage, something the restoration model cannot predict.

F05-02 & F05-05 (Both Dry)

The restoration model shows that near these wells the Posidonia Shale is absent. The Posidonia is only present east of F05-03 and F05-04 (Appendix 6). The hydrocarbons generated at these areas, however, did not migrate towards F05-05 and F05-02, but migrated eastwards through the Middle Graben Formation (Appendix 7). Therefore the model predicts that these wells are indeed dry.

F05-03 (Dry) & F05-04 (Oil)

Although the Posidonia has reached oil maturity in an area east of these wells since the Early Cretaceous, the oil has migrated away from the wells, once in the Middle Graben formation. Therefore the entry-points, where the hydrocarbons entered the Chalk units are actually quite far away from these wells (Appendix 8, 9). It is shown that it is impossible that hydrocarbons have migrated through the Chalk over long distances towards these traps, since the chalk is largely absent at these entry points. A more sensible explanation of the oil shows in F05-04 is that one of the faults in the area has resulted in leakage of oil directly from the source rock into the Chalk. Once in the Chalk it is only a short distance up-dip towards the structural high on which F05-04 is located. The reason that F05-03 is dry and F05-04 has oil shows might be that F05-04 is located on a high and F05-03 is located on a high that has been deformed through time. This deformation might have resulted that hydrocarbons have leaked during this deformation from F05-03 up into F05-04.

F08-01 & F08-02 (Both Dry)

The model predicts that the Posidonia Shale becomes oil mature in an area nearby since the mid-Miocene (Appendix 6). The hydrocarbons migrate eastward through the Middle Graben formation to a point east of the wells where they entered the Chalk (Appendix 7). The restoration of the Chalk units (both Danian and Maastrichtian) shows that the hydrocarbons might have migrated towards these wells where they become trapped in stratigraphic traps (the Chalk is absent at these wells). It is unclear what the impact of the faults near these wells is. At F08-01, the fault might be sealing, which might have inhibited the hydrocarbons to migrate to well F08-01. Another possibility is that the well does not contain chalk (it is at the boundary of the Chalk). F08-02 might be dry because a clear trap is absent. It can be seen in Appendices 8, 9 that the oil will probably migrate slightly more southwards away from this well.

F09-02 & F09-03 (Both Dry)

The Posidonia is not mature in proximity of these wells (Appendix 6). However, hydrocarbons are generated further away from this well. It is possible that they migrated through the Middle Graben Sandstone towards areas in proximity of these wells (<2km). The Chalk unit dipped in the wrong direction for the hydrocarbons to migrate from the entry point into these wells. Rather, the hydrocarbons migrated in an opposite direction from the entry point away from the wells (Appendix 8, 9).

F06-02 (Oil)

The model shows that the Posidonia Shale has been in the oil window during the entire time span in an area west of F06-02. The hydrocarbons migrated eastward to areas slightly west of the well. Here they entered the Chalk and migrated further eastwards towards the well. The well is located on a structural high and the hydrocarbons became trapped. This high remained undeformed through time, so significant leakage is unlikely to have occurred.

F05-01 (Oil)

The Posidonia has been oil mature in an area north of F05-01. The hydrocarbons migrated westward through the Middle Graben formation to an entry-point north-west of well F05-01. From this entry-point the hydrocarbons migrated in three directions. They might have migrated further west in the Chalk units towards the salt wall at the edge of the Central Graben. Another possibility exists that they migrated eastwards towards a small high north of F05-01, or even more eastwards towards the center of the Dutch Central Graben. A third possibility is however, that they migrated southward towards F05-01. Especially the Danian Chalk formed a high near F05-01 (it leaked however during HST5, S11, Elsterian, and present). The Maastrichtian trap has been less pronounced through time and leaked during certain most spans. Also it is unclear whether the fault near F05-01 was permeable for hydrocarbons.

F06-03 (Dry)

The Posidonia Shale has been oil mature north-west of this well. They migrated towards the south-east through the Middle Graben formation. Here they have entered the Chalk units and migrated in several directions. Sometimes they migrated through the Danian Chalk towards F06-04 or the eastern flank of the Dutch Central Graben. It is also possible that they have migrated southwards towards F06-03. Often a trap has been present at F06-03, and hydrocarbons can expected to be present. However, the trap has sometimes leaked (during the Elsterian) and hydrocarbons might have migrated out of it again. This might explain why the well is dry. Another possibility exists that the trap has simply been leaking because the prospect does not have a good seal.

F06-04 (Oil)

The Posidonia has been oil mature in proximity of F06-04. The generated hydrocarbons migrated only over a small distance towards an entry point south of this well. As can be seen in Appendix 7 chalk is barely present above this entry point. Therefore they have probably remained trapped in the Middle Graben formation. This is also what the well data indicate: oil shows are found in the Middle Graben formation (Table 4).

F09-01 (Gas)

The Posidonia has reached oil maturity in an area east of F09-01 after the mid Miocene. From its source, oil could have migrated through the Middle Graben formation towards the east. In the Chalk, it migrated further towards the east towards a Danian trap east of F09-01. This trap has been less pronounced through time in the Maastrichtian strata. The Danian trap leaked after deposition of HST5, and hydrocarbons were able to migrate further east towards F09-01. This prospect has gas shows. The Posidonia Shale, however, has not been gas mature according to this model in the area near F09-01. The Posidonia is located below the base Schieland (which is the restored layer), therefore the possibility exists that the base Schieland has not been in the gas window, but the Posidonia Shale has. In that case, well F09-01 can be sourced from the area east of this well. Alternatively, the gas found at F09-01 may originate from another source rock.

4.5 Leads of EBN

The results of the restoration model were also compared to EBN gas and oil leads in the study area. The shallow gas leads are in the Upper North Sea Group and are indicated by the purple polygons in Fig. 9. Also indicated are the oil leads in the Chalk (green polygons). Two oil leads are not shown, since they are located in areas without Chalk. The leads are numbered as indicated in Fig.9.

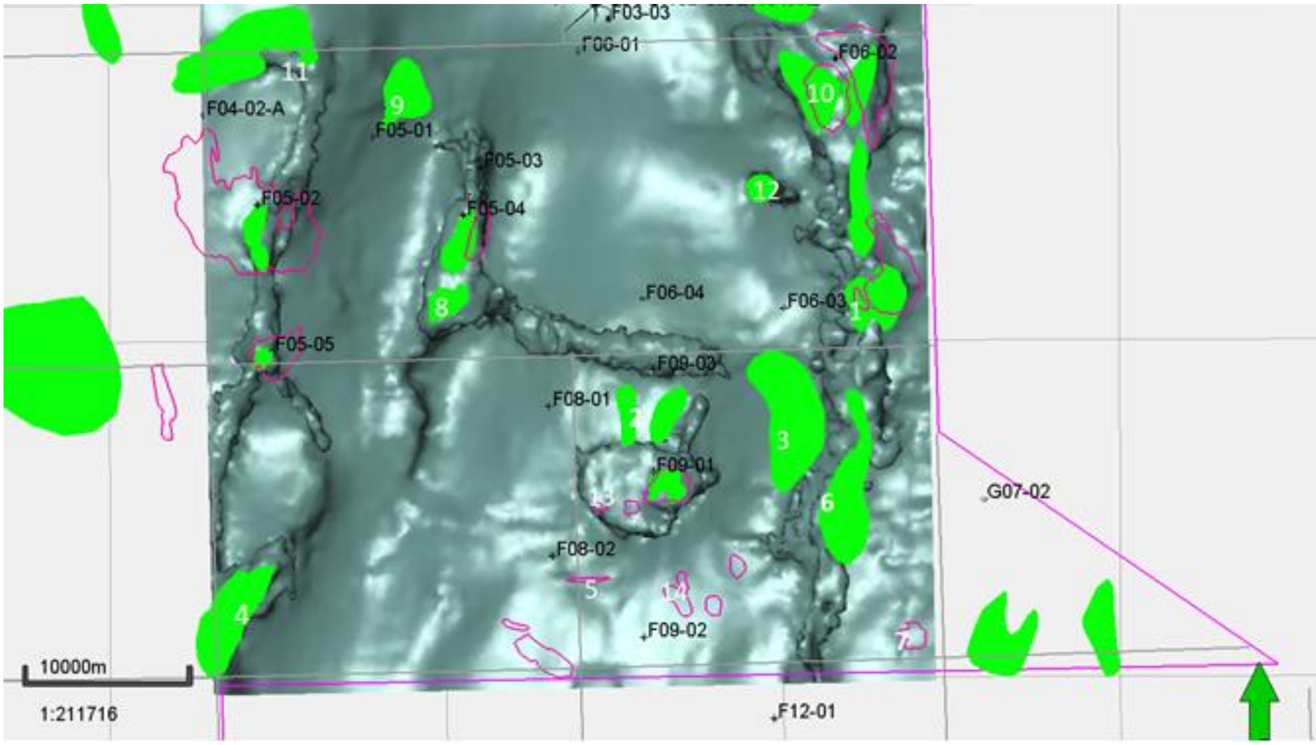


Figure 9: EBN's preliminary leads (two leads removed) (EBN, 2015). Green polygons indicate Chalk leads (based on structural closures), purple polygons indicate shallow gas leads (based on seismic anomalies). The numbers indicate the leads as they are discussed in the text.

Lead 1

According to this model, it seems likely that Lead 1 contains oil (or gas). The reason is that hydrocarbons migrated from the entry point to well F06-03 (as discussed in the previous chapter). That well formed a high, but has leaked before the late Mid-Miocene. It is possible that hydrocarbons have migrated towards the salt wall near Lead1. This lead remained a high after the late Mid-Miocene, so hydrocarbons remained trapped. Also during the Elsterian hydrocarbons were probably able to migrate from the entry point towards this lead, so a later second pulse of hydrocarbons is possible.

Lead 2

Also Lead 2 seems unlikely to contain hydrocarbons. Hydrocarbons from the northern source migrated towards the north. They cannot have passed the salt wall north of Lead 2. The hydrocarbons (oil west of this lead has migrated westward or southward, but not eastward towards Lead 2.

Lead 3

Lead 3 might contain hydrocarbons. The hydrocarbons got trapped at well F06-03 and could not migrate down dip away from this well. Only during the Elsterian a chance exists that hydrocarbons migrated away from well F06-03 towards the south. If this happened than this Lead might contain hydrocarbons (oil or gas). It is also possible however, that the source of hydrocarbons is south of this Lead. From the early Elsterian onwards, the Possidonia was oil mature in this region. In that case, hydrocarbons were able to migrate upwards where they became trapped in this lead. The precise migration path through the Middle Graben formation is unclear, since it is not present everywhere in this region.

Lead 4
Lead 4 does not contain any hydrocarbons. The source rock became oil mature east of this lead during the mid-Miocene. However, they have migrated eastward through the Middle Graben formation away from this lead. Also in the chalk, the hydrocarbons have not migrated to this lead. Therefore this lead is definitely empty.

Lead 5
Lead 5 probably contains hydrocarbons (only oil). The Posidonia Shale was oil mature north-west of this lead (the source rock was only gas mature in the Elsterian). From this point they migrated eastward through the Middle Graben formation, where they entered the Chalk north of this lead. In the Chalk they migrated southwards, where they became trapped in this lead, which formed a pronounced high during the late Mid Miocene. During other time spans, a stratigraphic trap was present at this location (it is at the boundary where the chalk is present).

Lead 6
The chance that this lead contains oil depends on its exact location. If it is located east of the salt wall, the lead is not sourced according to this model. However, if its location is west of the salt wall, the source rock became oil mature after the early Elsterian (Appendix 6). Then it is possible that the generated hydrocarbons migrated through the Middle Graben formation towards this lead (Appendix 7), which formed a high since latest Danian (Appendix 8, 9).

Lead 7
This lead is located at the boundary of the study area. It cannot have been sourced from the study area. However, it might be possible that a source rock was mature outside the study area and hydrocarbons have migrated towards this lead. This is simply unknown.

Lead 8
This lead is probably empty. Although the Posidonia Shale has been oil and gas mature in an area in proximity of this well, hydrocarbons have migrated through the Middle Graben formation away from this well. The entry points were located quite far away from this well and from these entry points it is not possible that hydrocarbons have migrated to this lead. The only possibility for this well to have hydrocarbons is through leakage along faults. The fault(s) east of this lead might have resulted in leakage of hydrocarbons directly in the chalk. The chalk dips towards the east, so that hydrocarbons migrated westwards once in the chalk. They became trapped at this lead which formed a high since the latest Danian.

Lead 9
This lead probably contains oil as explained already in the previous chapter (Well F05-01). The source rock was oil mature north of this area and generated hydrocarbons migrated southwards where they became trapped. Well F05-01 is located south of this lead and contains oil. Therefore it is a very high chance that this lead also contains oil. A risk exists however, that the trap has leaked during certain time spans (HST4, S11, Elsterian and present). During those time spans hydrocarbons have by-passed this lead.

Lead 10
This lead also contains oil (and potentially gas). This lead is located very close to well F06-02, which has oil shows. Therefore this lead will probably also have oil shows. Oil became trapped against the salt wall west of this lead.

Lead 11

As already explained in the previous chapter, the Posidonia Shale has been mature in the area east of this lead (Appendix 6). From this point hydrocarbons migrated westwards towards this lead. Here they became trapped against the salt wall. It is uncertain whether the location of this lead is very precise. It can also be that oil is trapped further south-westward.

Lead 12

This lead contains hydrocarbons. The Posidonia Shale has been oil and gas mature west of this lead since the start of the Cretaceous. The hydrocarbons migrated through the Middle Graben formation eastwards, where they entered the chalk at a point in proximity of this lead. In the chalk the hydrocarbons migrated towards this lead which formed a high and has not leaked. Another migration path exists via the south. South of this lead another entry point exists. Also from this entry point it is possible that during certain time spans (e.g. Mid Miocene, S13) hydrocarbons have migrated northwards through the chalk towards this lead.

Lead 13

As already discussed in the previous section, the Posidonia has been oil mature in the area west of this lead. The source rock was only gas mature during the early Elsterian. The hydrocarbons migrated eastwards through the Middle Graben formation, where they entered the chalk west of this lead. In the Danian chalk they migrated eastwards to this lead, which formed a high during most of the time (it leaked since the Pre-Elsterian). Therefore it might be that these leads are empty by now, due to long time leakage. The high was less pronounced in the Maastrichtian Chalk (Appendix 8), therefore the Maastrichtian strata probably do not contain hydrocarbons at this location.

5. Discussion

5.1 Salt

One of the problems encountered when making the restoration was modeling the halokinesis over time. In MOVE, the flow of salt is not modeled, only other parameters, like compaction and isostacy are taken into account. Therefore in this restoration, the shape of the diapirs through time is not the actual shape. The determination of diapir shape and restoring it, is already a tedious work in a 2-D restoration. Often it is done manually by leaving the diapir shape blanc and restoring the on lapping layers. Afterwards the diapir can be drawn manually as the empty space in the restoration.
This approach might also be a solution when making a 3-D restoration. However, in this restorations too few (pre-Cretaceous) on-lapping horizons were used to recreate the shapes of the diapirs. If more horizons were restored that on-lap onto the diapirs, an impression of the shapes of the diapirs through time could be created. Still following this approach the diapir shape should be drawn manually after each restoration step. The diapirs are surfaces in 3-D restorations (rather than lines). This makes it a tedious work to draw them and most likely it would result in erroneous restorations.

Another major problem encountered when restoring basins encountered by halokinesis is the possibility of significant amount of salt dissolution through time. Salt dissolution is likely to affect not only the diapir shape. Cartwright et al., 2001 explained in their paper how salt dissolution can lead to passive diapirism, where salt flows out of the rim-synclines into the diapirs. Therefore, by ignoring salt dissolution, a possibility exists that not only the area around the diapirs is restored erroneous, but the entire area. By restoring the layers overlying the diapir, the chance of a wrong restoration is reduced. Cartwright et al., 2001 already state that salt dissolution is most likely to occur only when a diapir is close to the surface. In this restoration, it is shown that the diapir is only close to the surface during the late Danian and early-mid Cretaceous. Therefore, large amounts of salt dissolution are not expected to have occurred (at least not from the Cretaceous till present).

5.2 Compaction

Compaction and porosity, are known to vary very locally (both vertically and horizontally). Therefore rather than taking the compaction coefficients from the literature (Sclater and Christie, 1980), it was chosen to determine the compaction coefficients for every horizon used, based on the porosity data from well logs in this study area. Several problems were encountered: First of all, porosity is assumed to be directly related with compaction. In reality more processes might have effected porosity change that did not result in a change in compaction (e.g. karstification, cementation due to precipitation). Secondly, local overpressure is common in the study area. These effects may cause erroneous coefficients. Also as shown, certain horizons (e.g. Danian) appear to have more than one porosity depth trend, due to an impermeable intra-layer, or a facies change in one horizon. This resulted in an apparent positive porosity depth trend or an unrealistic initial porosity (for the Danian it would be >100% intitial porosity, see Fig. 14 Appendix 2). Ideally this should be solved by making more horizons, each with its own compaction coefficient. Adding more horizons was beyond the scope of this project. Therefore, it was chosen instead to force the regression to a certain initial porosity, so that always positive porosity depth relationship existed and a realistic initial porosity was used.

Another problem occurred when layers were at the same depth in all wells. Here the risk existed that rather than a compaction coefficient, a vertical change in facies was detected, this might have been the case for the Lower North Sea Group (Fig. 13 in Appendix 2).

Furthermore one compaction coefficient is used for all pre-Cretaceous Strata. It is well known that especially the pre-cretaceous strata have significant lithology changes. Therefore all these different strata should be mapped and each should be given its own compaction coefficient. These compaction coefficients should be calculated from porosity data from wells (if available). This would be beyond the scope of the project.

The impact of compaction on the restoration might be significant. The formula for compaction shows that compaction is an exponential power. To see its impact the Danian is chosen as an example. Danian is at present at a depth of ~1500m and has a porosity ~20.4. Decreasing its depth by 100m to 1400 meters results in a porosity of ~20.5. However, if the same compaction factor as for the Maastrichtian is used (0.53) than its current porosity is 23.0 and at depth of 1400 meters its porosity is 24.3. This implies that with other compaction factors the strata can change in thickness significantly. If strata have a change in thickness, this can also result in different tilting of overlying strata when different compaction factors are used.

5.3 Creating Horizons

Most of the horizons in this project were imported from different projects. Some of the horizons of these project needed to be extended. The extension was mostly not done by extra interpretation, but by automatically extending in Petrel. Therefore, errors might have occurred. Especially around salt domes this might have been the case. Also artificial drag around faults needed to be removed before a restoration in MOVE could be performed. This was also an automatic process in Petrel, but resulted in small gaps around the faults. Therefore also around faults care should be taken and the result should not be considered completely solid. Furthermore, all horizons were depth converted using an existing velocity model from EBN. This might also have resulted in vertically mismatch.

5.4 Erosion

One of the most difficult aspects in making a structural restoration is the quantification of the amount of erosion. To estimate it several sources were used. Literature gave an estimation about the regional erosion through time. However, since the amount of erosion probably differed between areas located above salt diapirs and areas located above the rim-synclines, also seismic velocity data of well logs from the area were used. The seismic velocity data gave an indication about the erosion after a layer had reached its maximum burial. For the Chalk this was probably the case in the early Miocene, however this could not be stated with 100 percent confidence. Misdating the erosion events results not only in adding extra material to the wrong horizon, it also results in a different amount of erosion.

Ideally all wells were used to give an impression of the geographically difference in erosion. However, many wells did not have seismic velocity data and therefore could not be used. Even if all wells would have had velocity data, still the amount of erosion of areas between the wells would remain uncertain. It would take a lot of time to create a new horizon (manually) that would show the amount of erosion. Therefore the difference in geographically distribution of erosion was neglected, and one estimate of erosion was used for the entire area. Earlier smaller erosion events could not be extracted from velocity data and only vitrinite reflectance data could be used. The vitrinite reflectance data was already described in the literature. However, the amount of erosion during the different events was not always consistent in the different literature sources used. This was solved by making two models, one with the minimum amount of erosion, the other with the maximum amount of erosion.

5.5 Paleo-water depth

Paleo-water depth was used from studies about areas outside this study area (e.g. Amoco 2/8-1). The paleo-water depth was used in the restoration to unfold the layers to a datum. It is well known that during certain periods there was a topographic relief. The clinoforms of the Eridanos delta were not unfolded to a horizontal datum, but were only shifted vertically, so that a topographic relief was modelled. Whether the clinoforms are the actual topographic relief remains to be seen, since the diapirs did deform some of them. However, following this approach a more accurate paleo-relief was provided compared to simple flattening.

It is also known that during the late Cretaceous paleo-relief existed, which can be seen by slumping in the Chalk strata (Heijnen, personal correspondence). Creating a new grid with the paleo-topography of the Chalk horizons and unfolding the layers to this datum, requires very detailed mapping, which was beyond the scope of the project. Therefore, the layers were unfolded to a horizontal datum. Since the topography during the late Cretaceous is not expected to be too significant (~100m), no major errors are expected by ignoring this.

The paleo-water depth also impacts the compaction, by changing the overburden. Therefore it was chosen to incorporate it in the restoration, since ignoring it would result in a definite erroneous restoration (then a paleo-water depth of 0 meters would be assumed). The exact paleo-depth in this study area is unknown. However, because of the low density of water and relative small range in paleo-water depths (<500m), no major errors in compaction are expected by using the wrong paleo-water depth.

5.6 Ice Age

To model the effect of ice sheets on the subsurface, two horizons were created. One horizon shows the fully extended ice sheet, where the ice is 1500m thick and does not change in thickness. The other horizon is created to model the retreat of the ice sheet (it decreases in thickness and it is short-lived). In reality, the retreat of an ice sheet goes not in one step, but in many steps. If perfectly modeled even more horizons should be created, and they should be even more short-lived. This was beyond the scope of the project however. In future work it might be interesting whether such an approach would result in different conclusions. Also an ice sheet of 1500m is assumed in this model. As stated earlier, the exact thickness of the ice sheets is unknown and large variations in thickness are found in the literature. It would be interesting to see whether an ice cap of 1000m or 2000m would significantly change the modelling results.

5.7 Modelling Hydrocarbon Migration

The source rock maturity was simulated using the results of Verweij et al., 2012. They determined the depth at which Posidonia Shales become mature in their study area (south of this study area). It is not certain however, that the depth at which the Posidonia becomes mature in the study of Verweij et al., 2012 is the same as the depth at which the Posidonia becomes mature in this area. Maturity depends on an interplay between temperature and pressure, both are related to depth. However, also other aspects besides depth affects pressure and temperature regimes: Salt diapirs have a so called chimney effect, where the upper layers have an increase in temperature and the lower strata have a decrease in temperature, compared to areas without halokinesis. Also, local overpressure might have effected maturity by changing the local pressure regime.

There are uncertainties to how the hydrocarbons have migrated towards the potential traps. To model hydrocarbon migration it is assumed that the hydrocarbons always migrate up-dip. In reality migration depends on pressure regimes, where the hydrocarbons migrate from high pressure regimes to low pressure regimes. Since it is unknown what the paleo-pressure regimes were, this was neglected. Furthermore, it is assumed that faults have only affected migration in the Chalk. In the Middle Graben formation, faults do not seal and hydrocarbons can migrate through faults. This assumption might be too simplistic. Also it is well known that large differences in lithologies exists in the Middle Graben formation. It is much sandier in the north than in the south. This can have large influences on the migration.

In this study it is assumed that the hydrocarbons use the Middle Graben Sandstone as a migration path and do not migrate over large distances in the Chalk. Whether this assumption is valid is not tested in the model, but is simply assumed. If the hydrocarbons take other migration paths, the model may not hold. Another problem encountered when modeling the migration of the hydrocarbons, concerns the Middle Graben Sandstone which is assumed to be the formation in which the hydrocarbons migrate laterally. This horizon, however, is not incorporated in the restoration model. Only the Base Schieland is restored and it is assumed that the Middle Graben Sandstone is parallel to the Base Schieland. If the orientation of the Middle Graben Sandstone changes with respect to the Base Schieland through time, this assumption does not hold. Therefore it is strongly recommended to make an extra restoration with the Central Graben Sandstone incorporated in the model.

6. Conclusions

In this study a 3-D structural restoration was made in the F5, F6, F8, and F9 blocks in the Dutch Central Graben. This area is associated with a complex tectonic history, where faults are orientated in practical every direction. By making a 3-D restoration, the assumption of volume balancing was not violated. Furthermore, 3-D restoration has the benefit that analysis of hydrocarbon migration is much better visualized (no hydrocarbons are flowing out of the section).

The restoration showed, among other aspects, the effect of ice sheets. The ice sheets caused compaction of shallow layers, but compaction of deeper strata was limited, because they were already compacted. Also the weight of the ice sheets caused subsidence due to isostatic subsidence. Due to this effect also deeper strata subsided during the Pleistocene glaciation (Elsterian). The model showed that ice sheets should be taken into account when making a restoration model, since their effect is not neglectable.

The inclusion of the Eridanos Delta in the restoration model did result in lateral differences in compaction. The clinoforms in this delta show (little) variations in thickness. Therefore, in the north layers were more compacted than in the south. However, since the thickness differences in the clinoforms were very small, the differences in lateral compaction of the under burden was also very small.

Including small erosion events in the restoration model, should make the restoration more accurate. However, the amount of erosion still remains uncertain and no clear answer in the literature can be found. By including well data an estimate of Tertiary erosion was obtained. This amount of erosion can only be obtained for erosion after strata have reached their deepest point. All erosion events before, are overwritten and other measures should be used to obtain the amount of erosion during those events. Including different amounts of erosion in the restoration showed the impact of erosion. It only has large effects on shallow strata (e.g. Chalk units), deeper strata (e.g. Base Schieland) are not much affected by different amounts of erosion. Therefore, before making large efforts in obtaining the accurate amount of erosion through time, the purpose of the restoration should be clear.

Compaction of the strata has large effects on restorations. If strata change in thickness laterally, compaction can result in tilting of the underlying strata. Therefore, in this restoration, compaction was modeled in detail. Many layers were incorporated in the model, each with its own compaction coefficient. The compaction coefficients were determined using porosity data from well logs. In this restoration only two pre-Cretaceous strata were used. Therefore only three lithologies are assumed for the entire Zechstein-Cretaceous interval. An even more accurate restoration can be obtained by including more pre-Cretaceous strata.

Also, a good understanding of the paleo-bathymetry should be obtained in the next restoration. Literature only showed the general paleo-bathymetry of areas outside the study area. The paleo-bathymetry affects the restoration in two ways: it changes the amount of overburden, and a difference in paleo-relief results in different unfolding. Especially much remains unknown about the paleo-relief in the Cretaceous. It is well known that there was a paleo-relief in the Cretaceous, as can be seen by slumping in the Chalk. Even if the exact paleo-relief is known, a surface should be created to include it in this 3-D model. This would require much more additional work.

The area where the restoration was made, was severely affected by halokinesis. Making a restoration in such an area is not easy, since the software cannot model the flow of salt through time. Therefore, salt movement can only be modeled indirectly e.g. restoring other layers around the salt structures. The resultant gaps in the restored area are the restored salt structures. The boundaries around the gaps should be outlined to get the restored salt structures, this is a tedious work since it requires to make new surfaces at each restoration step. In this study, an understanding of the salt shapes through time was not the main goal. Therefore, salt was not restored in such a way and the salt as presented in this study may not be the actual salt shape through time. Also it is possible if salt structures are restored to have an understanding of the amount of salt dissolution. This is simply the change in the volume of the salt structures as they are restored. Salt dissolution is assumed only to happen if the salt diapirs are close to the surface. This happened only during a few time spans (late Danian, early-mid Cretaceous). Therefore the amount of salt dissolution after the start of the Cretaceous is probably small. If the goal of the restoration is to have a detailed understanding of the development of traps against salt diapirs, more effort should be taken in the restoration of the salt diapirs.

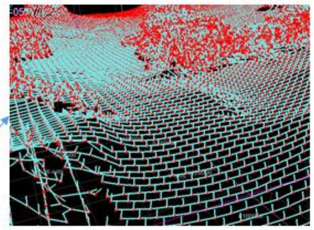
To model the migration of hydrocarbons through time, many assumptions were made. If these assumption are proven to be valid, the migration model can be used. The restoration proved to be very useful to understand the maturity, migration, and trapping of hydrocarbons. The model showed a high degree of predictability of where the hydrocarbons can be found.

7. Appendices

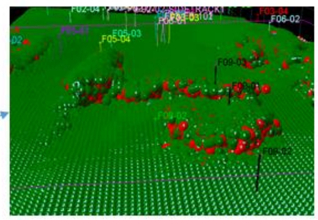
Appendix 1 Workflow for 3-D restoration in areas affected by halokinesis, using MOVE and Petrel software

1. Multi-Z interpretation

1.1 Interpret salt structures in Multi-z (make sure you snap the nodes (white crosses) and do this as accurate as possible)
1.2 Interpreted top salt in single-z (make sure you use a proper density interpretation e.g. 50m)
1.3 Draw polygons around the salt structures
1.4 Eliminate multi-z outside the polygons and single z inside the polygons
1.5 Append the surface to the Multi Z (seismic operations



1.6 Perform QC-normals (shown in a different folder)
1.7 Flip normals where necessary

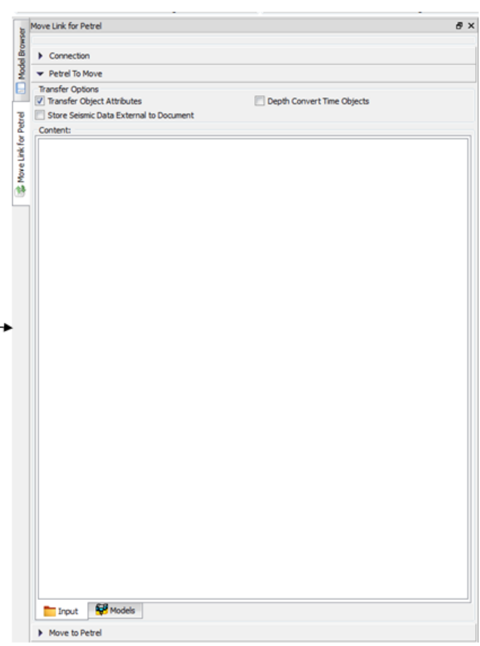


1.8 Create the Triangle Mesh (make sure you use the right grid density)
1.9 If the riangle Mesh needs to be in depth both the seismic cube and the interpretations need to be depth converted

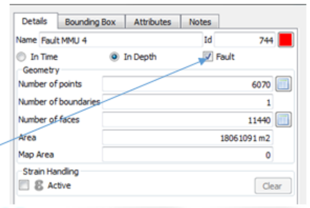
2.Export in MOVE

2.1 Import Petrel Files in Move:

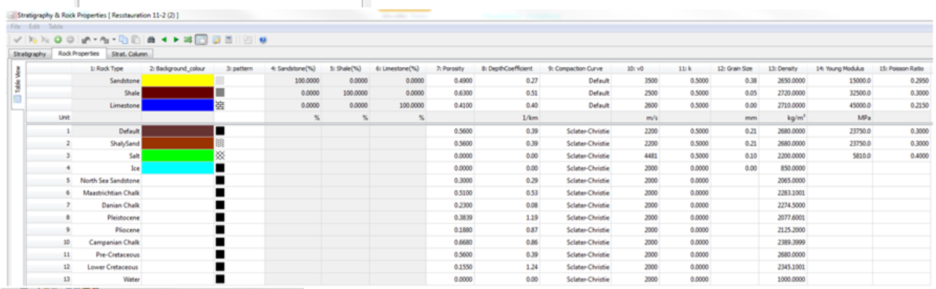
- Manually
    - Traingle Mesh and faults as .ts files
    - Grids as Zmap+ grids (ASCII)
- Using Petrel Move Link

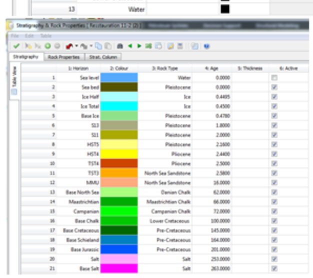


3. Input in MOVE:

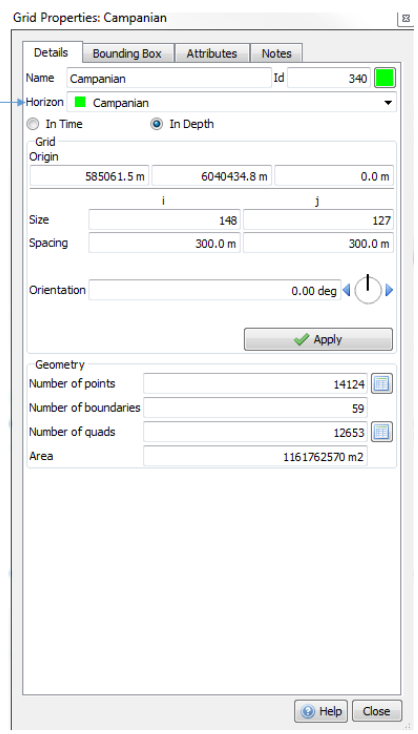


Check on Fault for all the faults



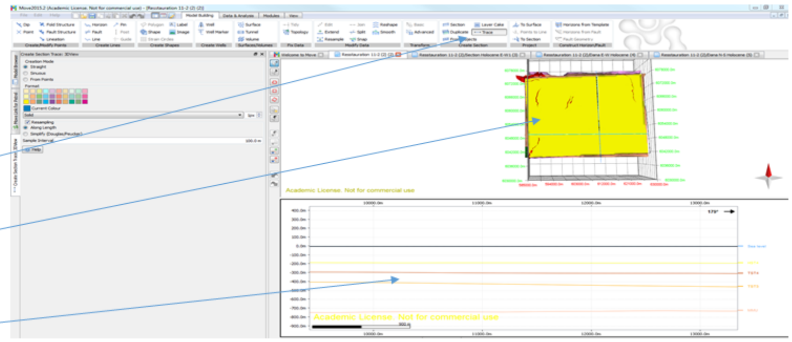


Go to Data and Analysis→ Rock Properties and stratigraphy need to be filled in correct for all the horizons used



Make sure that all the grids have the proper horizon name, as in the stratigraphy table

4. Create 2-D Sections



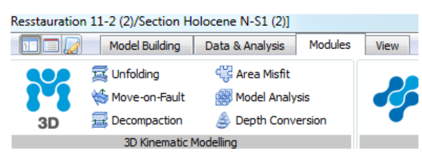
You are now ready to create sections by going to Model Building → create section → trace
Select two points in 3-D window and right click to finish.
To Project Faults and grids right click on the section→ view→ collect surface intersections

The Object Types in Model browser are different depending on 3-D or 2-D view.

With each 3-D restoration step the section view is not updated. This has to be done manually: ctrl A → Del → Right click → view → collect surface intersections

5. 3-D Restoration

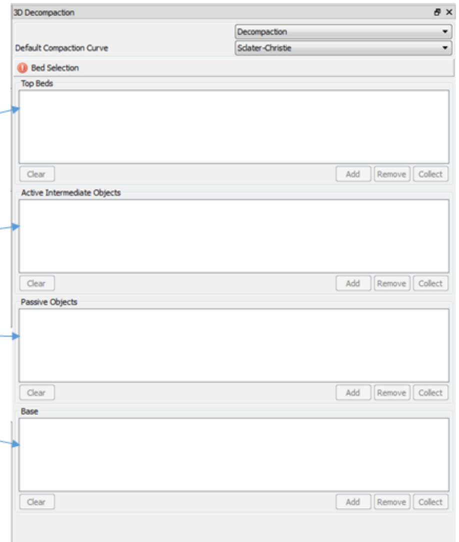
- The Restoration is a loop with 3 sequential steps (in this order):
  - 1. Decompaction
  - 2. Move on Fault (if necessary)
  - 3. Unfolding



- These steps have to be repeated for all horizons starting with the youngest, finishing with the oldest

5.1: 3-D Decompaction →Bed Selection

1. Bed Selection:
- select grid surfaces in Model Browser, make sure 3-D window is active
- Top Bed: the bed that is removed
- Active Intermediate objects: All the strata below
- Passive objects: faults
- Base: Base salt



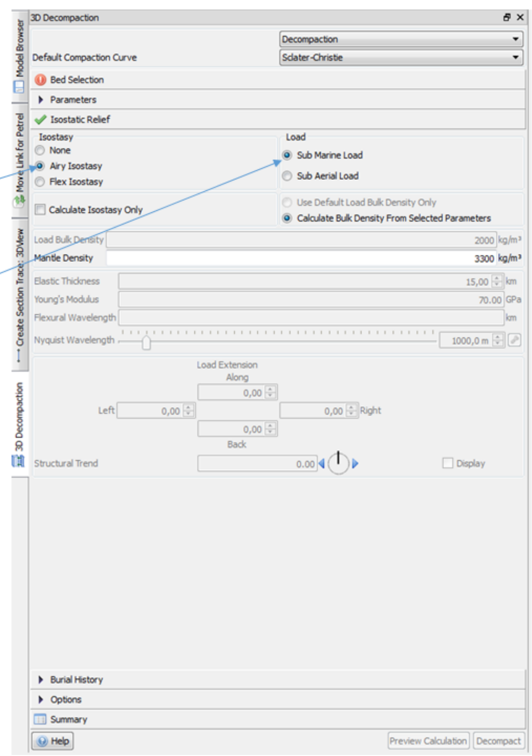
5.1 Decompaction: Parameters & Isostatic Relief

Parameters: Toggle on Database and check if input is still correct

Isostacy Airy or Flex Isostacy depending on size of the section and variations in thicknesses of the strata (see MOVE manual)

Sub-Marine load if the area is below sea level, otherwise sub Aerial Load.
Leave all other parameters as default (MOVE is designed based on North Sea data, so for EBN it should be fine).

Click on Decompact.
In 3-D there should be a change.
In two 2-D window it should be updated manually (see page5).



5.2 3D Move on fault

Select Simple Shear in case of normal faults.

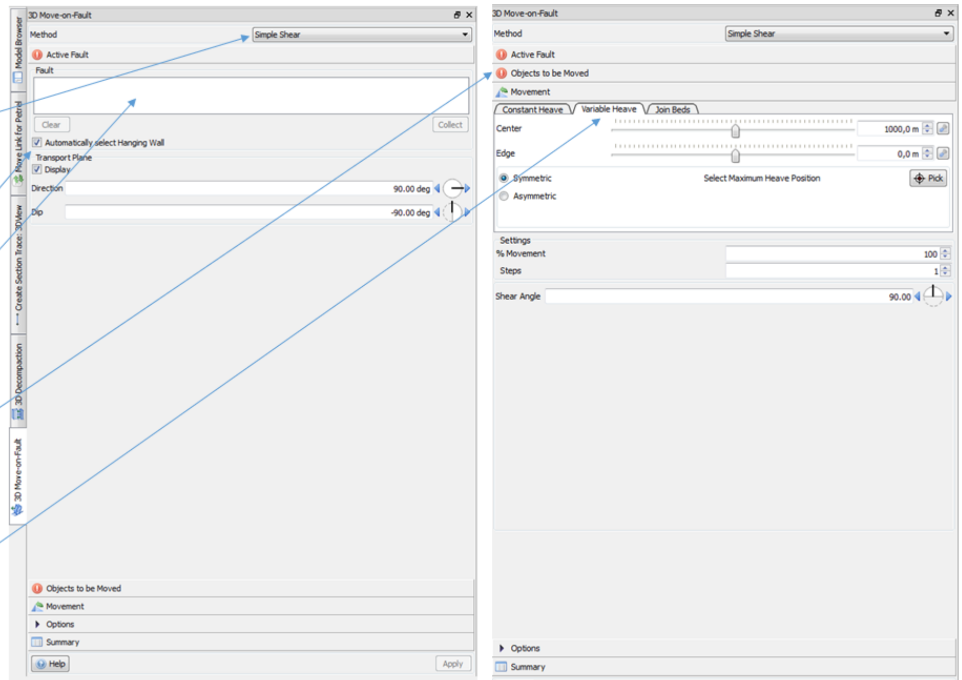
Toggle on automatically select Hanging Wall

Fill in one fault each time. (Select in Model Browser). Repeat for all relevant faults

Objects to be Moved: All the Horizons that are cut-off by the fault.

Movement: Variable Heave → fill in the heaves of the upper stratum

Note: Move On Fault converts the grids to Triangle Meshes



5.3 Unfolding

Select Simple Shear

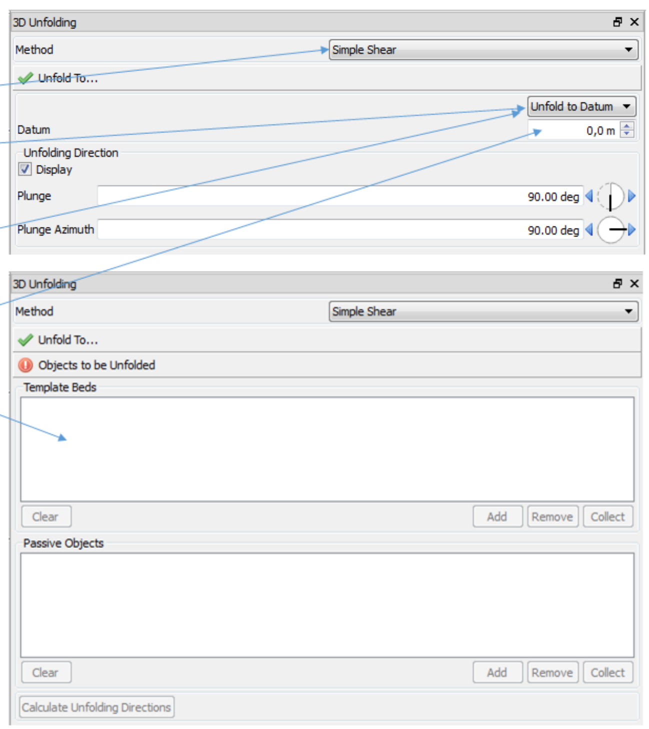
Select Unfold to Datum if you want to unfold to horizontal.

Select Unfold to Target if paleo-bathymetry is known and you have made a grid.

Fill in the paleo-water depth in Datum

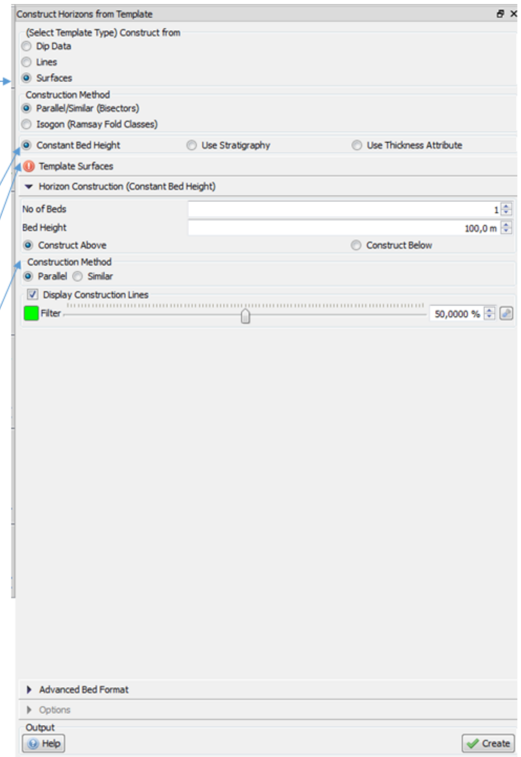
Template Beds: upper horizon that needs to be unfolded.
Passive Beds: All other Horizons.

In case of Eridanos Delta, the clinoforms are not unfolded (they represent the paleo-bathymetry), but the entire section is simply shifted upwards to the right paleo-depth. To do this click on 3-D window. Ctrl A → z → fill in the amount of uplift/subsidence



Erosion

- To recreate eroded strata go to model → Horizons from template
- Click on surfaces
- If you don’t have detailed information about erosion use constant bed height
- Template surface: the surface that was eroded (3-D Construction, fill Holes)
- Fill in the amount of erosion in bed height, Construction method: parallel, construct above.
- A new surface without erosion should be created



Finishing the restoration

- Check in each step whether the result makes sence
- The best way is to do this in 2-D sections
- Repeat the process from upper strata to younger strata
- At each step export all the faults and horizons back into Petrel using the Move-Petrel Link
- Note: All the horizons will be overwritten with each restoration loop in Petrel. Therefore open a new Petrel Project when a loop is finshed

Potential Technique to restore salt structures

- Salt structures are now only restored indirectly.
- The overlying strata are restored. The gaps in between the onlapping strata against salt diapirs are the restored salt diapirs.
- To Visualise the restored diapirs you might try this:
  - Create boundaries around the strata that onlap the diapirs
  - Try In Petrel whether you can connect these polygons to form 3-D suraces (in Multi-Z)
  - Append these to the Top salt below the rim-Synclines

Appendix 2 Porosity depth

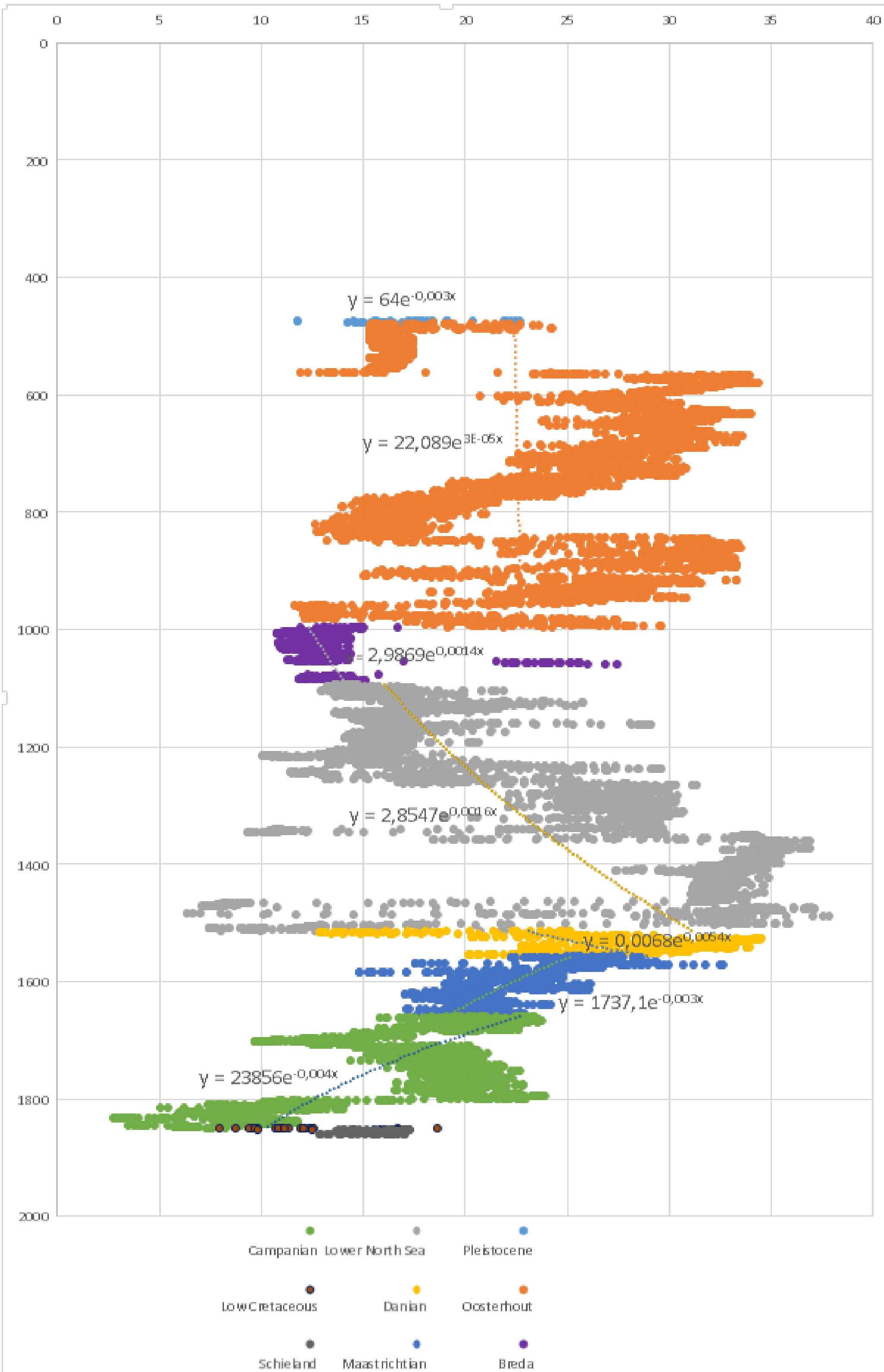


Figure 10: Porosity depth relationship for well F06-03. As can be seen there are many intra layers within the horizons, causing erroneous compaction coefficients.

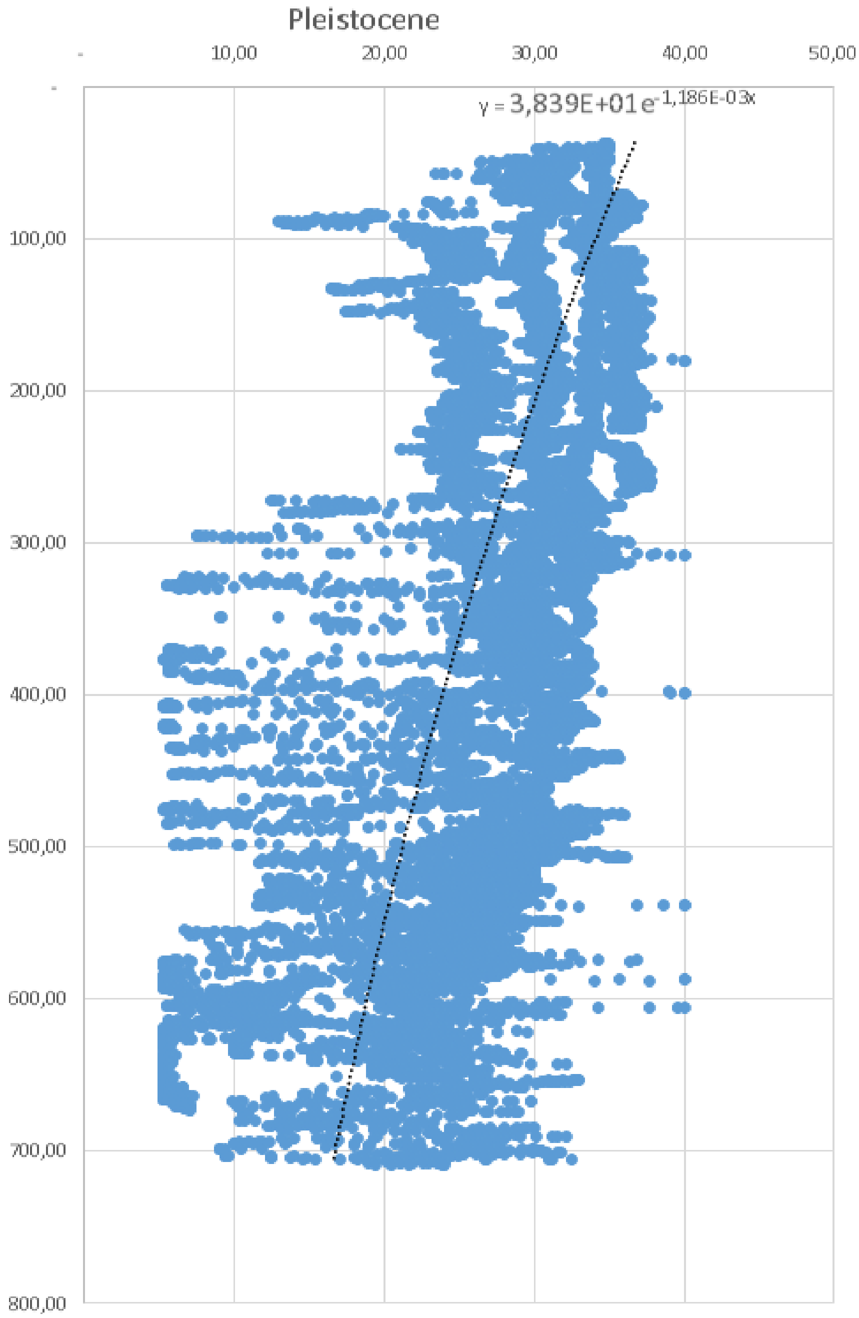


Figure 11: Porosity (y-axis) depth (x-axis) relationship for the Pleistocene stratigraphic unit. The graph is based on 6 wells.

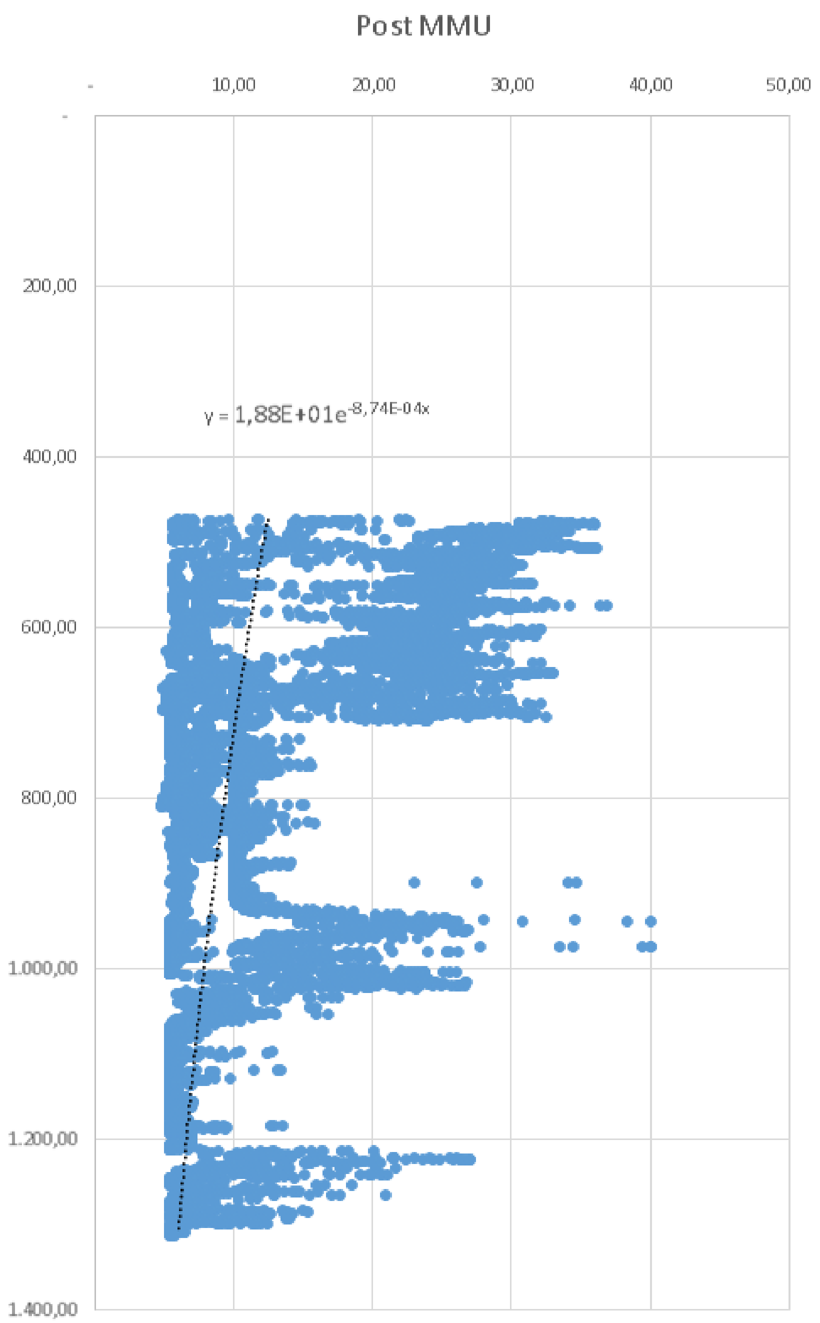


Figure 12: Porosity (y-axis) depth (x-axis) relationship for the Post MMU-Pleistocene stratigraphic units. The graph is based on 6 wells.

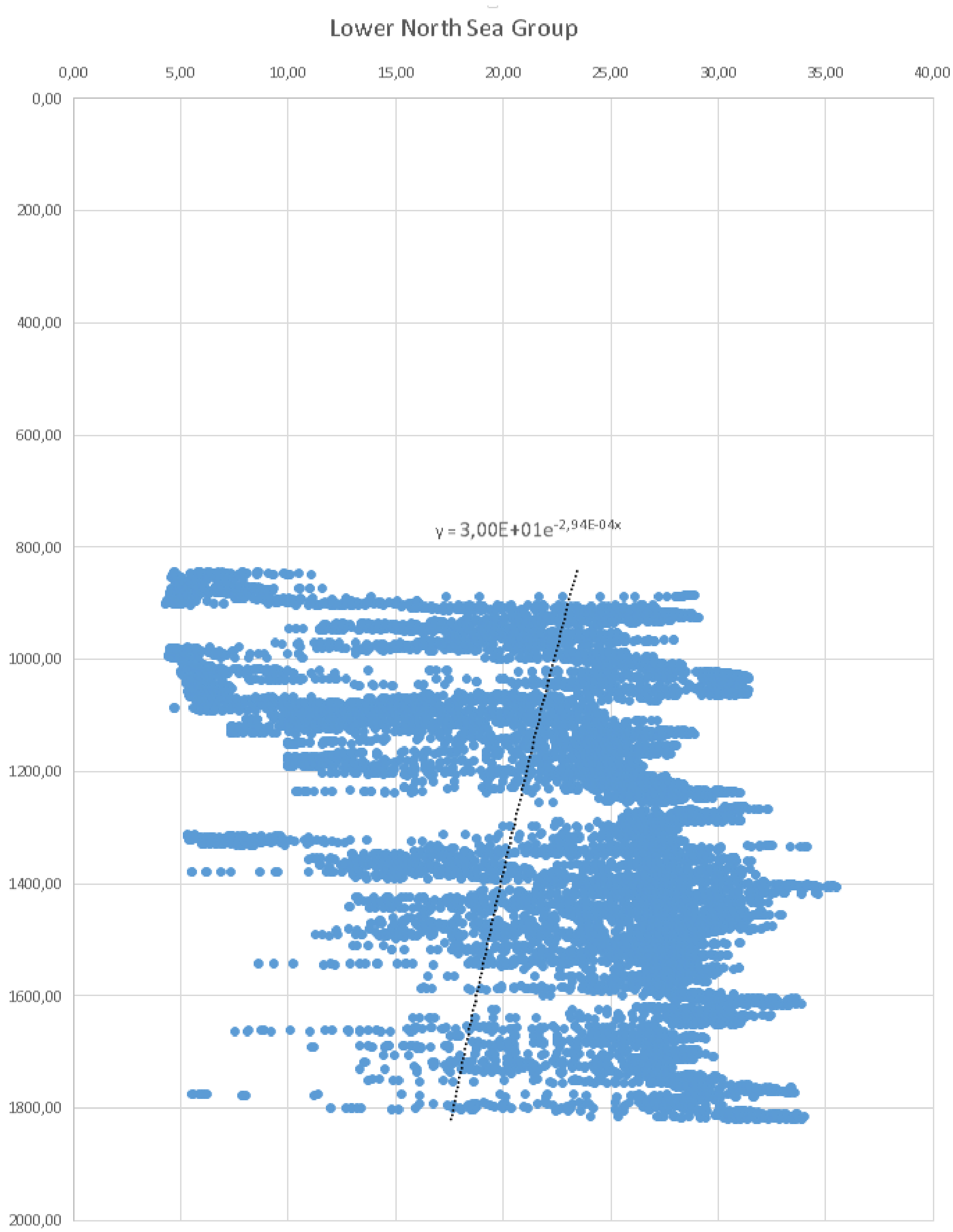


Figure 13: Porosity (y-axis) depth (x-axis) relationship for the Lower North Sea stratigraphic unit. The graph is based on 6 wells. The regression is forced to intersect at a porosity of 30%.

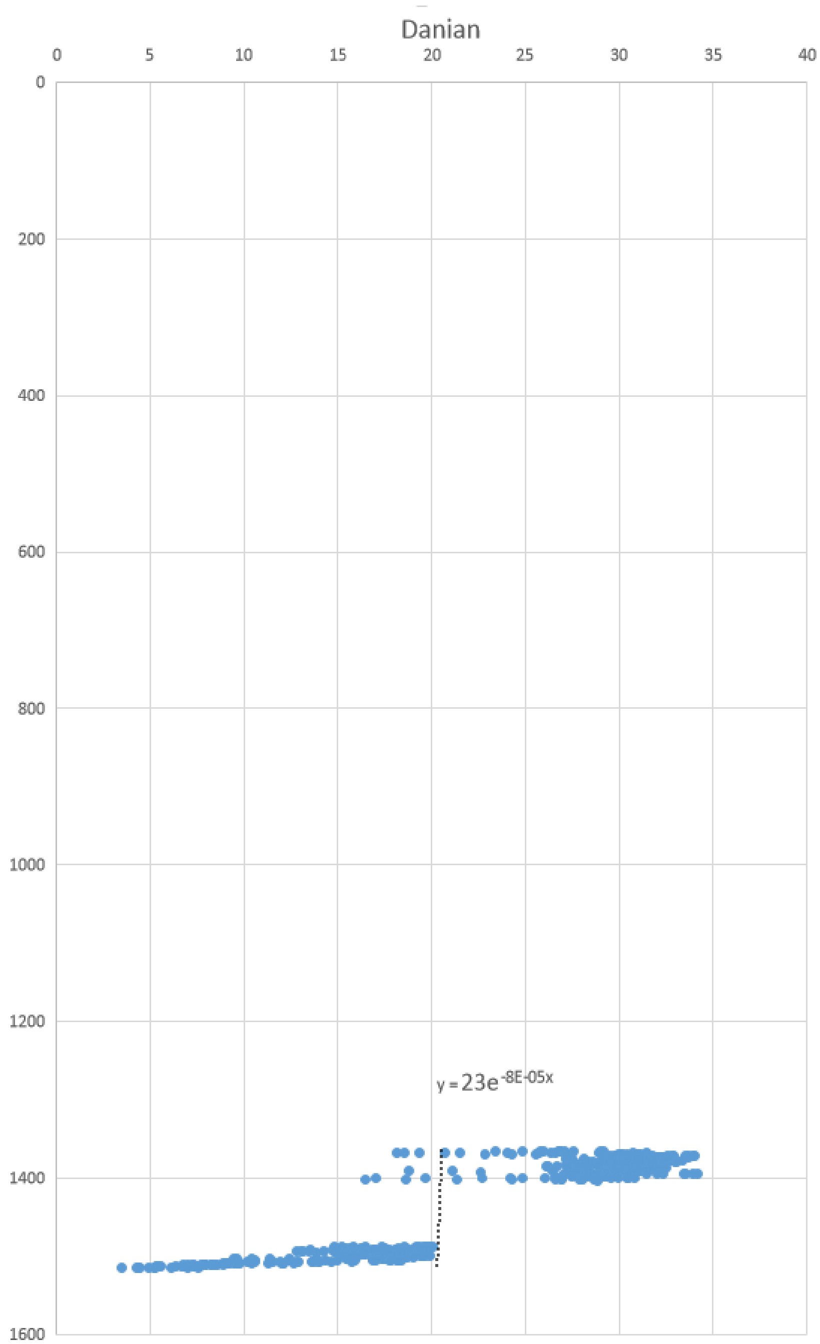


Figure 14: Porosity (y-axis) depth (x-axis) relationship for the Danian stratigraphic unit. The graph is based on 3 wells. The regression is forced to intersect at a porosity of 23%.

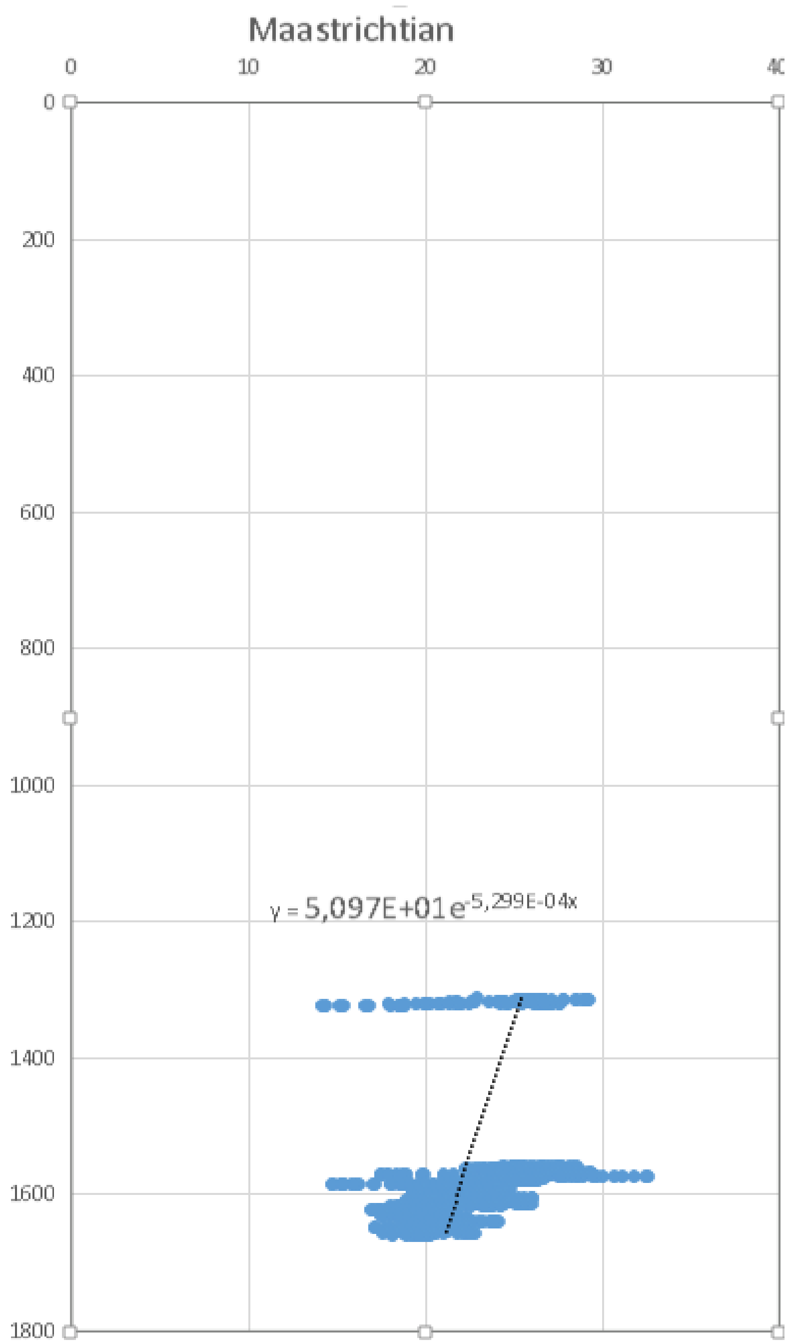


Figure 15: Porosity (y-axis) depth (x-axis) relationship for the Maastrichtian stratigraphic unit. The graph is based on 4 wells.

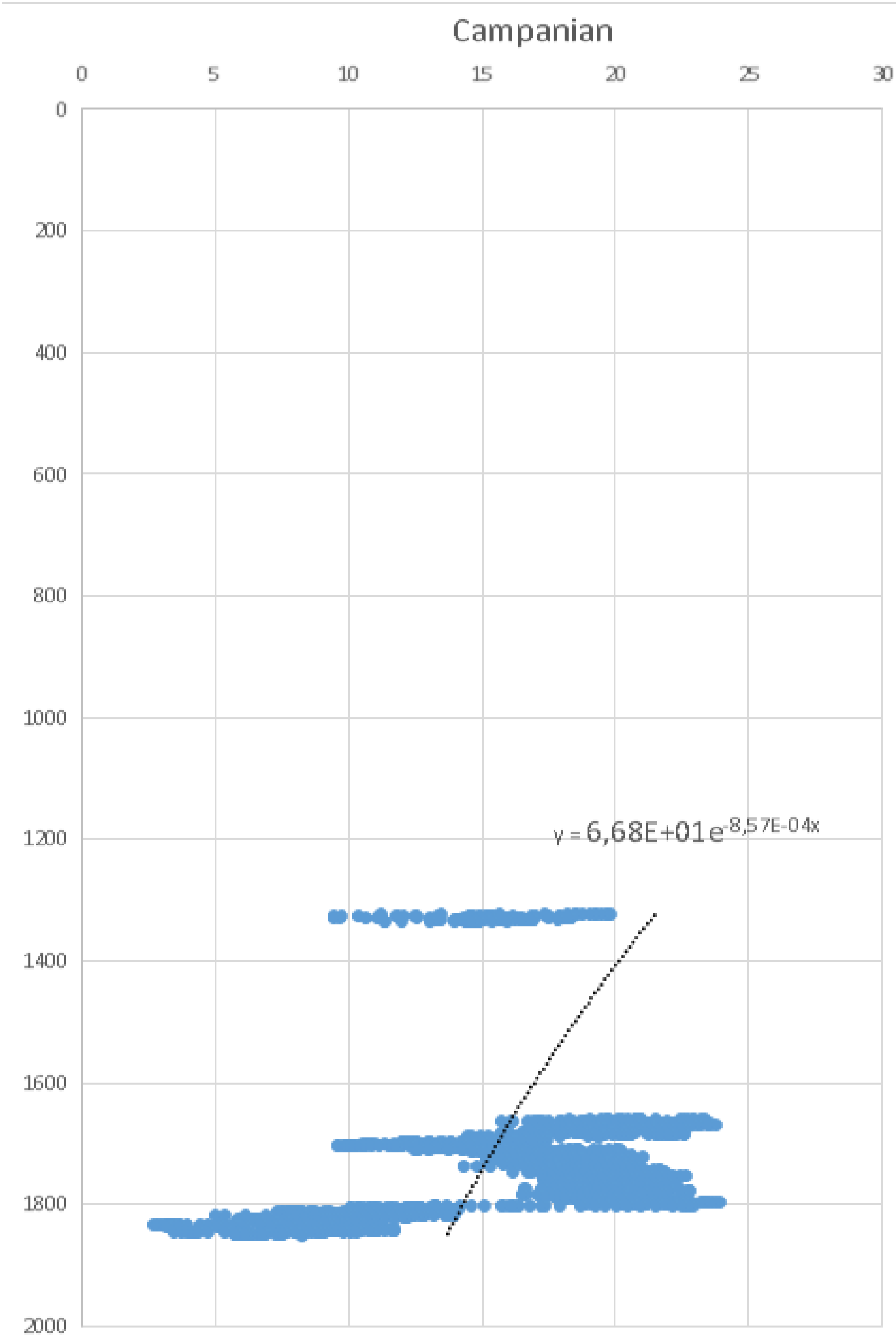


Figure 16: Porosity (y-axis) depth (x-axis) relationship for the Maastrichtian stratigraphic unit. The graph is based on 4 wells.

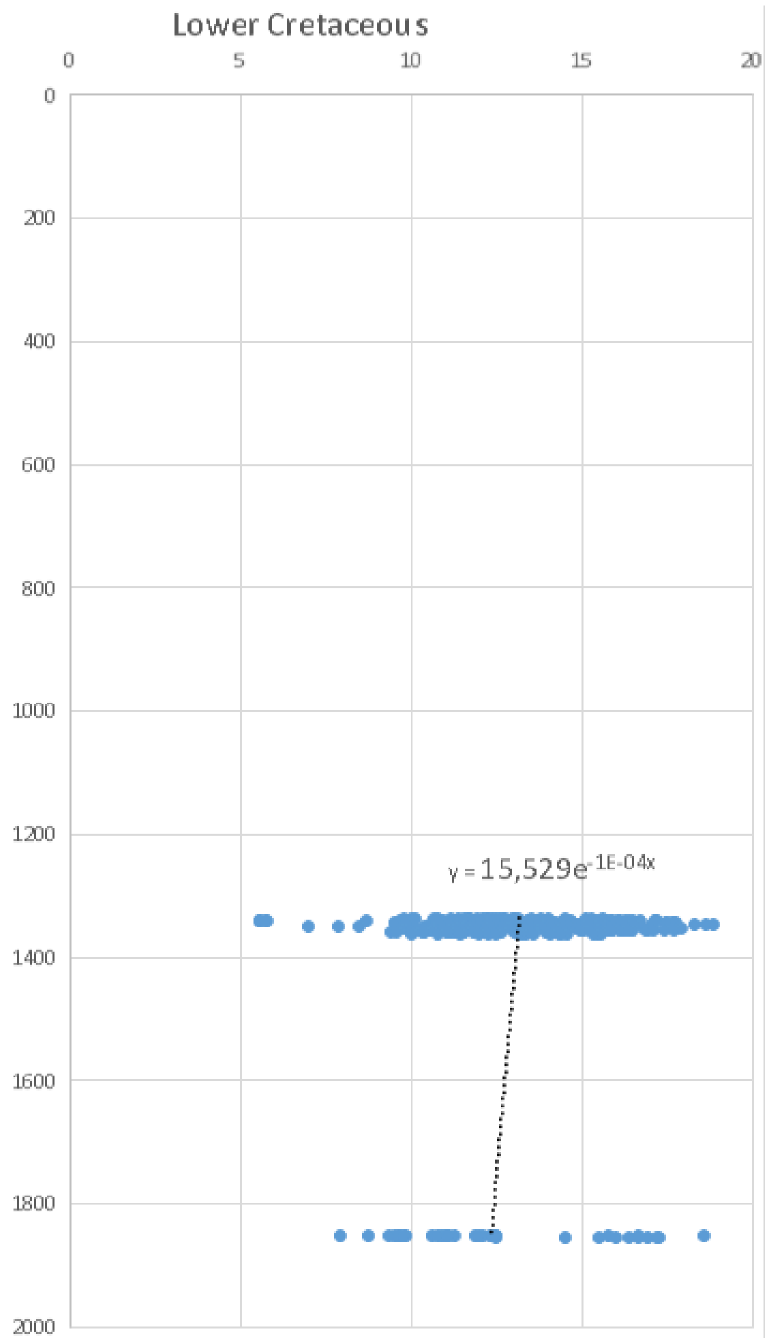


Figure 17: Porosity (y-axis) depth (x-axis) relationship for the Lower Cretaceous stratigraphic unit. The graph is based on 3wells.

Appendix 3 Fault heaves

measured heave		Top Danian	Maasrtrichtian	Base Chalk	Base Cretaceous
NS 1	Centre	20	-	-	70
	Edge	94	-	135	135
NS 2	Centre	76	-	150	150
	Edge	88	-	180	-
NS 3	Centre	217	-	180	-
	Edge	34	-	110	152
NS 4	Centre	34	-	95	95
	Edge	20	-	0	0
NS 5	Centre	75	130	200	230
	Edge	0	-	-	150
NS 6	Centre	150	-	600	712
	Edge	0	-	400	400
NS 7	Centre	150	-	230	230
	Edge	133	-	280	280
NS 8	Centre	0	0	0	0
	Edge	0	0	0	0
NS 9	Centre	0	0	0	0
	Edge	0	0	0	0
NS 10	Centre	40	-		200
	Edge	52	-		119
NS 11	Centre	0	0	0	0
	Edge	0	0	0	0
NS 12	Centre	45	27	-	231
	Edge	34	-	-	360
NS 13	Centre	40	-	16	16
	Edge	27	-	16	16
NS 14	Centre	10	-	170	170
	Edge	10	-	129	129
NS 15	Centre	53	-	-	138
	Edge	0	-	-	0
NS 16	Centre	82	-	164	164
	Edge	90	-	164	164
Camp1	Centre	0	-	0	0
	Edge	0	-	0	0
S13-1	Centre	20		83	83
	Edge	0	0	0	0
S13-2	Centre	0	0	0	0
	Edge	0	0	0	0
S13-3	Centre	360	-	360	360
	Edge	162	-	162	162
S13-4	Centre	100	-	0	0
	Edge	0	0	0	0
S13-5	Centre	0	0	0	0
	Edge	0	0	0	0
S13-6	Centre	0	0	0	0
	Edge	0	0	0	0
S11	Centre	230	-	290	290
	Edge	130	-	64	64
MMU1	Centre	30	-	40	40
	Edge	0	-	0	0
MMU2	Centre	160	-	0	0
	Edge	0	-	0	0
MMU3	Centre	130	-	190	190
	Edge	100	-	60	60

Figure 18: Faults and their heaves as measured at the center of the fault and at their edge. A bar indicates that the horizon is absent at that place or is equal to another horizon. Some faults have zero heaves, because their interpretation has zero heaves. In reality this can be more.

Appendix 4 Average density

Average Density	F05-04	F08-01	F06-03	Total Average density
pleistocene	2,077			2,077
Post MMU	2,125			2,125
North Sea	1,983	2,087	2,125	2,065
Danian	2,312		2,237	2,275
Maastrichtian	2,264		2,302	2,283
Campanian	2,403		2,375	2,389
Lower Cretaceous	2,264		2,426	2,345

Table 5: Average density for stratigraphic units. The table shows the average density per well for each unit, as well as the average density for all well combined.

Appendix 5 Cross-sections (restored in 3-D)

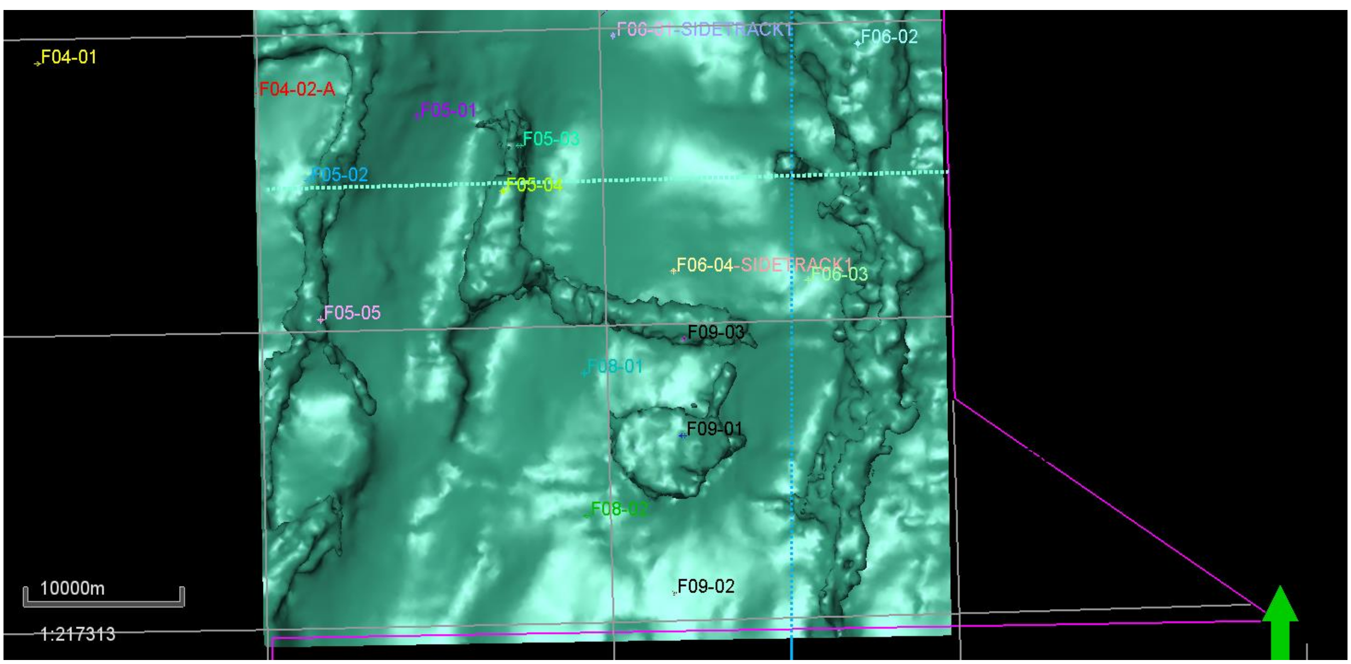


Figure 19: map showing the location of the two cross sections (one N-S, one E-W).

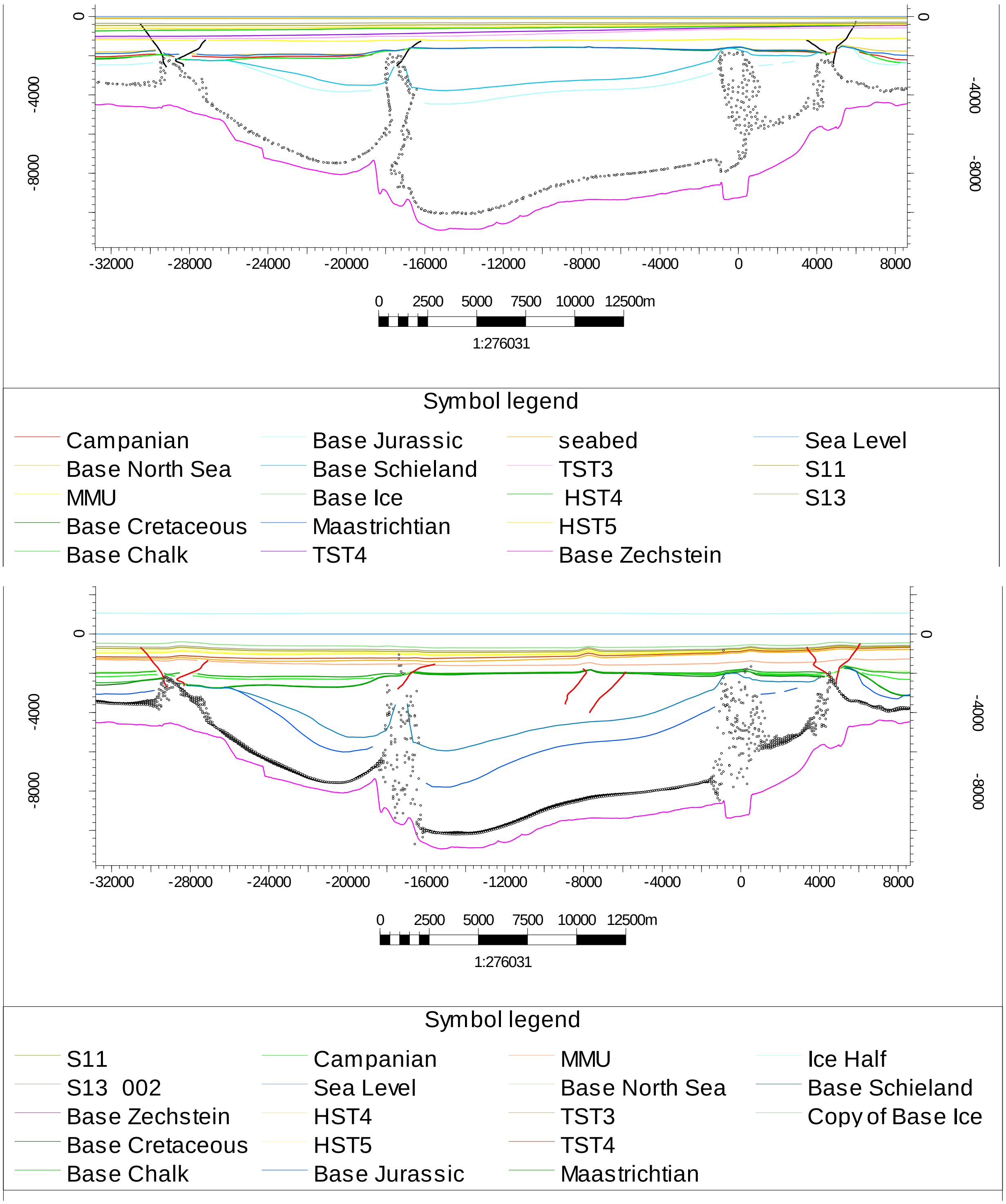


Figure 20: Cross sections with an E-W strike through time. From top to bottom: Present situation, Late Elsterian.

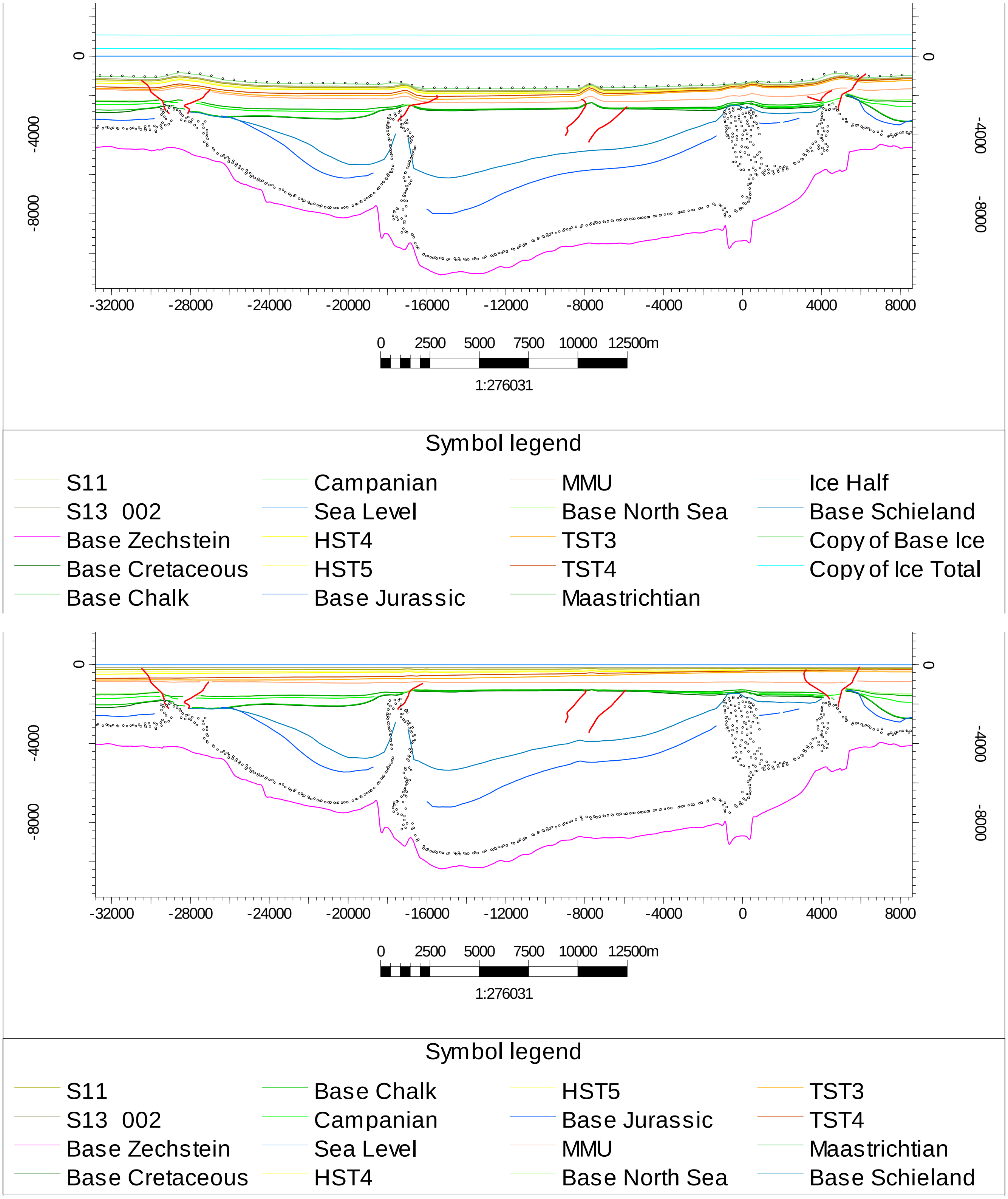


Figure 21: Cross sections with an E-W strike through time. From top to bottom: the situation during Early Elsterian, the situation during deposition of S13.

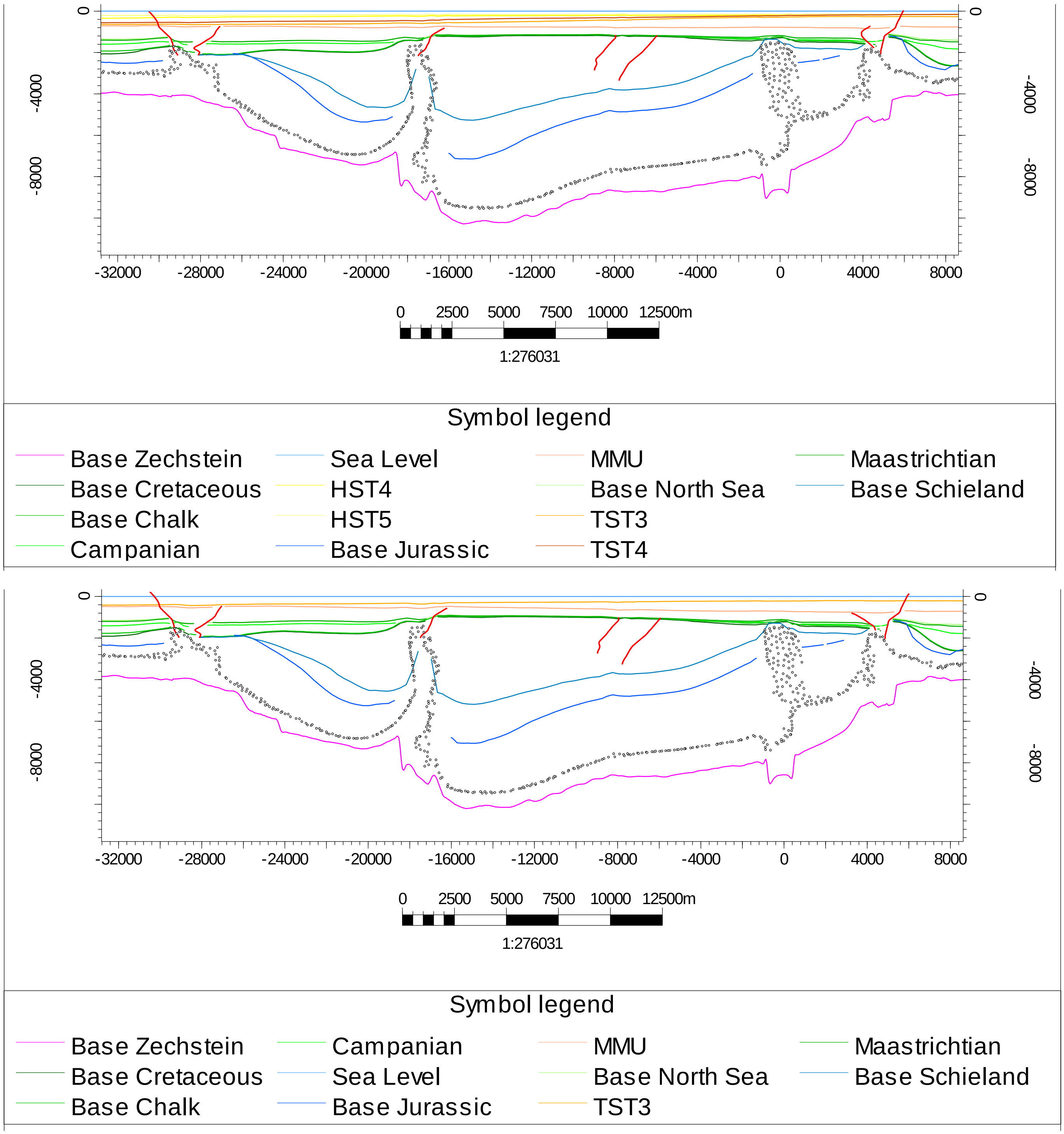


Figure 22: Cross sections with an E-W strike through time. From top to bottom: the situation during deposition of HST5, and TST3.

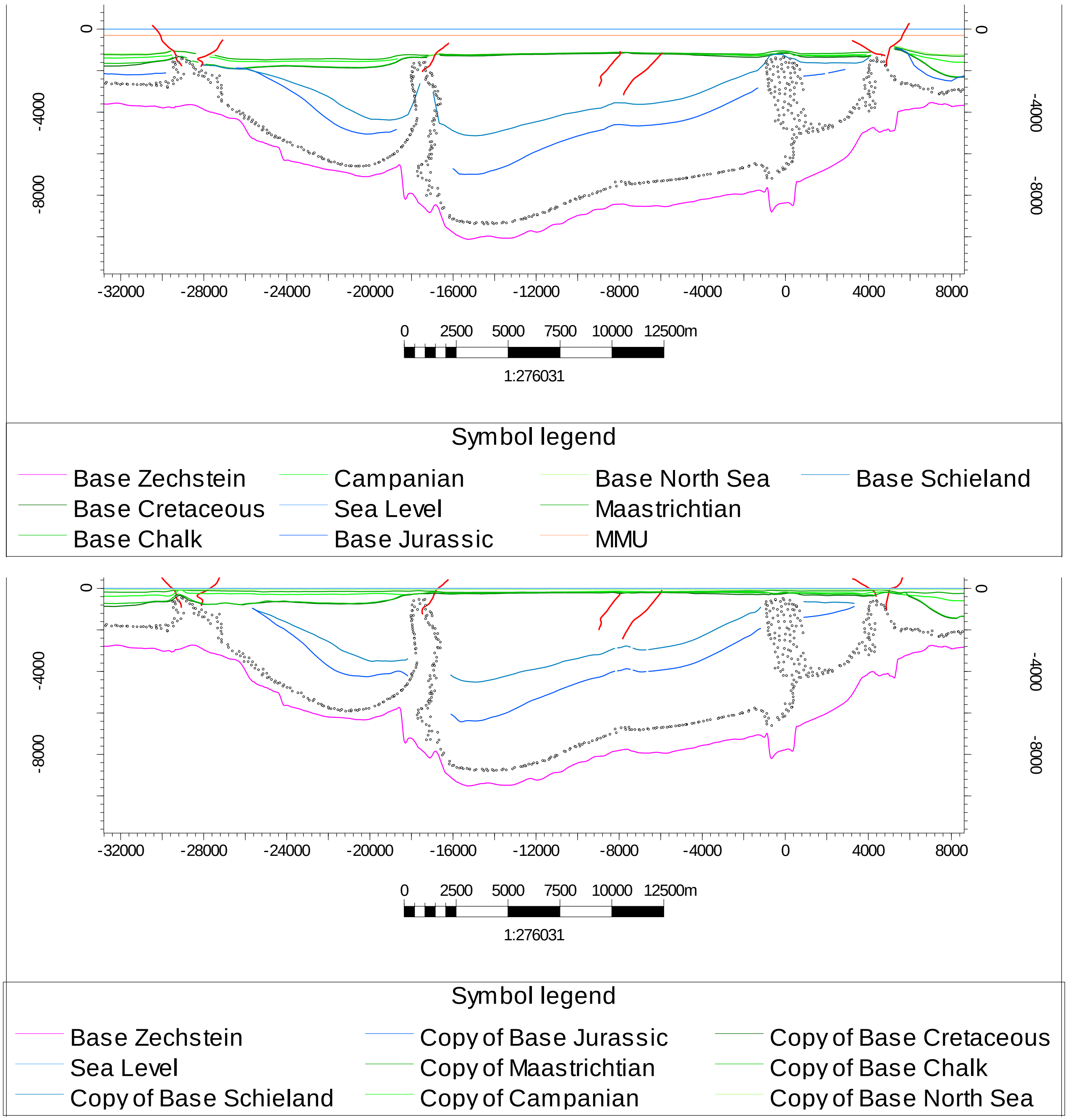
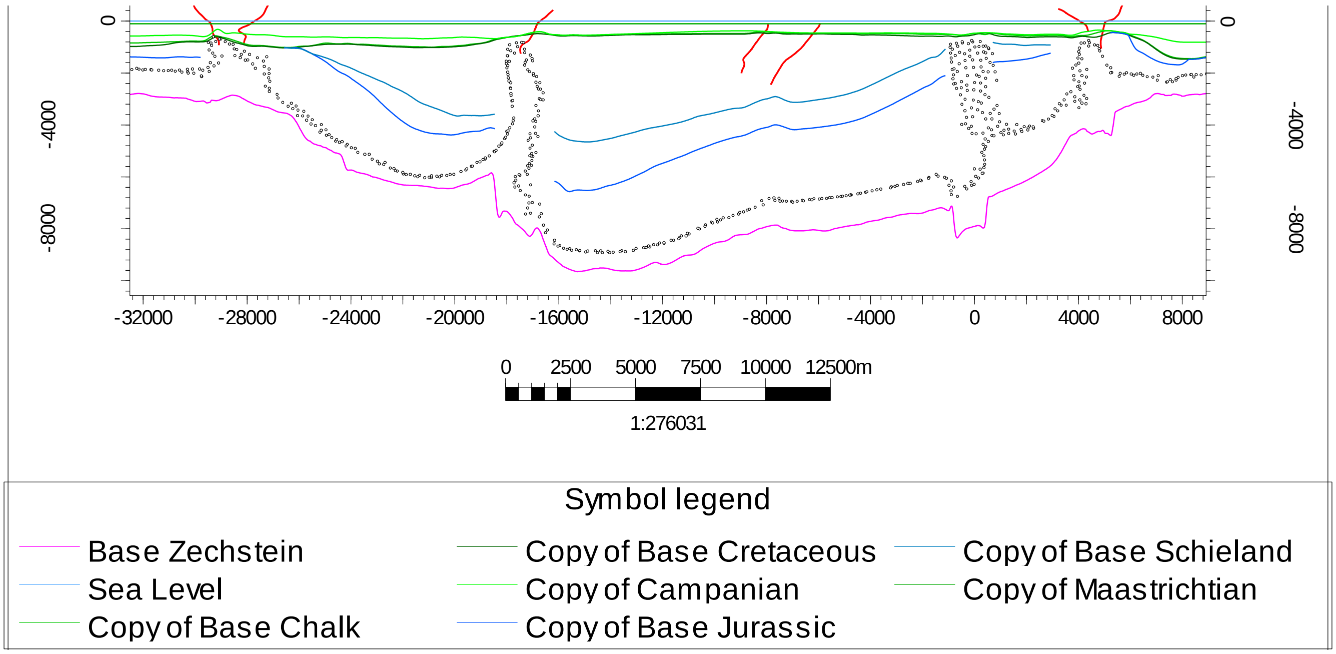


Figure 23: Cross sections with an E-W strike through time. From top to bottom: the situation during Early Mid Miocene (before erosion), and the situation during Early Danian (before erosion).



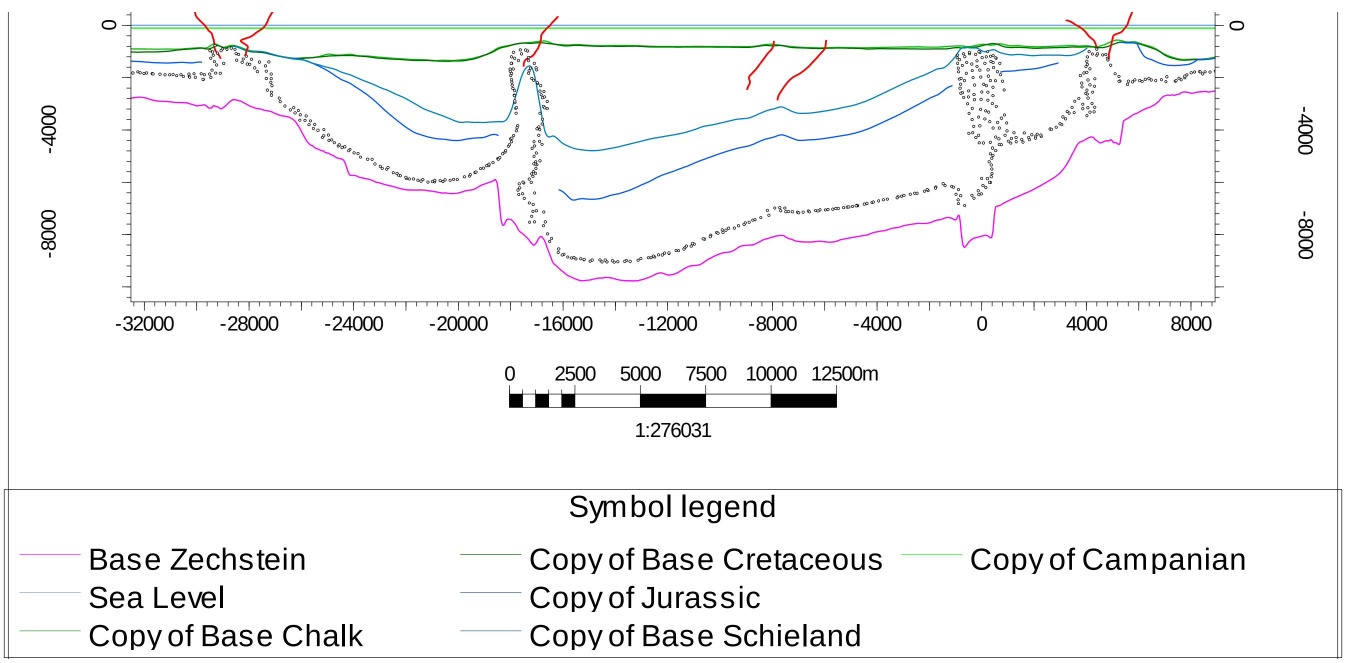


Figure 24: Cross sections with an E-W strike through time. From top to bottom: the situation during early Maastrichtian (before erosion), and the situation during early Campanian (before erosion).

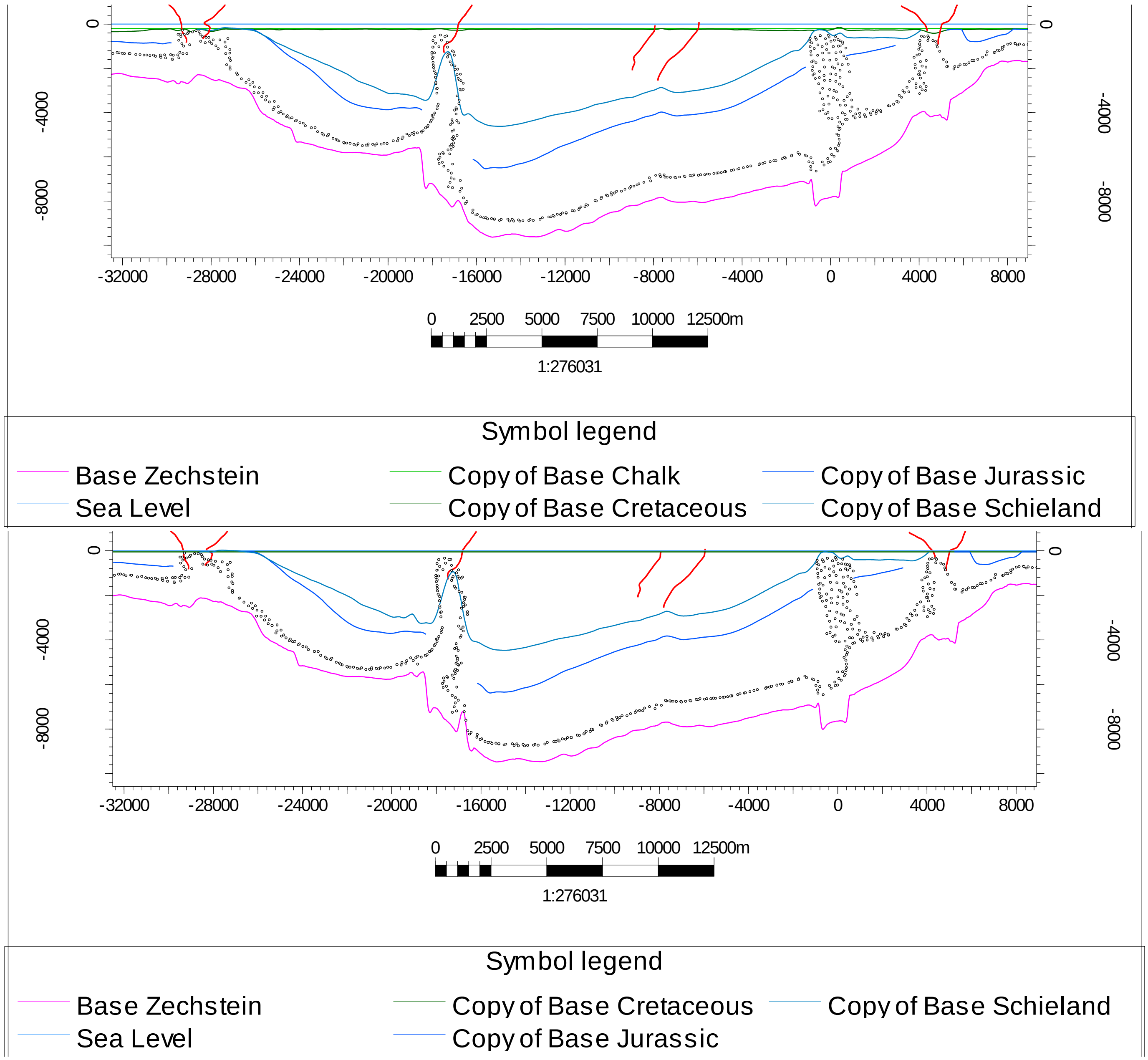


Figure 25: Cross sections with an E-W strike through time. From top to bottom: the situation during deposition of the lowermost Chalk, the situation during deposition of the lower Cretaceous.

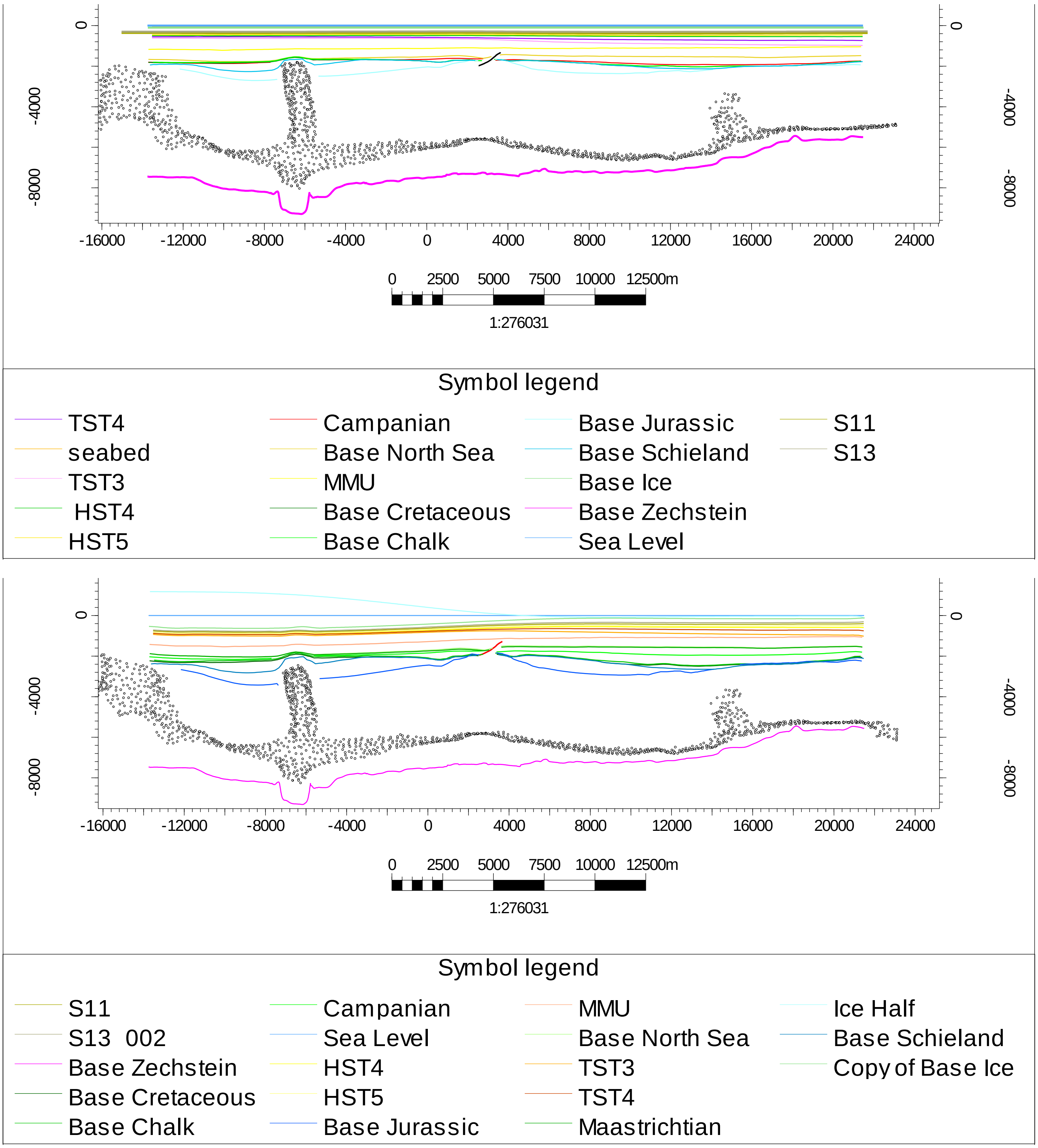


Figure 26: Cross sections with an N-S strike through time. From top to bottom: the situation during the Present, the situation during the Late Elsterian.

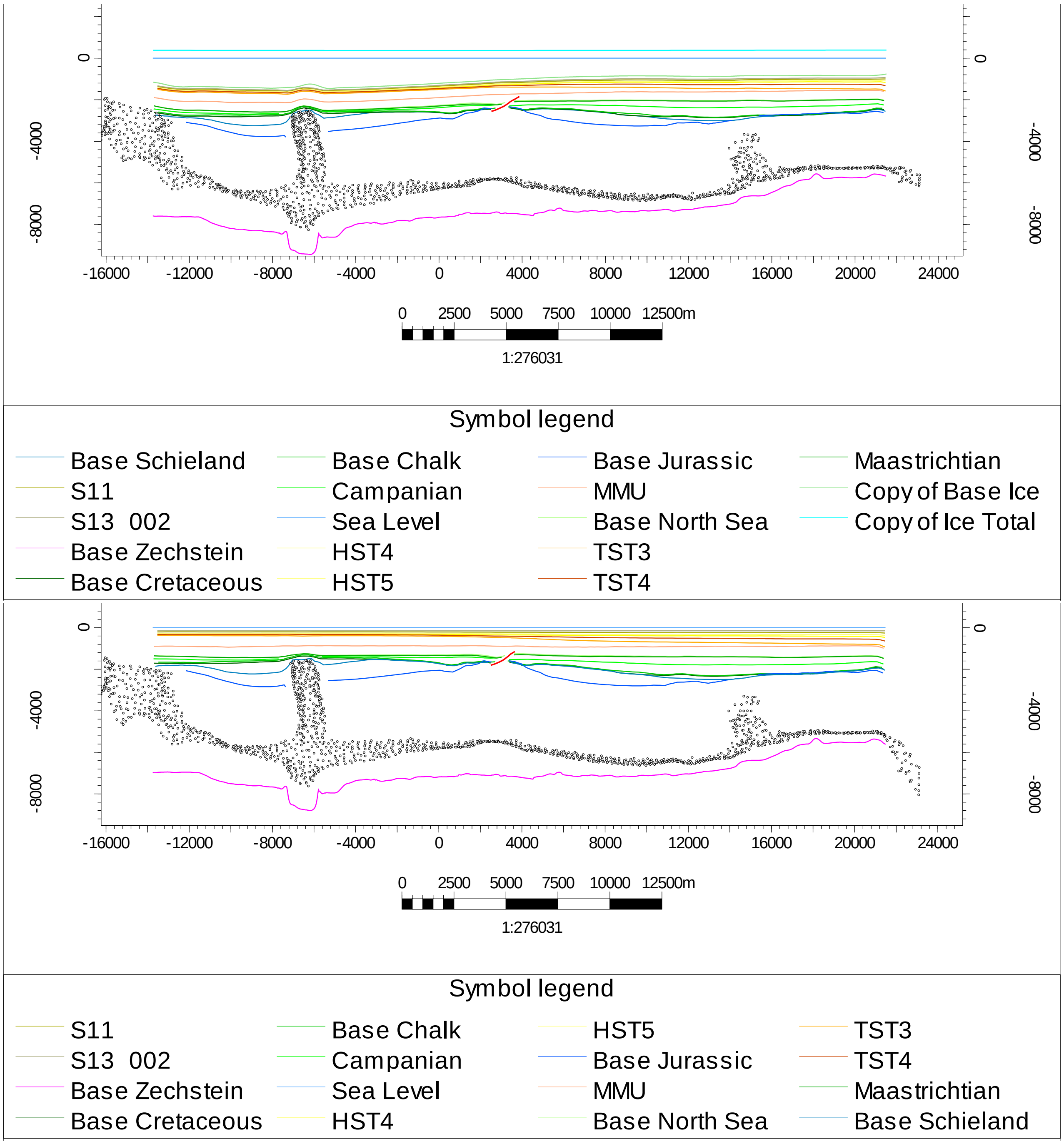


Figure 27: Cross sections with an N-S strike through time. From top to bottom: the situation during Early Elsterian and the situation during deposition of S13

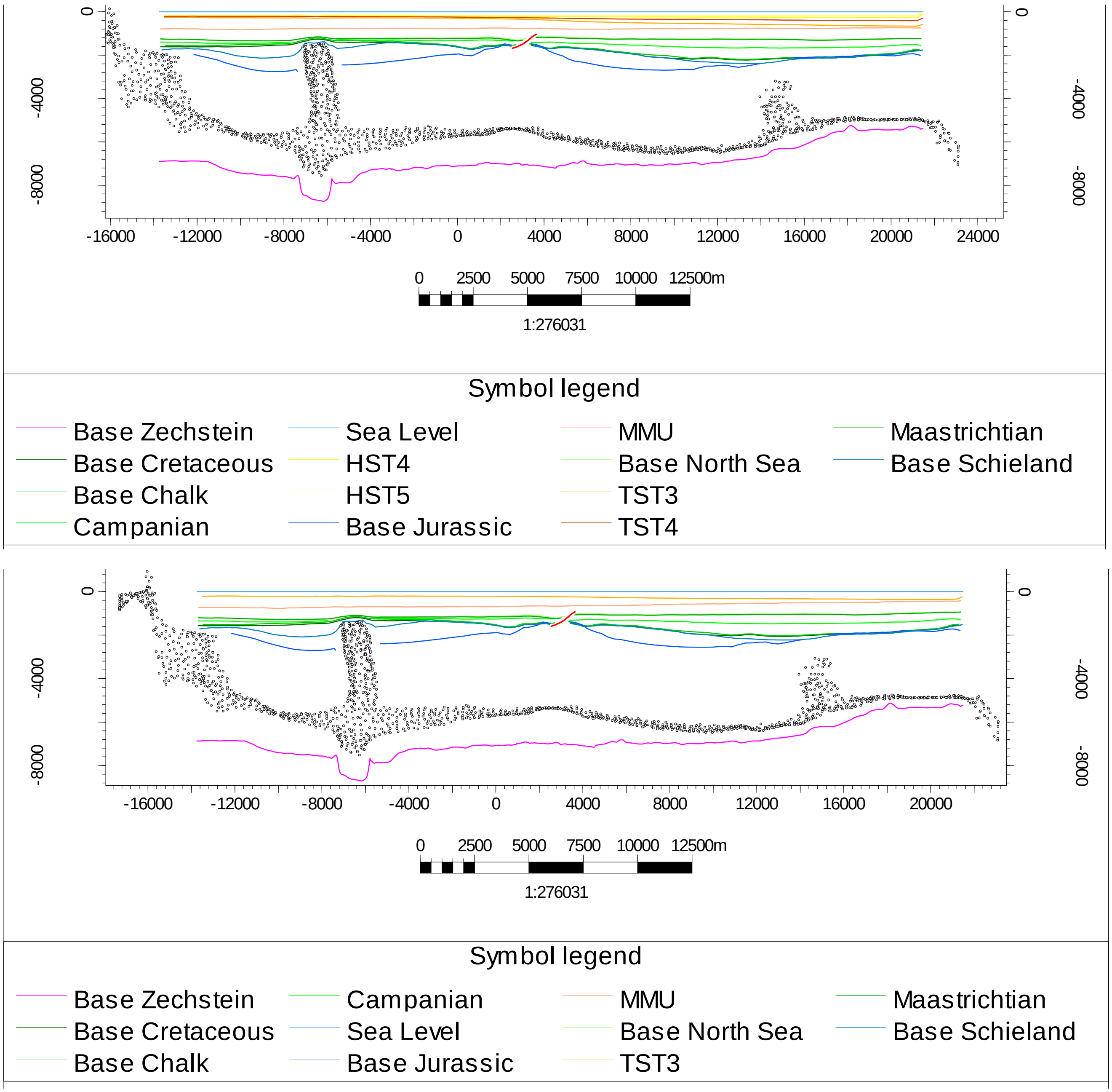


Figure 28: Cross sections with an N-S strike through time. From top to bottom: the situation during deposition of HST5, and the situation during deposition of TST3.

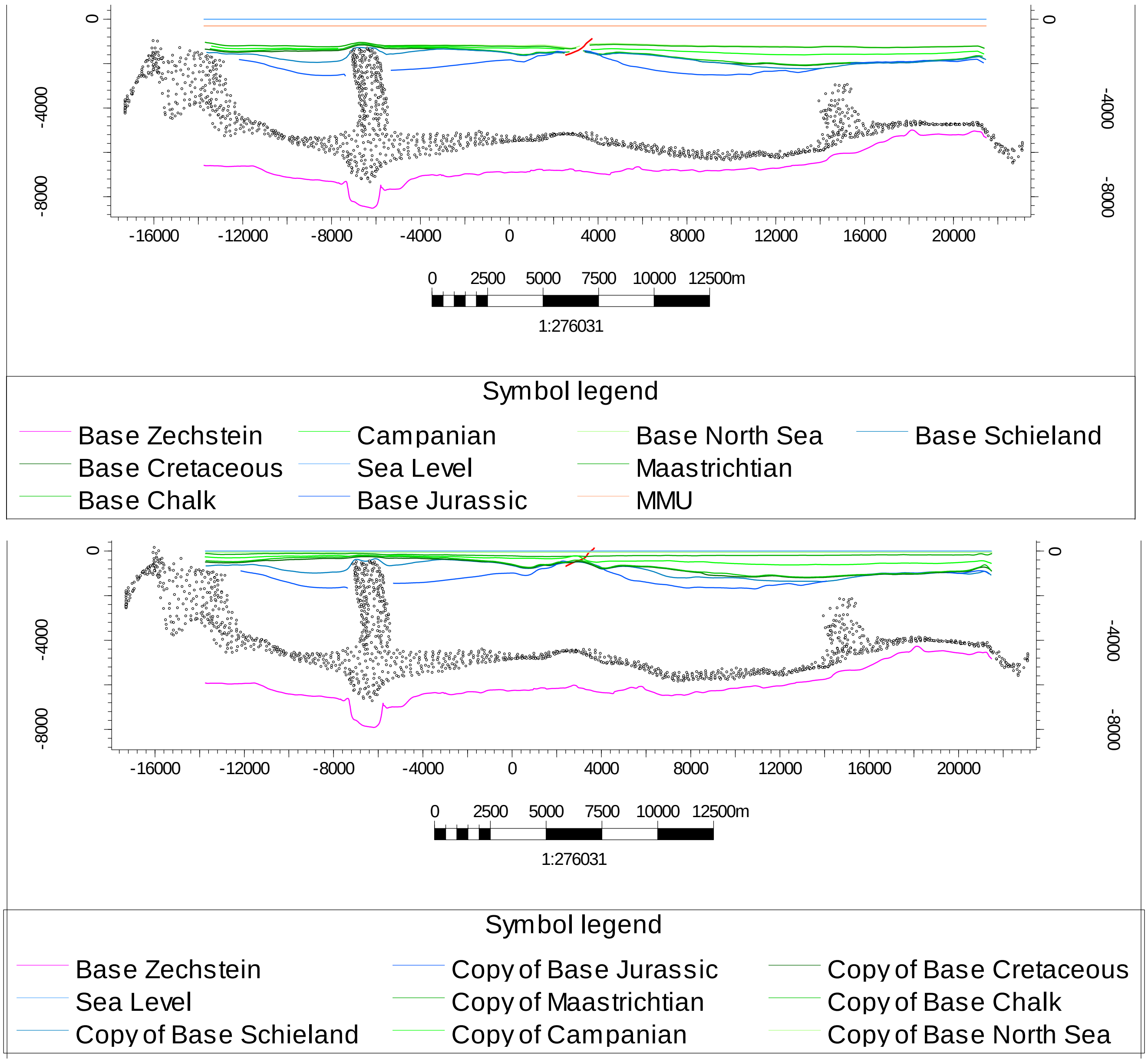


Figure 29: Cross sections with an N-S strike through time. From top to bottom: the situation during early Mid-Miocene (before erosion), and the situation during early Danian (before erosion)

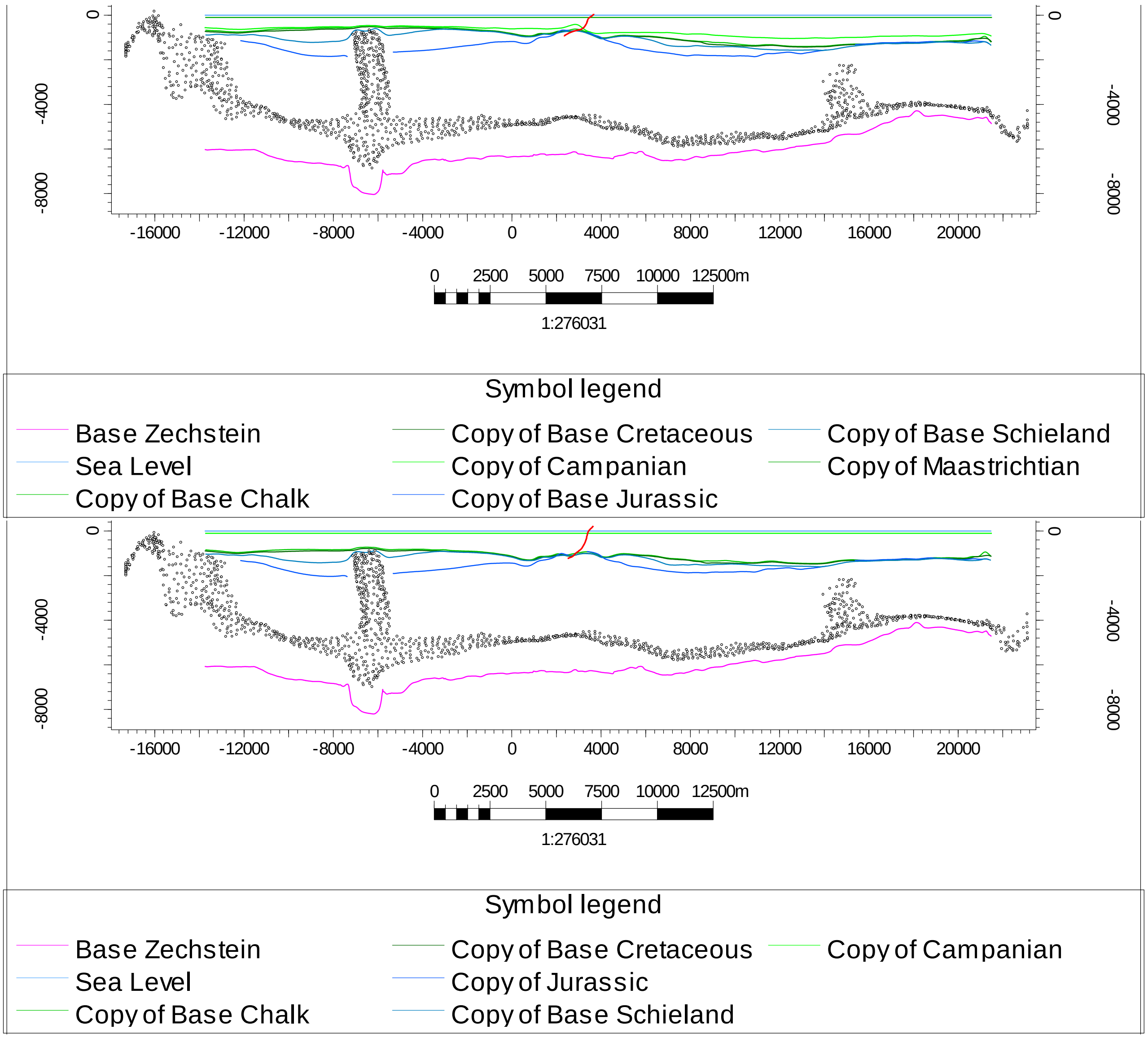


Figure 30: Cross sections with an N-S strike through time. From top to bottom: the situation during early Maastrichtian (before erosion), the situation during early Campanian (before erosion).

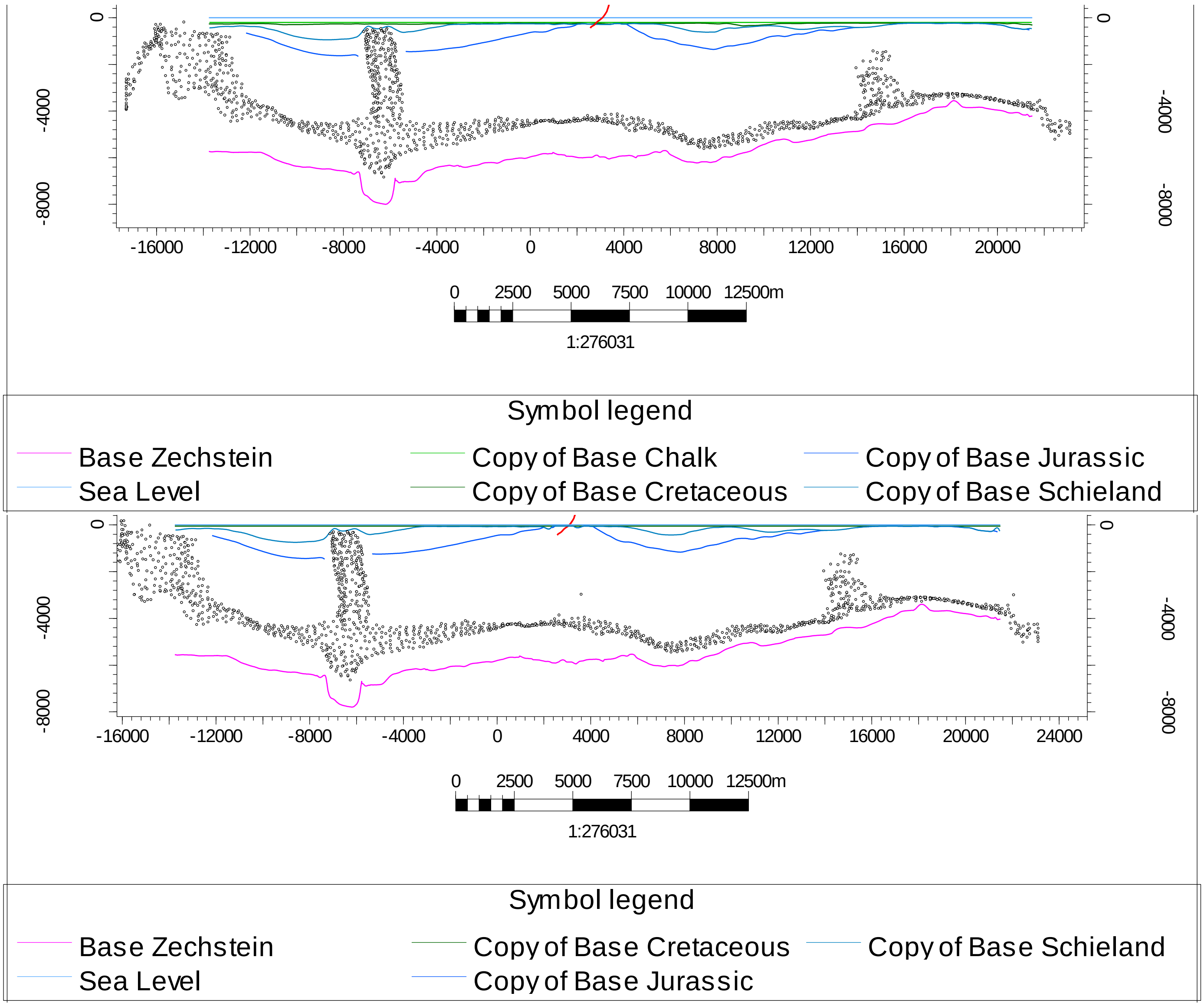


Figure 31: Cross sections with an N-S strike through time. From top to bottom: the situation during start of lower Chalk deposition, the situation during deposition of lower Cretaceous.

Appendix 6 Oil Maturity Posidonia Shale in Model 1

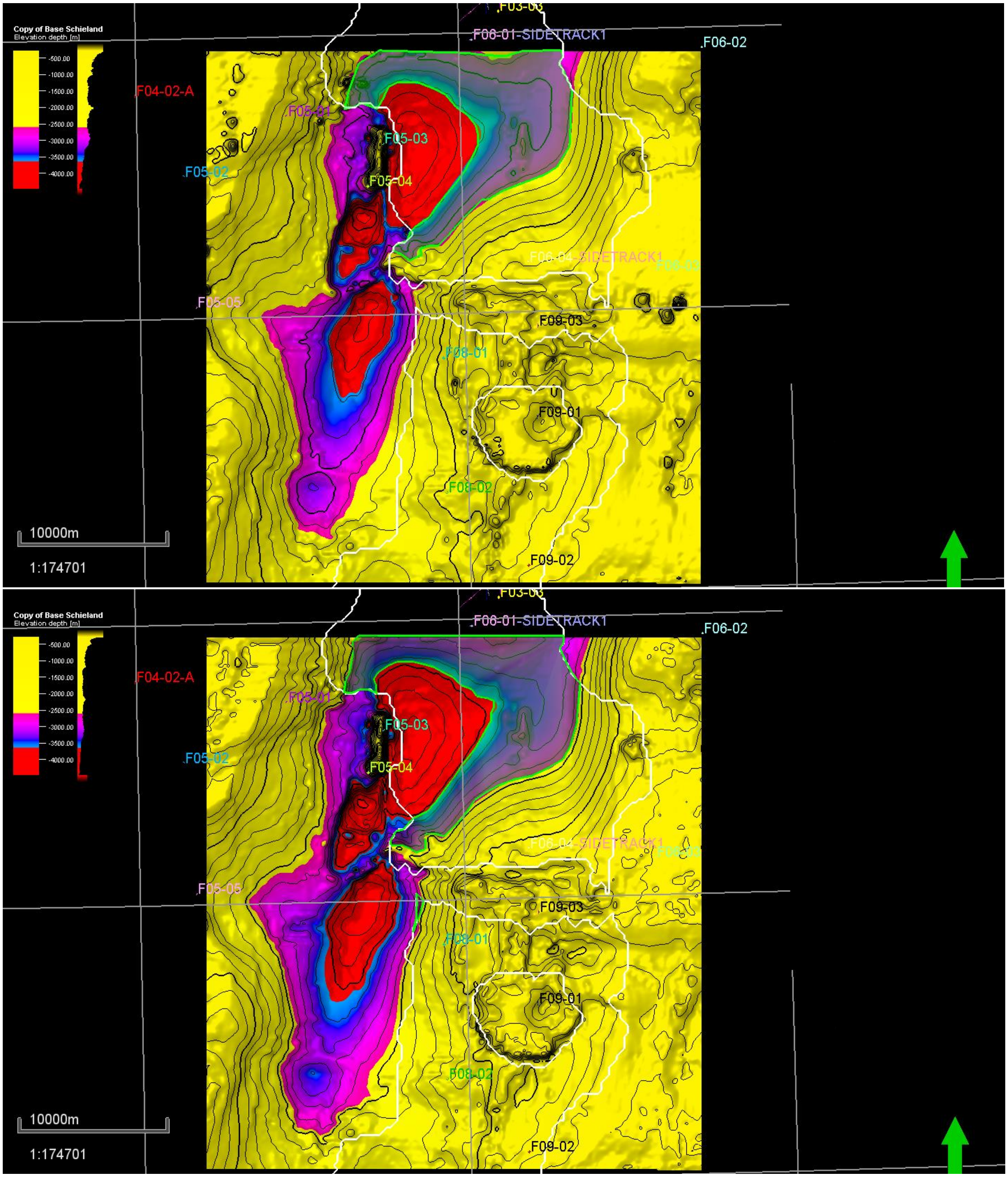


Figure 32: Showing the maturity of the Posidonia shale. Upper figure is the situation during the early Cretaceous, lower figure during the late early Cretaceous. In Green the area where the Posidonia is oil mature and present.

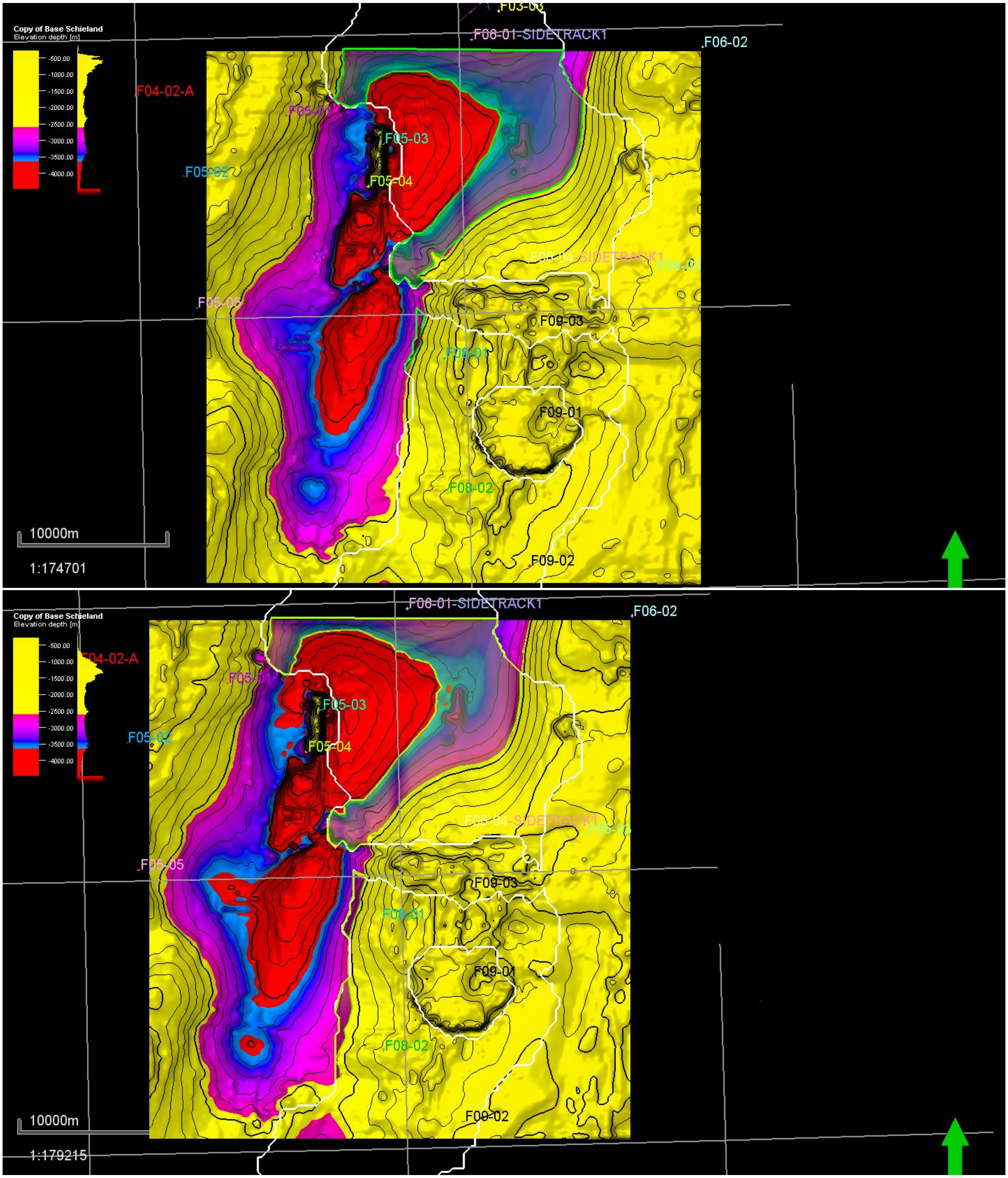


Figure 33: Showing the maturity of the Posidonia shale. Upper figure is the situation during the late base Chalk deposition, lower figure during the Campanian. In green the area where the Posidonia is oil mature and present.

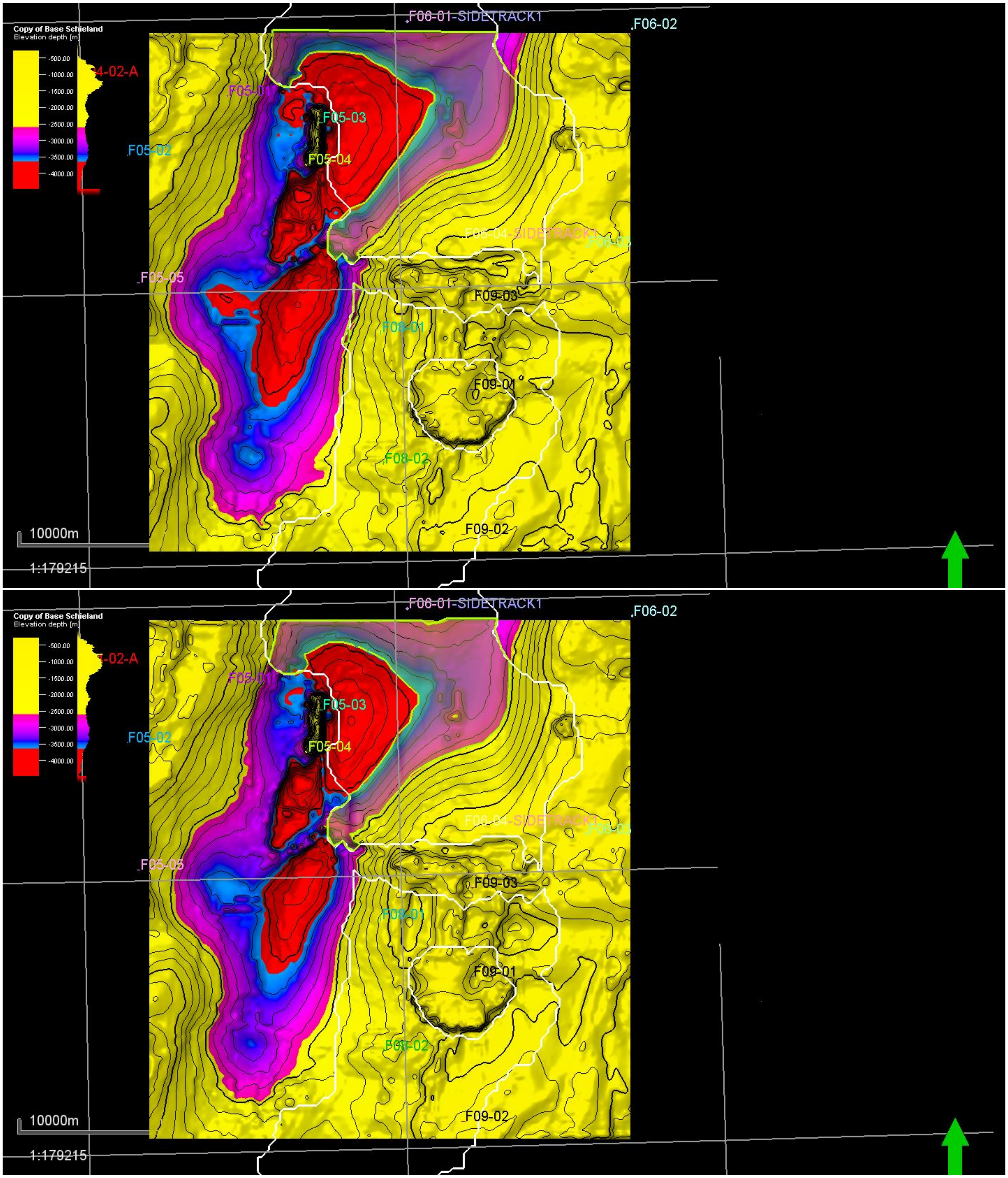


Figure 34: Showing the maturity of the Posidonia shale. Upper figure is the situation during the Maastrichtian, lower figure during the early Danian. In Green the area where the Posidonia is oil mature and present.

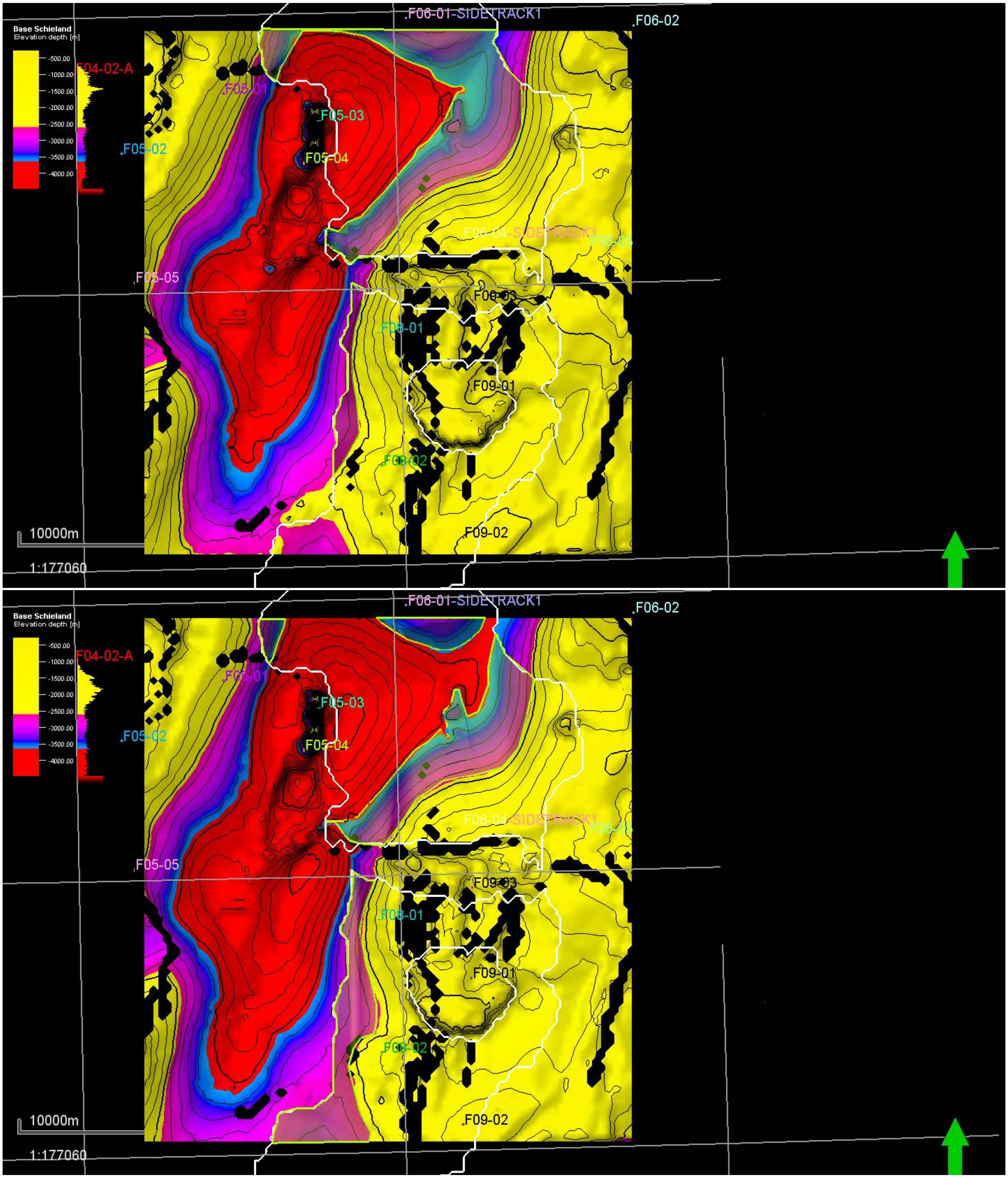


Figure 35: Showing the maturity of the Posidonia shale. Upper figure is the situation during the Late Danian, lower figure during the mid-Miocene. In Green the area where the Posidonia is oil mature and present.

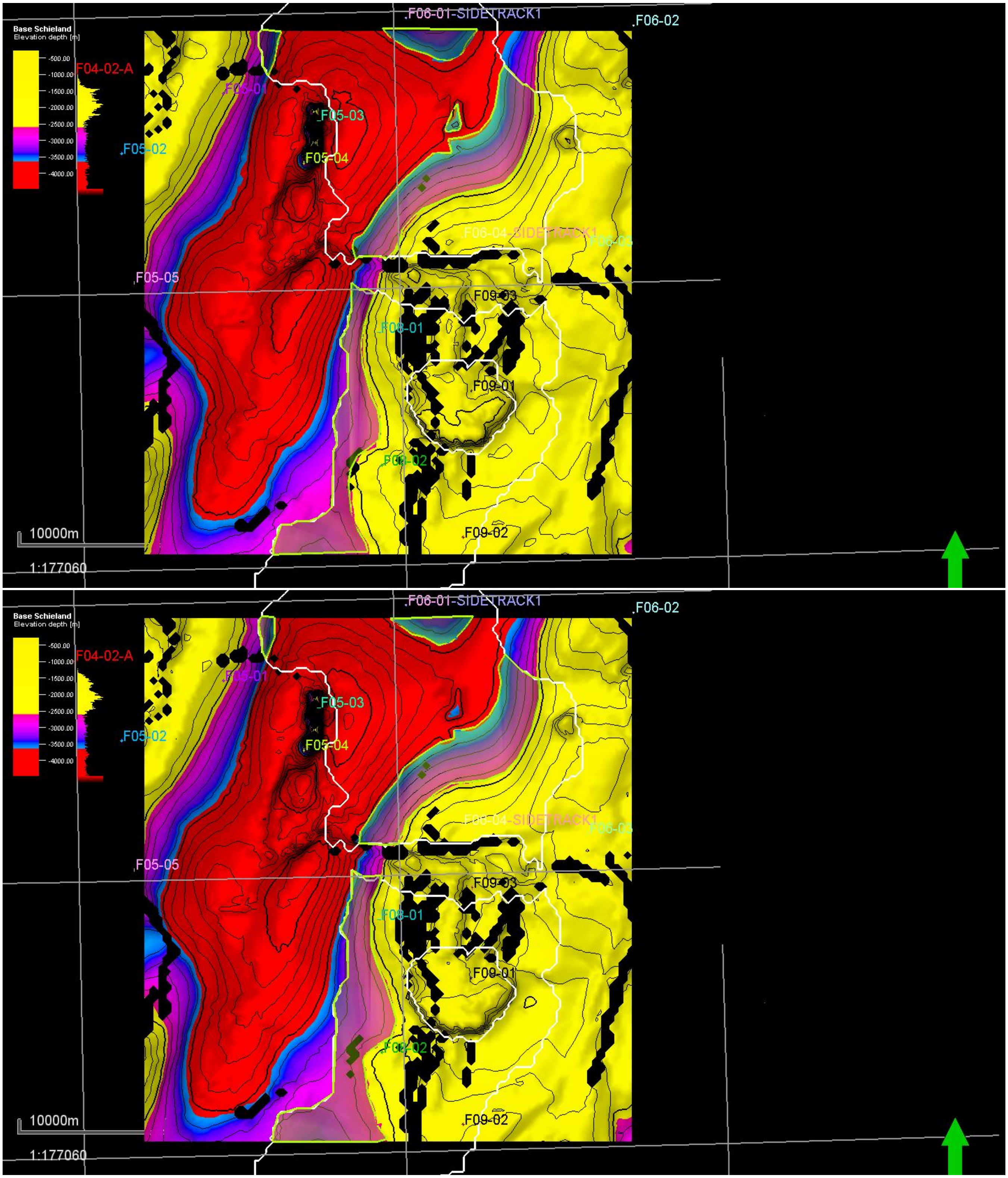


Figure 36: Showing the maturity of the Posidonia shale. Upper figure is the situation during the deposition of TST3, lower figure during the deposition of HST5. In Green the area where the Posidonia is oil mature and present.

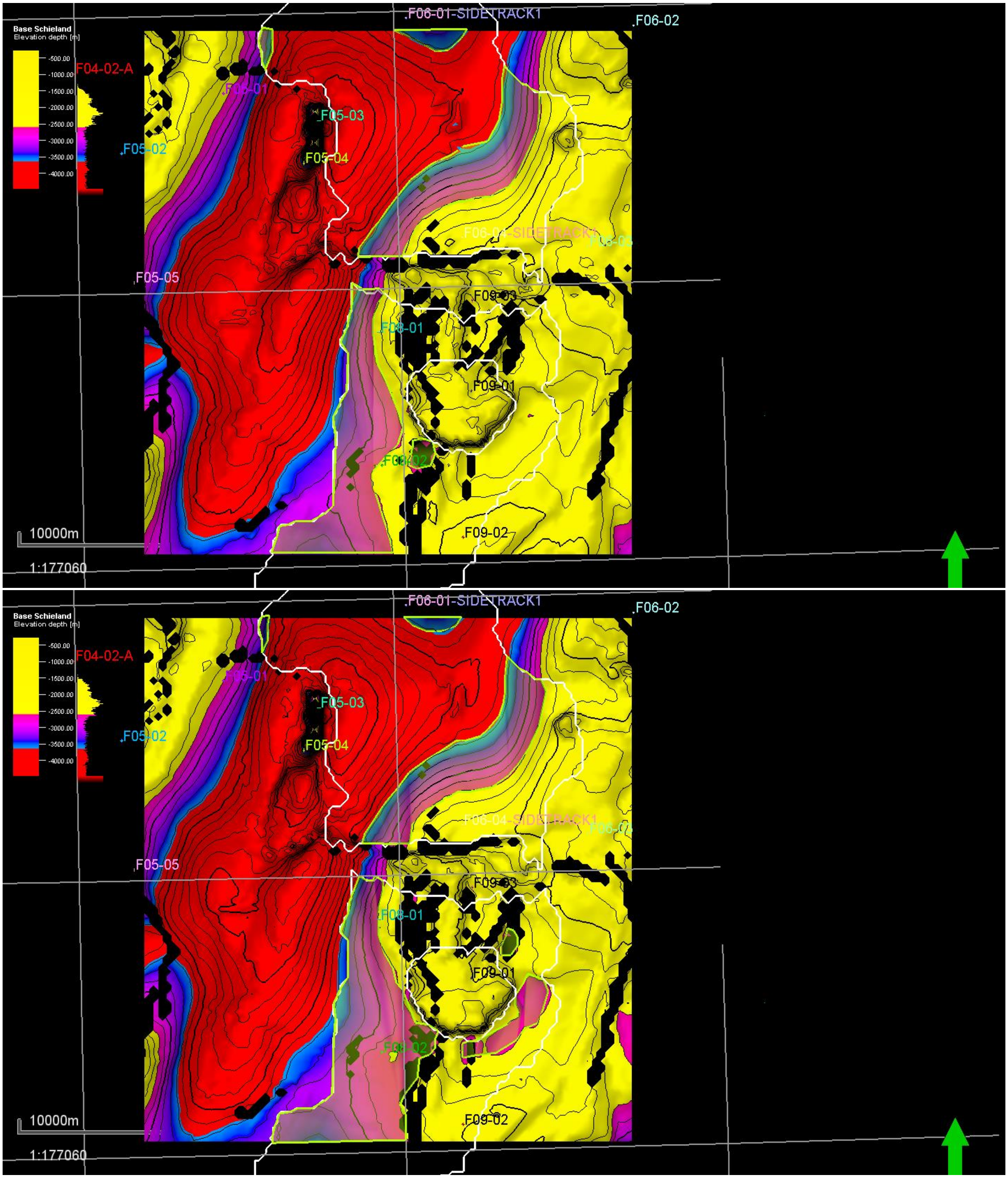


Figure 37: Showing the maturity of the Posidonia shale. Upper figure is the situation during the deposition of S11, lower figure during the pre-Elsterian. In Green the area where the Posidonia is oil mature and present.

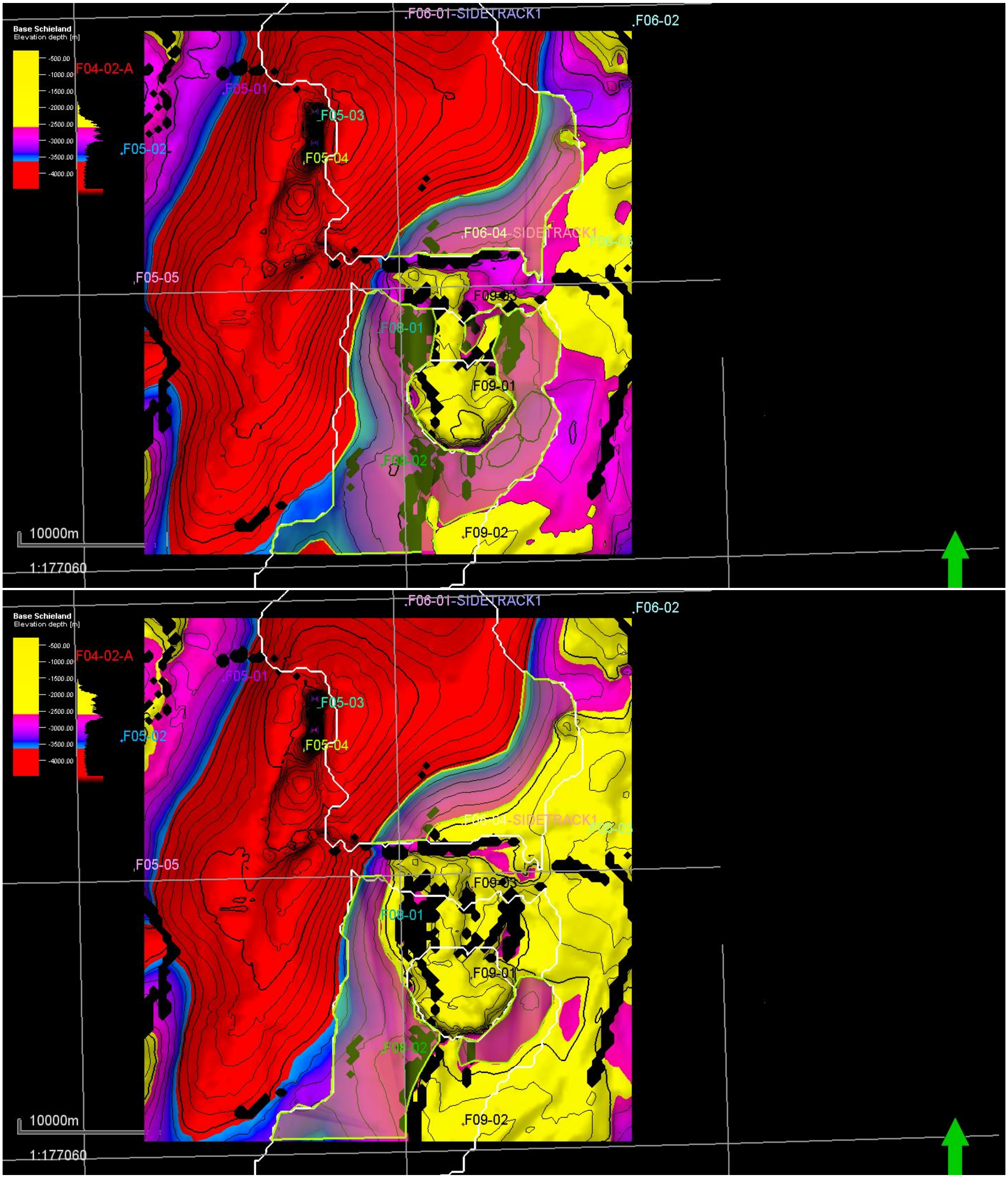


Figure 38: Showing the maturity of the Posidonia shale. Upper figure is the situation during the early Elsterian, lower figure during the late Elsterian. In Green the area where the Posidonia is oil mature and present.

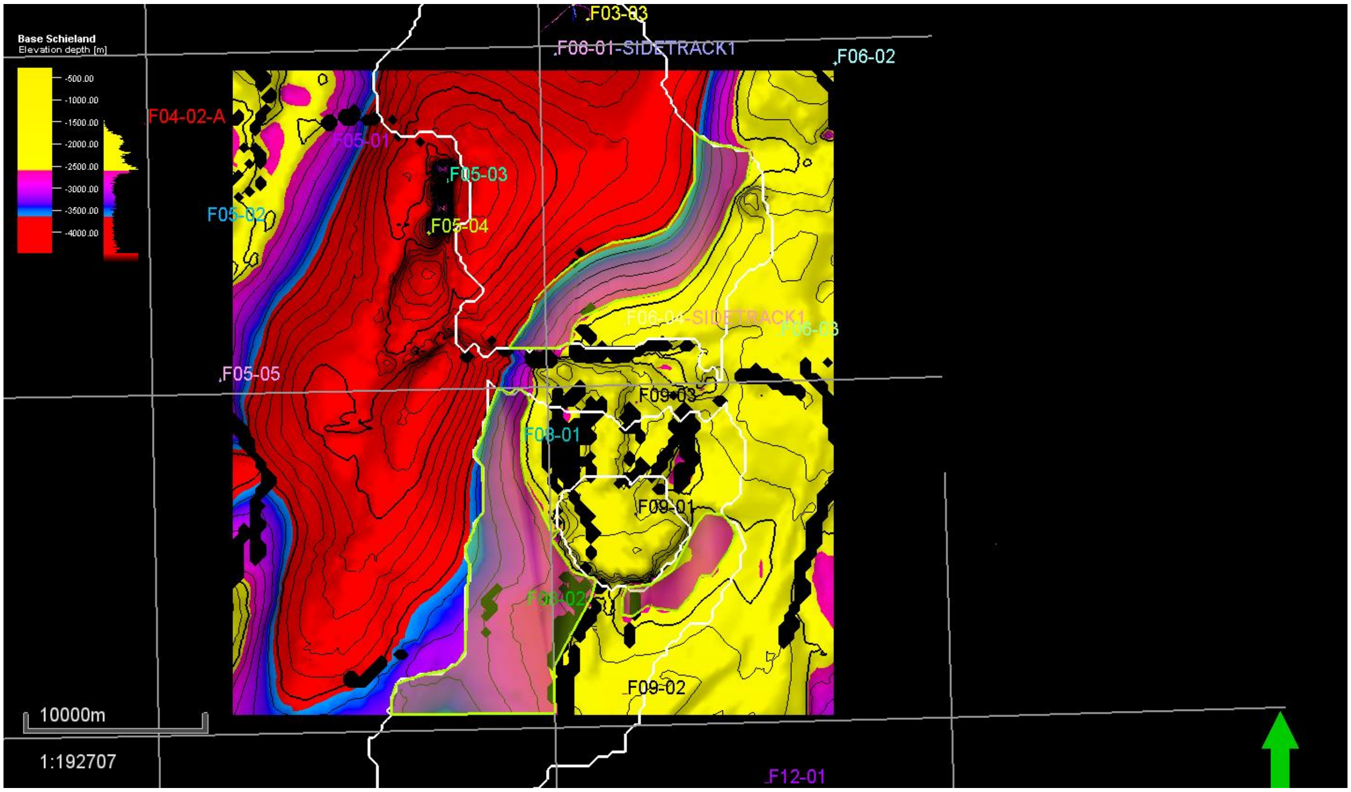


Figure 39: Showing the maturity of the Posidonia shale. Upper figure is the situation during the present. In Green the area where the Posidonia is oil mature and present.

Appendix 7 Oil migration paths in the Middle Graben Formation

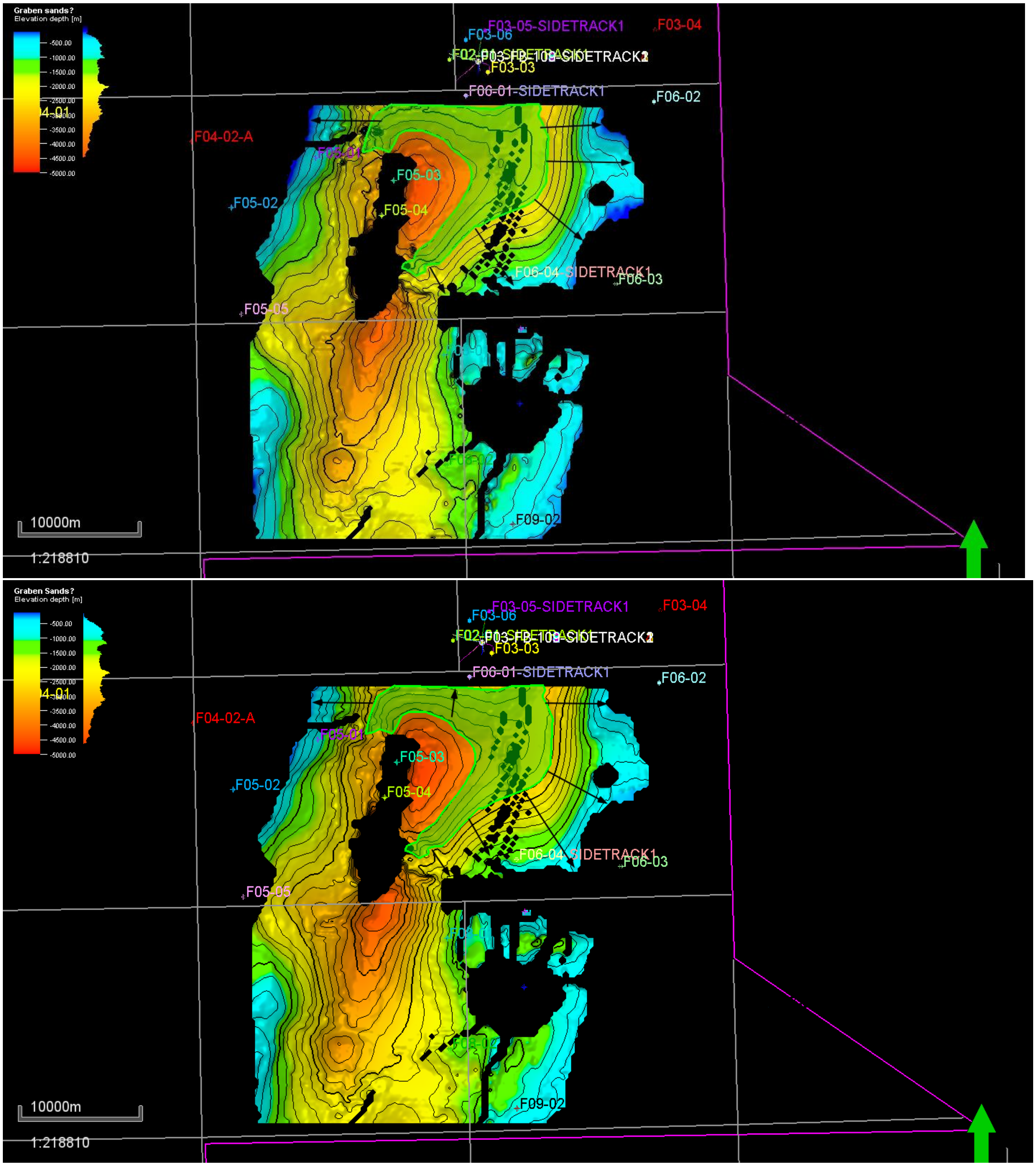


Figure 40: Maps showing the migration pathways of oil through the Middle Graben formation. In green is the outline of where the oil is mature, arrows indicate the up dip migration to a spill point. Upper figure is the situation during the Early Cretaceous, the lower figure shows the situation during the start of the Chalk deposition.

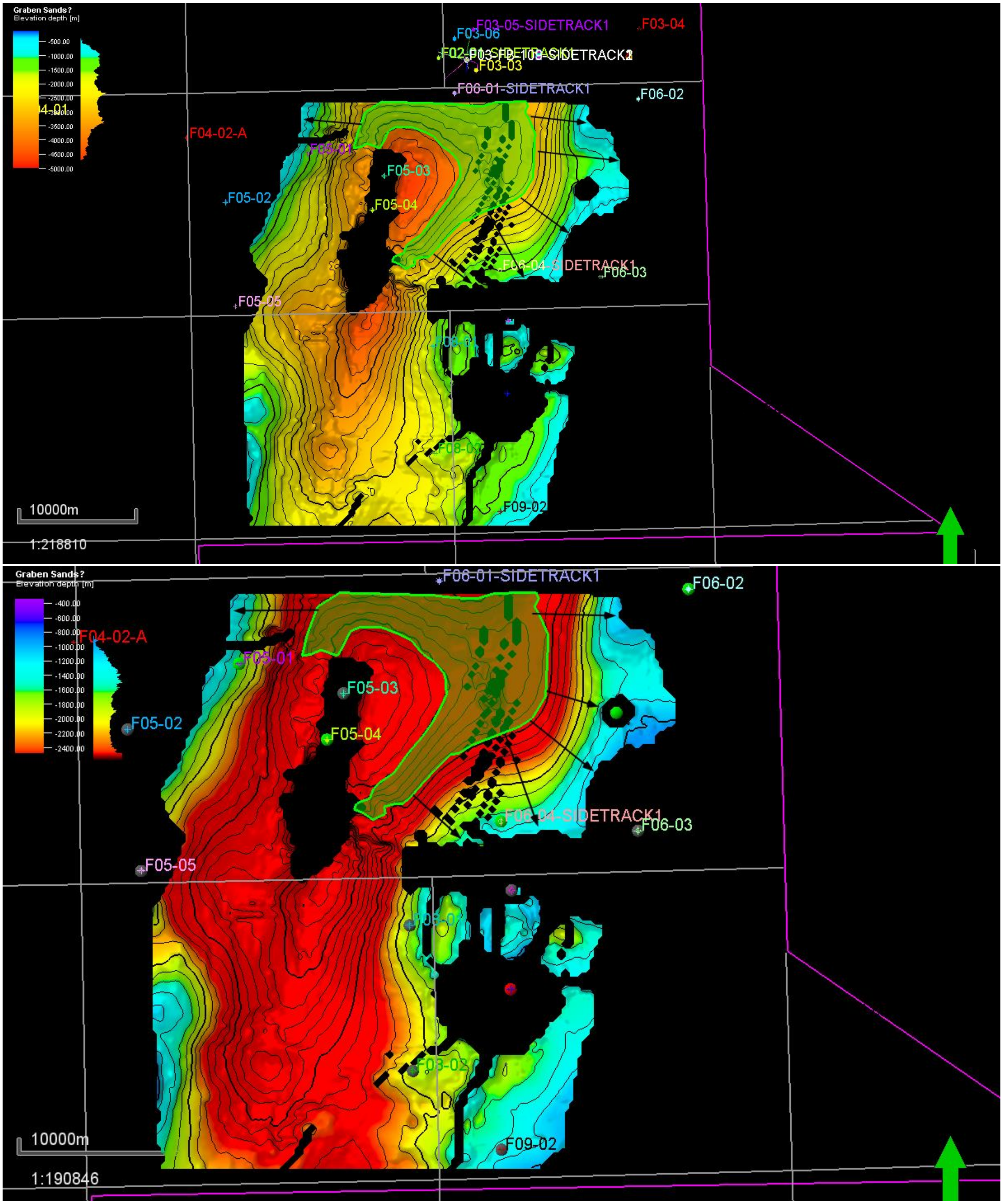


Figure 41: Maps showing the migration pathways of oil through the Middle Graben formation. In green is the outline of where the oil is mature, arrows indicate the up dip migration to a spill point. Upper figure is the situation during the end of the lower chalk deposition, the lower figure shows the situation during the start of the early Campanian.

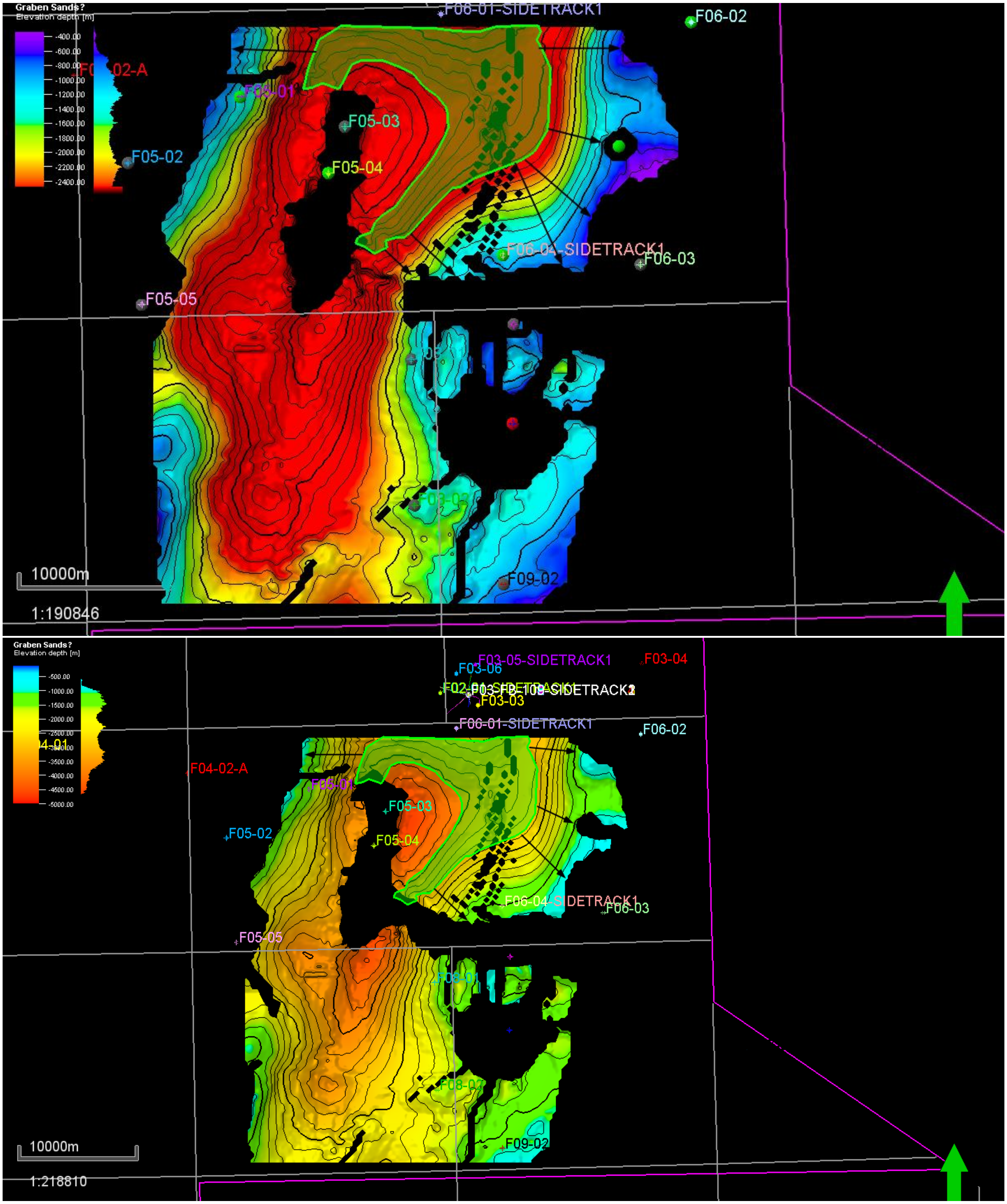


Figure 42: Maps showing the migration pathways of oil through the Middle Graben formation. In green is the outline of where the oil is mature, arrows indicate the up dip migration to a spill point. Upper figure is the situation during the end of the late Campanian, the lower figure shows the situation during the start of the early Maastrichtian.

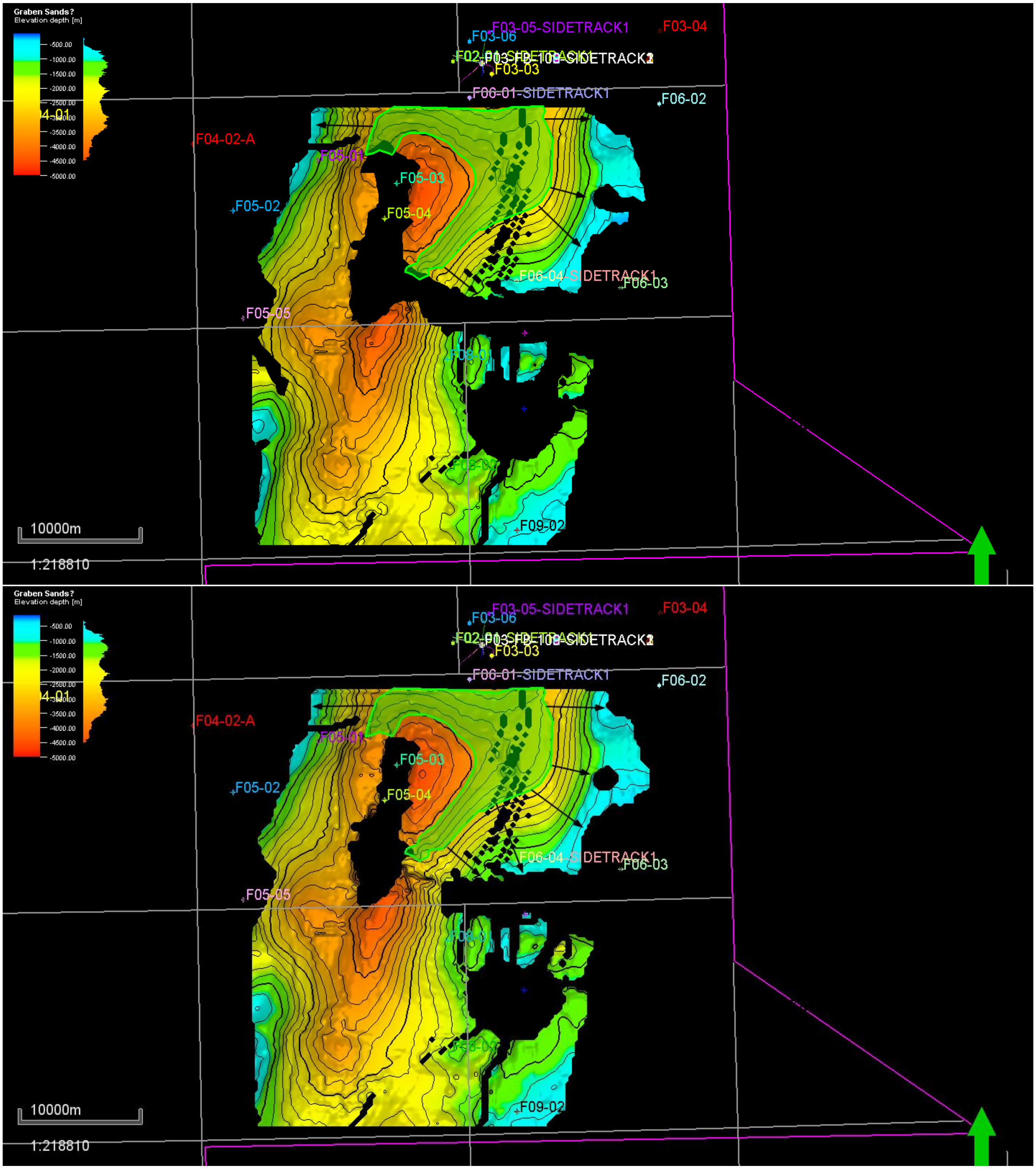


Figure 43: Maps showing the migration pathways of oil through the Middle Graben formation. In green is the outline of where the oil is mature, arrows indicate the up dip migration to a spill point. Upper figure is the situation during the Late Maastrichtian, the lower figure shows the situation during the start of the early Danian.

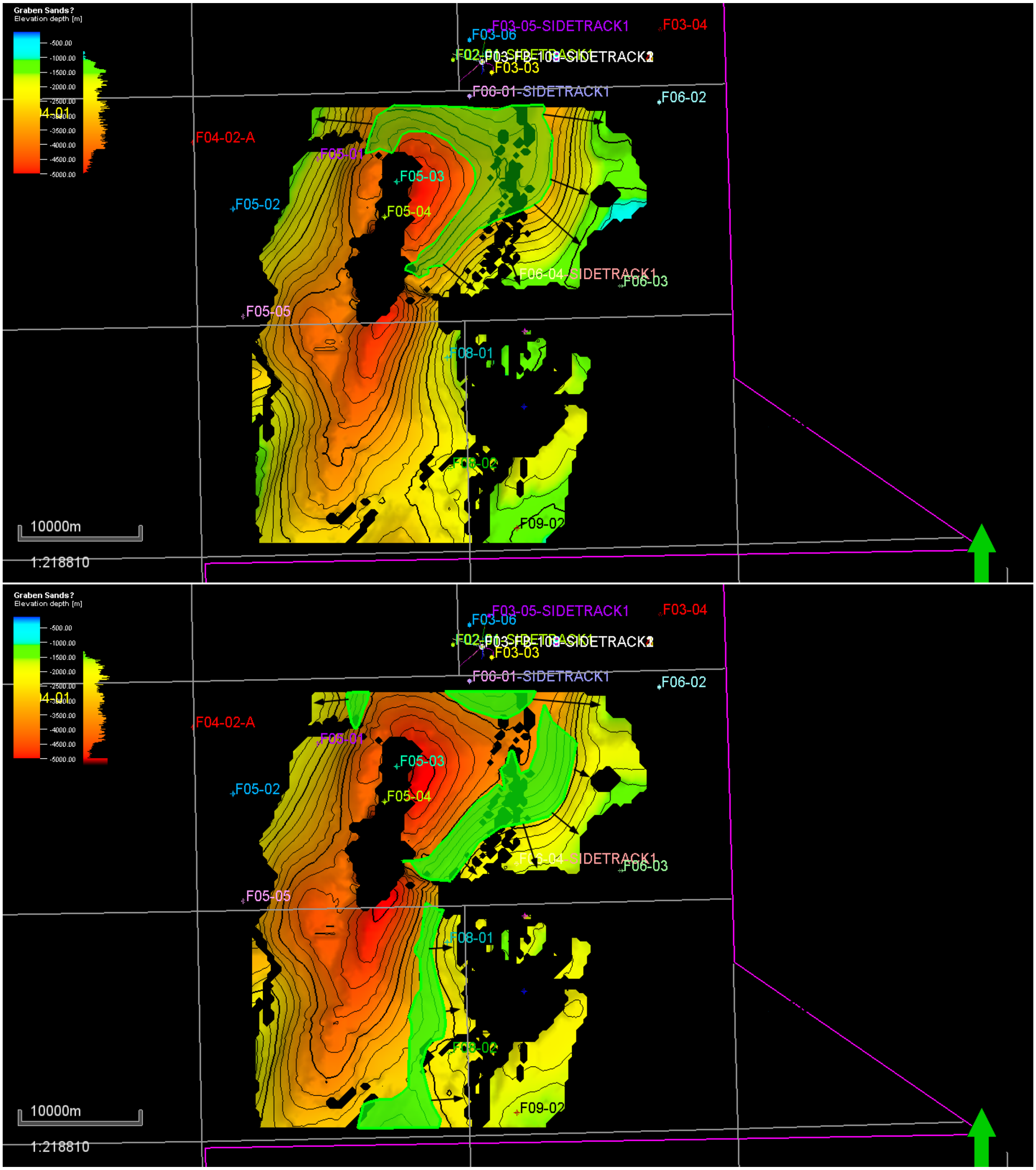


Figure 44: Maps showing the migration pathways of oil through the Middle Graben formation. In green is the outline of where the oil is mature, arrows indicate the up dip migration to a spill point. Upper figure is the situation during the late Danian, the lower figure shows the situation during the start of the early mid-Miocene. As can be seen in the figure the area where the source rock is oil mature changes significantly in the mid-Miocene.

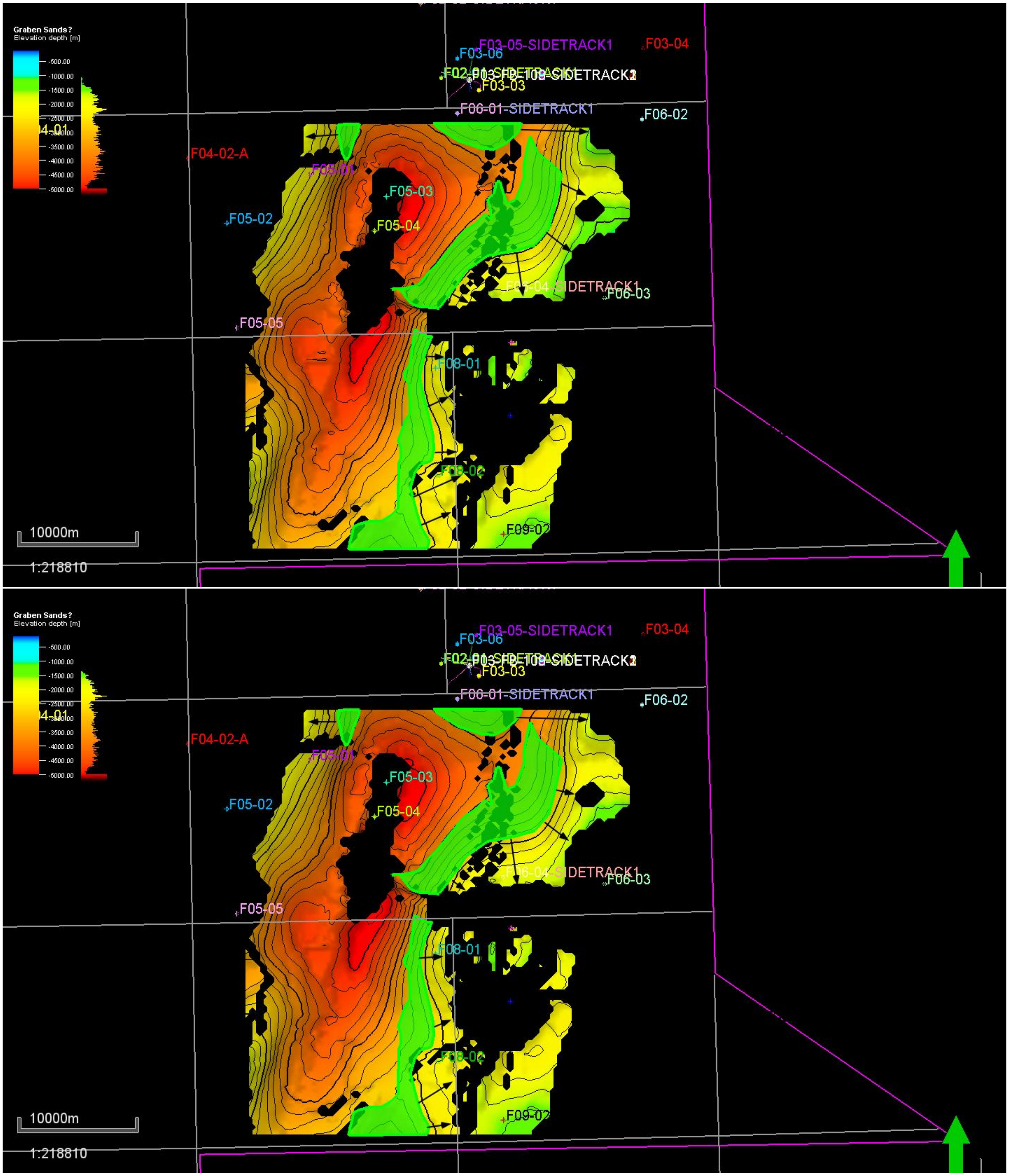


Figure 45: Maps showing the migration pathways of oil through the Middle Graben formation. In green is the outline of where the oil is mature, arrows indicate the up dip migration to a spill point. Upper figure is the situation during the late Mid-Miocene, the lower figure shows the situation during the deposition of TST3.

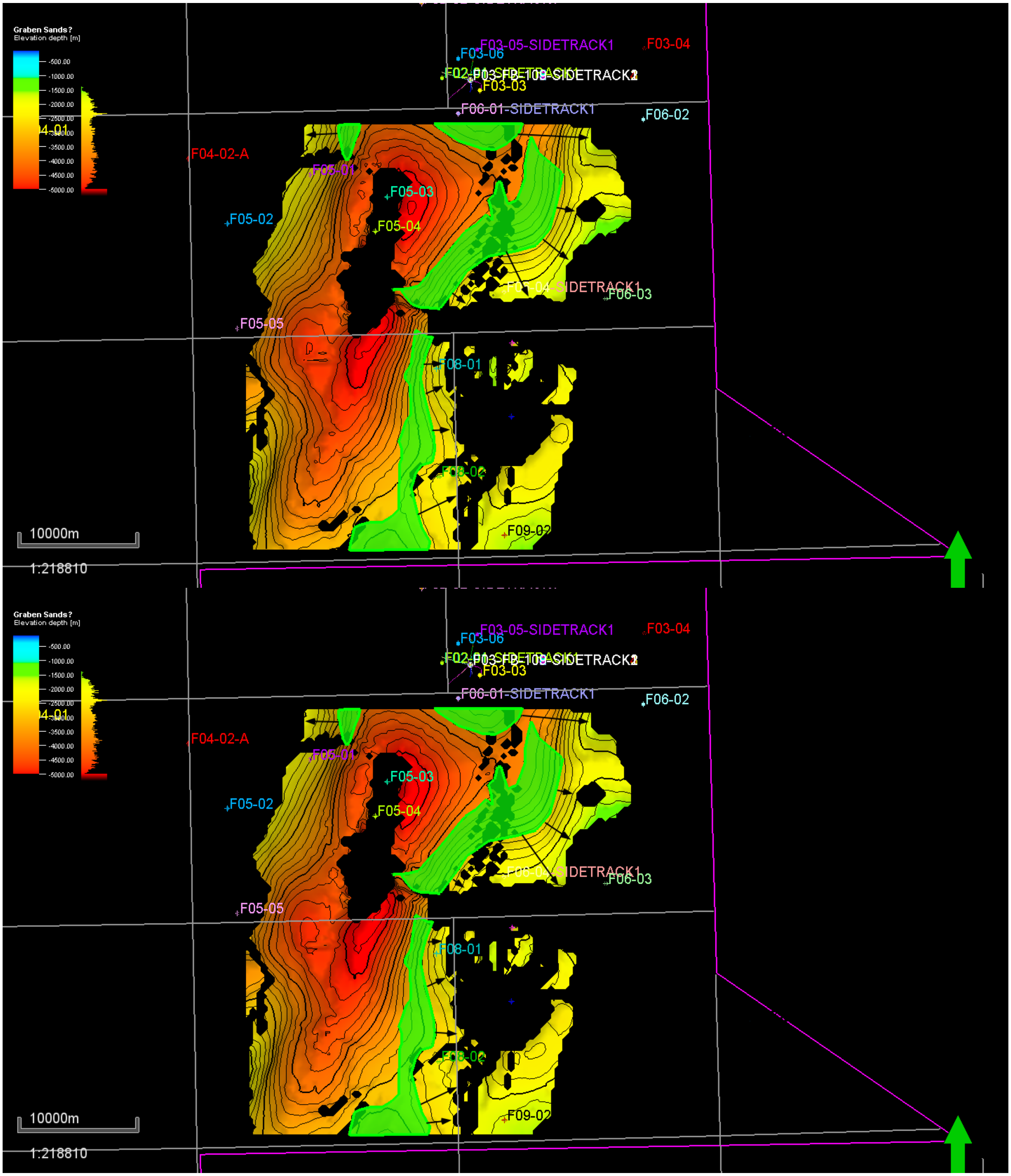


Figure 46: Maps showing the migration pathways of oil through the Middle Graben formation. In green is the outline of where the oil is mature, arrows indicate the up dip migration to a spill point. Upper figure is the situation during the deposition of TST4, the lower figure shows the situation during the deposition of HST4.

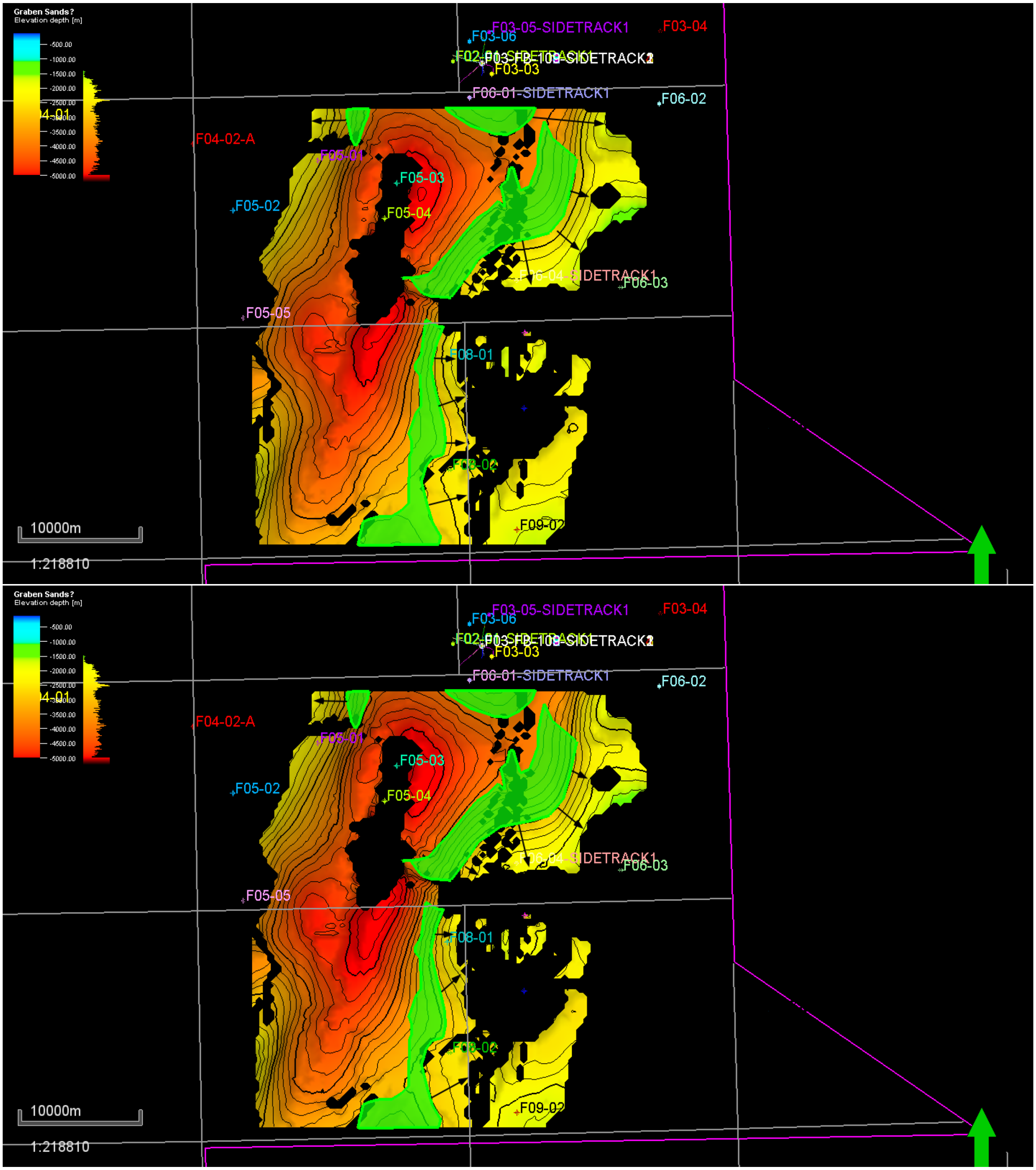


Figure 47: Maps showing the migration pathways of oil through the Middle Graben formation. In green is the outline of where the oil is mature, arrows indicate the up dip migration to a spill point. Upper figure is the situation during the deposition of HST5, the lower figure shows the situation during the deposition of S11.

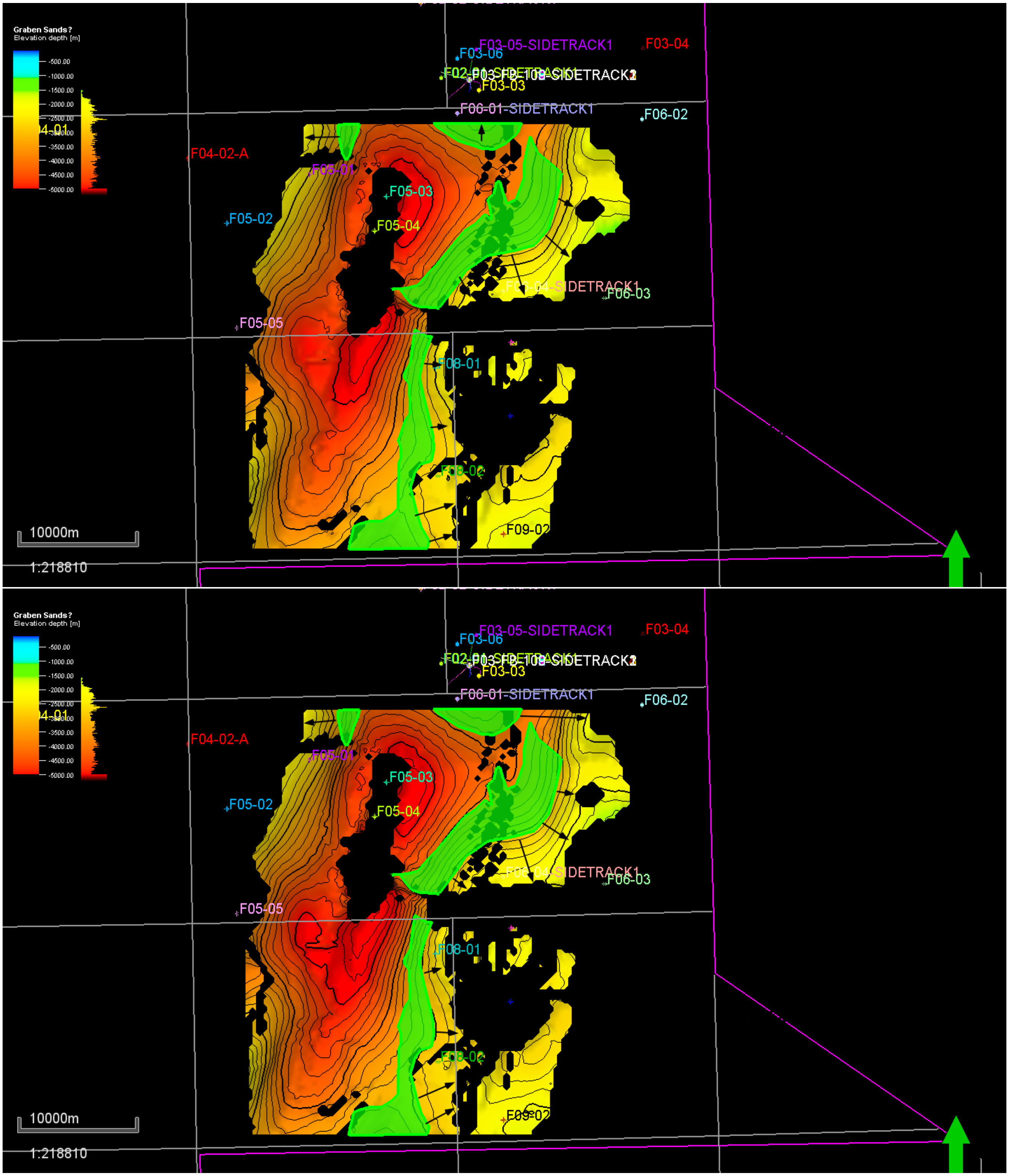
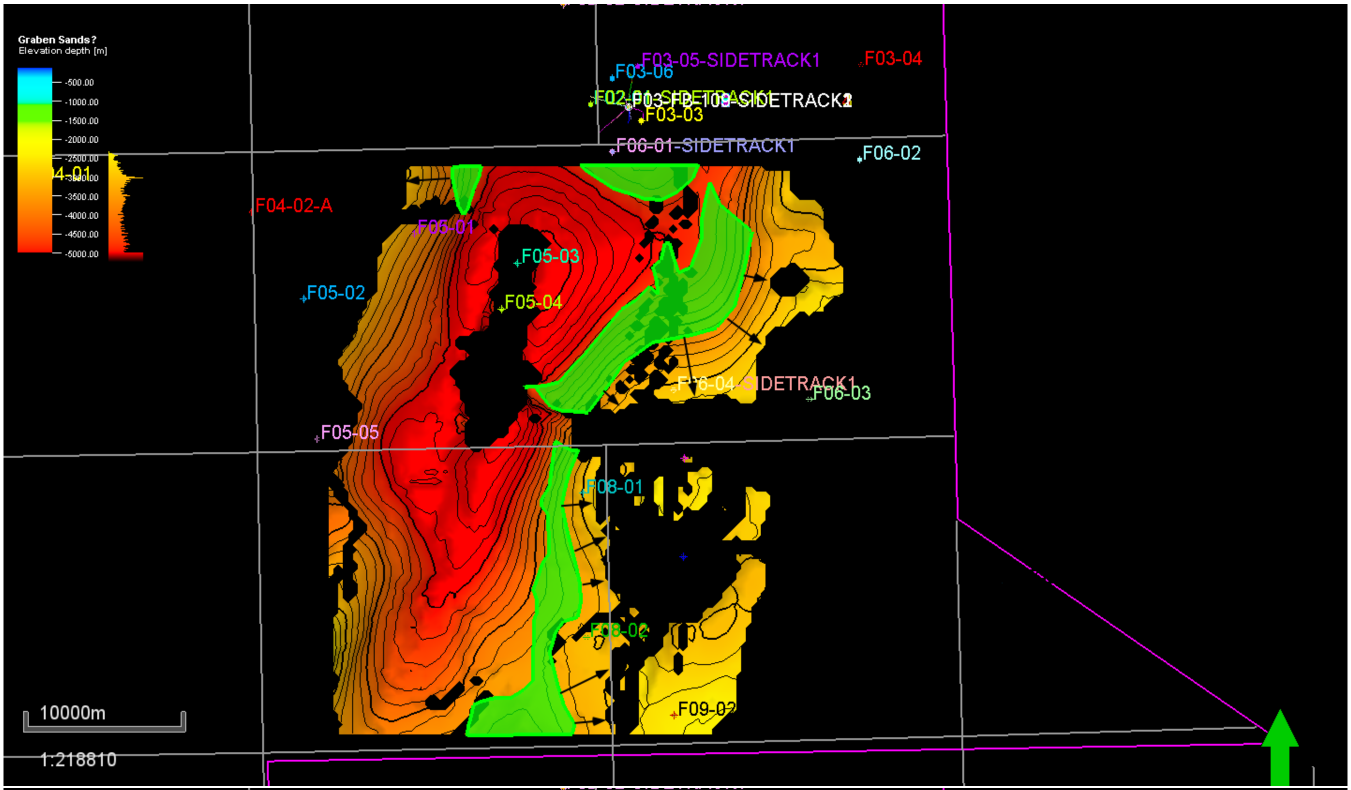


Figure 48: Maps showing the migration pathways of oil through the Middle Graben formation. In green is the outline of where the oil is mature, arrows indicate the up dip migration to a spill point. Upper figure is the situation during the deposition of S13, the lower figure shows the situation during the pre-Elsterian.



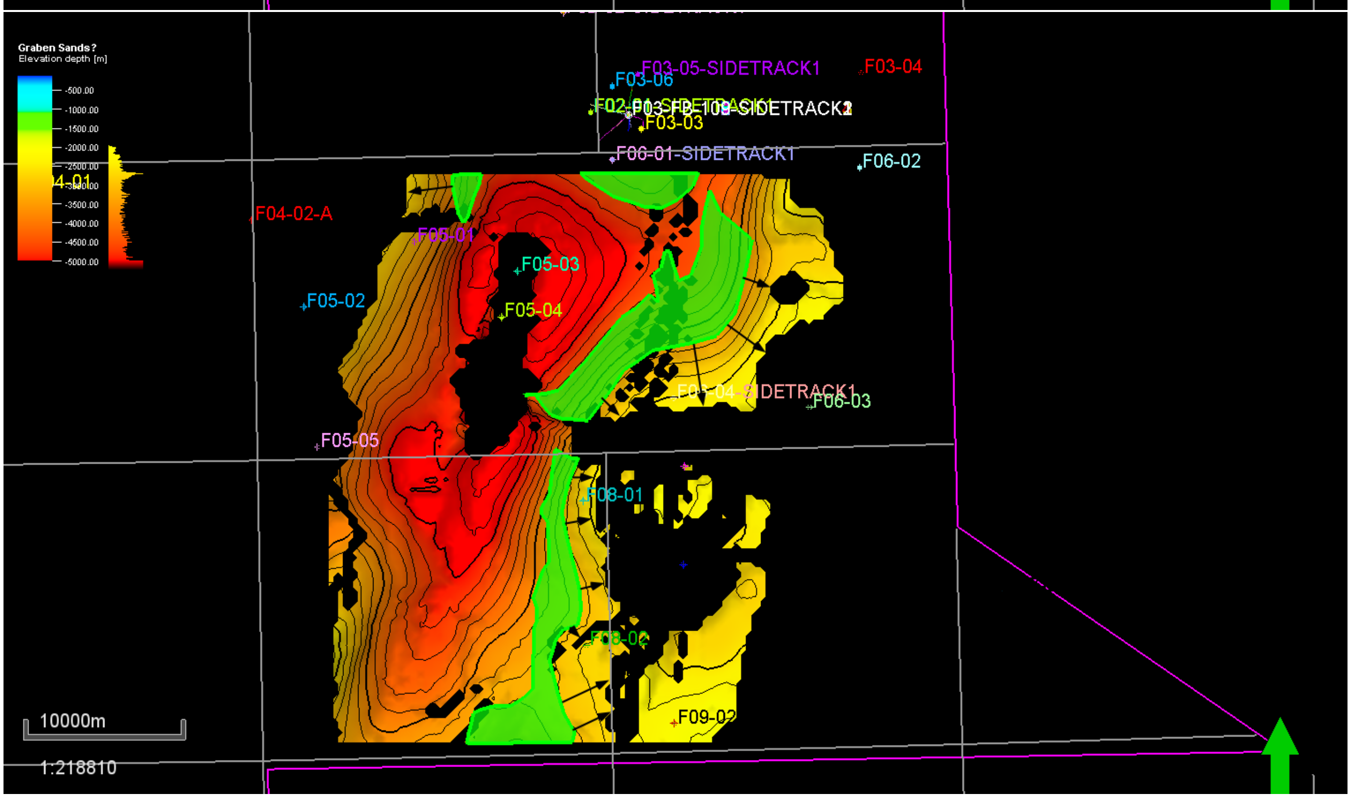


Figure 49: Maps showing the migration pathways of oil through the Middle Graben formation. In green is the outline of where the oil is mature, arrows indicate the up dip migration to a spill point. Upper figure is the situation during the early Elsterian, the lower figure shows the situation during the late Elsterian.

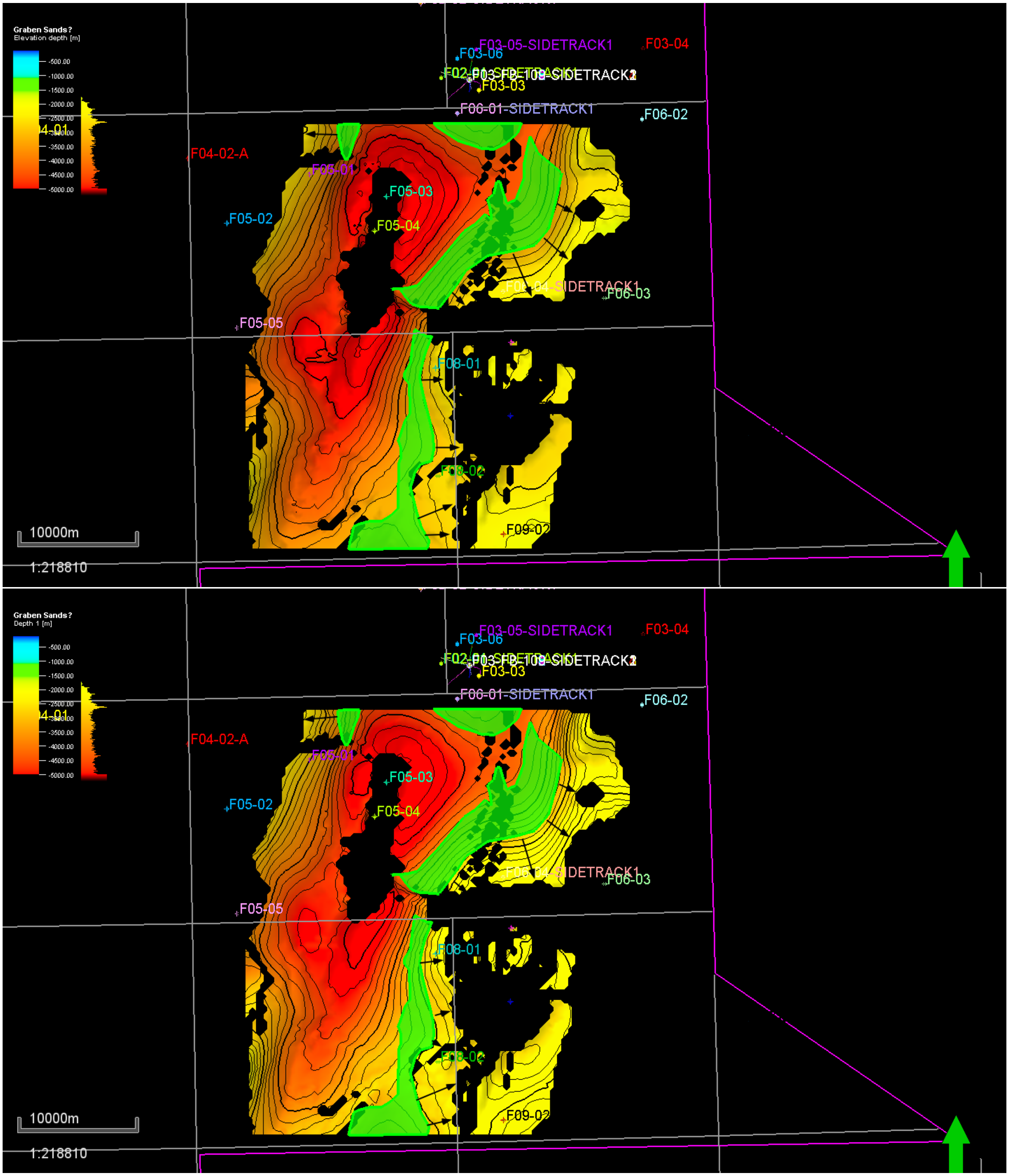
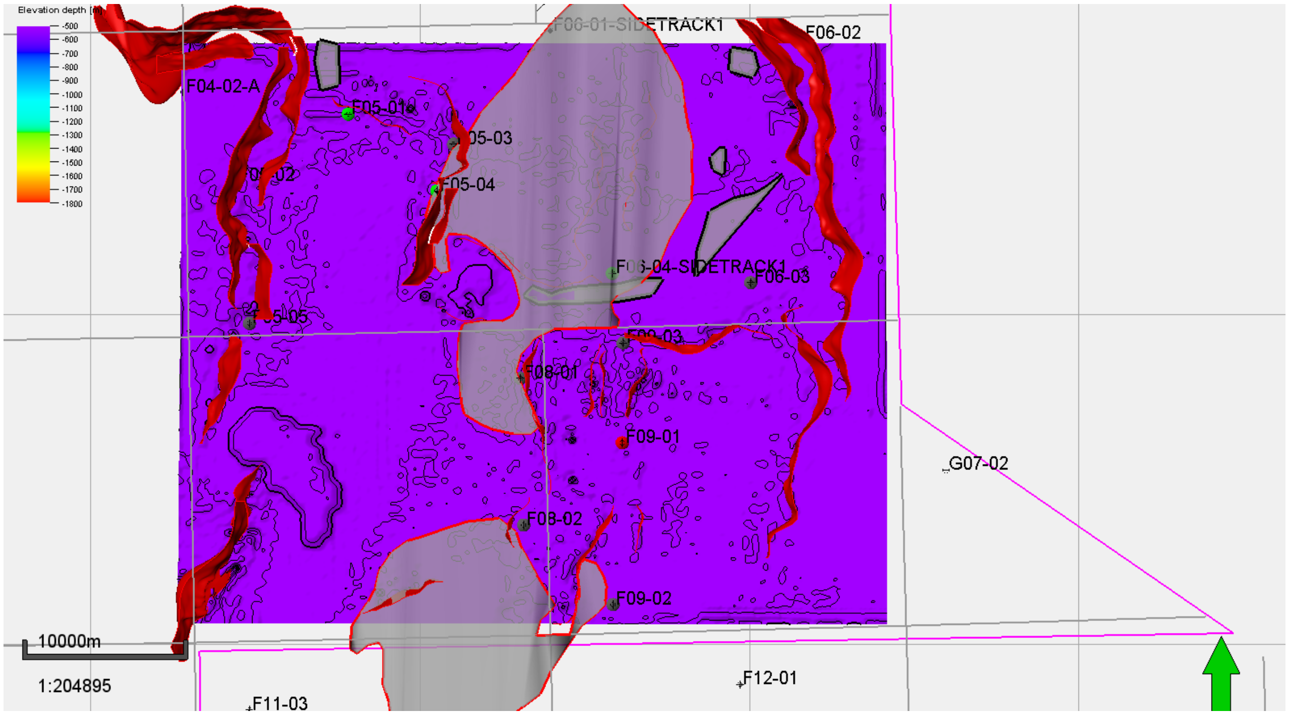


Figure 50: Maps showing the migration pathways of oil through the Middle Graben formation. In green is the outline of where the oil is mature, arrows indicate the up dip migration to a spill point. Upper figure is the situation during the post Elsterian, the lower figure shows the situation during the present.

Appendix 8 Maastrichtian Traps oil bearing



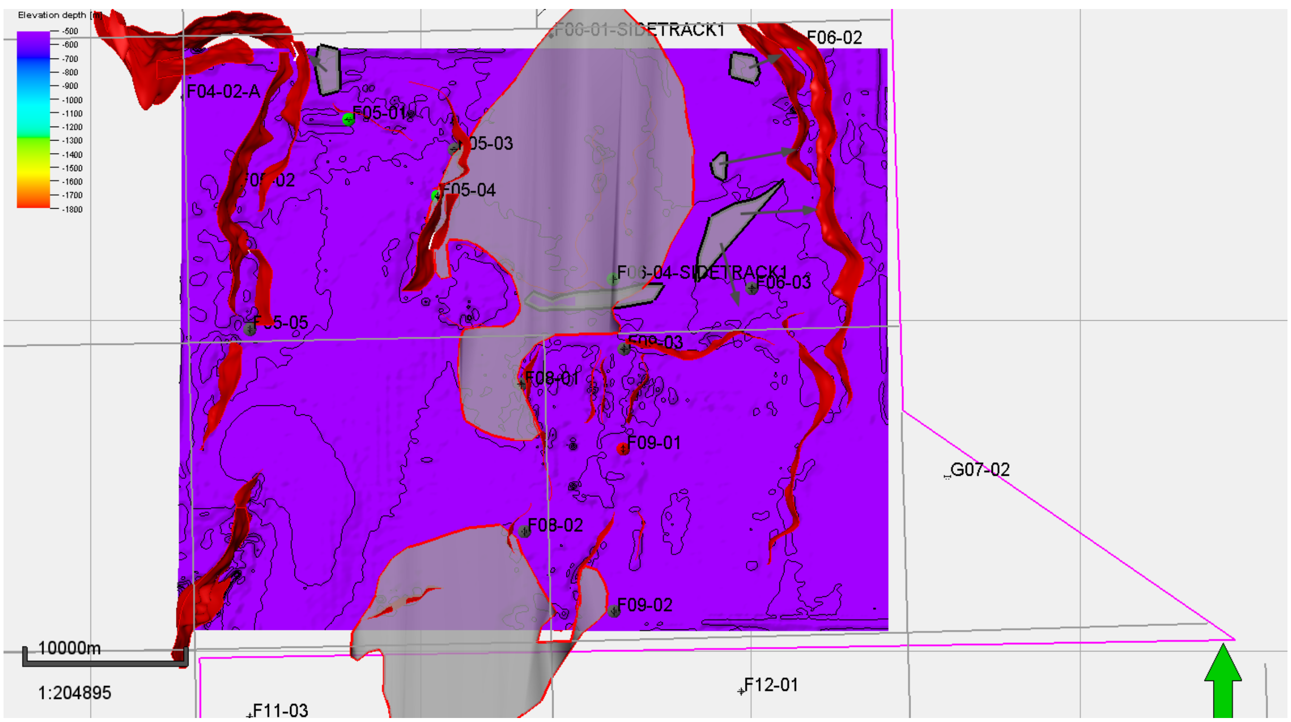


Figure 51: Possible traps in the Chalk (Maastrichtian) during the Early Danian (above and Late Danian (below). The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Maastrichtian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Maastrichtian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).

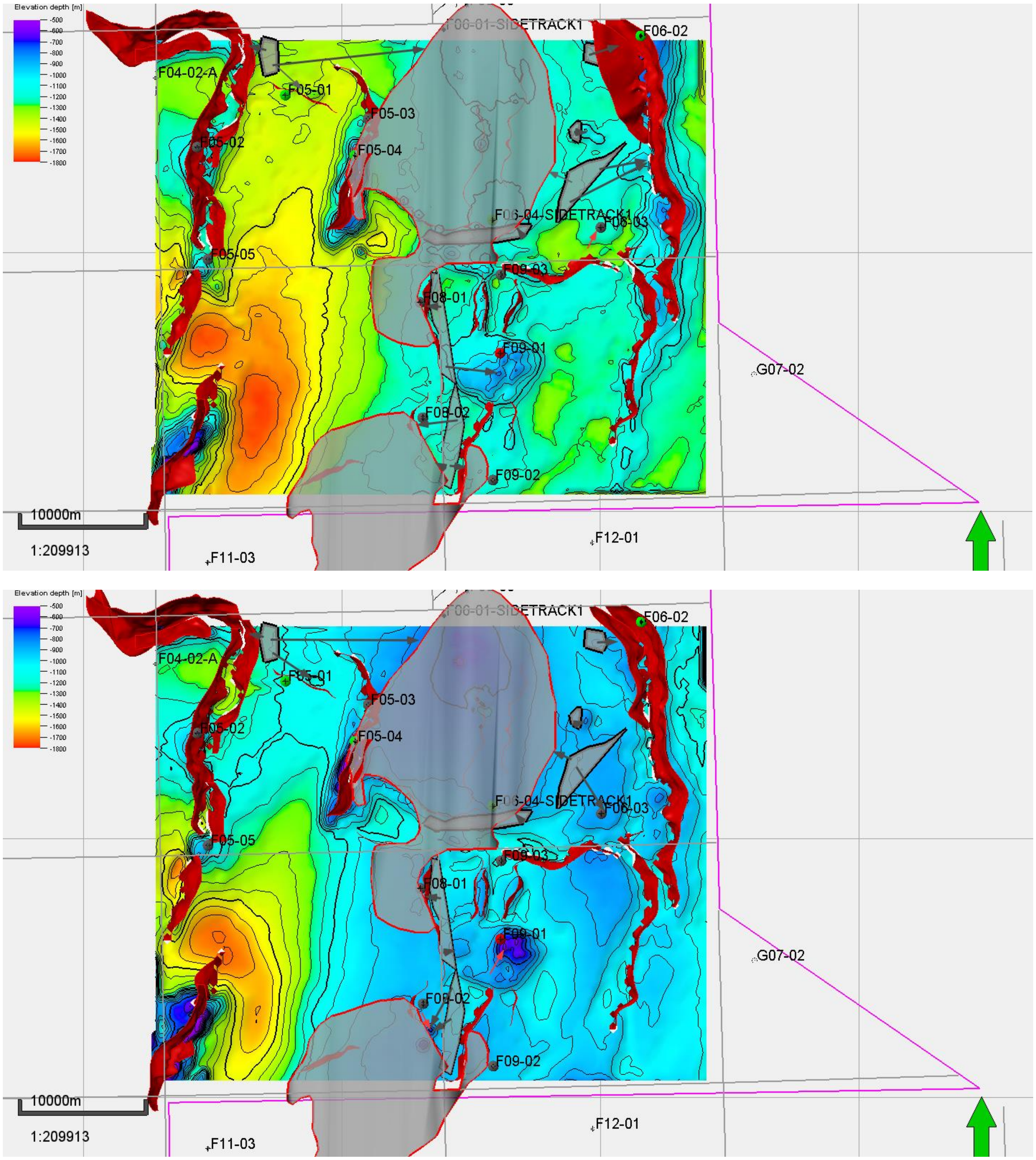


Figure 52: Possible traps in the Chalk (Maastrichtian) during the Early Mid Miocene (above) and Late Mid-Miocene (below). The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Maastrichtian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Maastrichtian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).

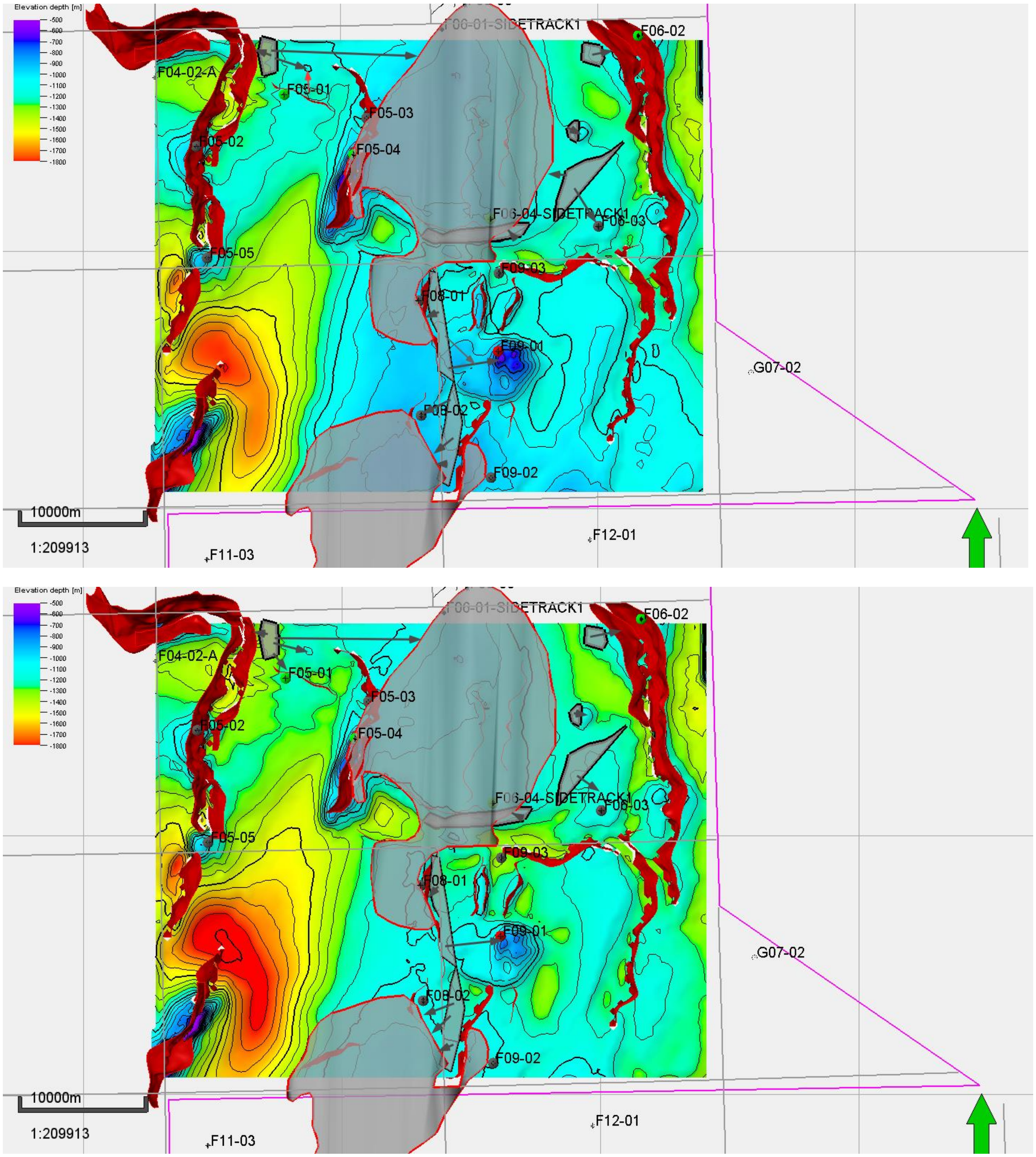
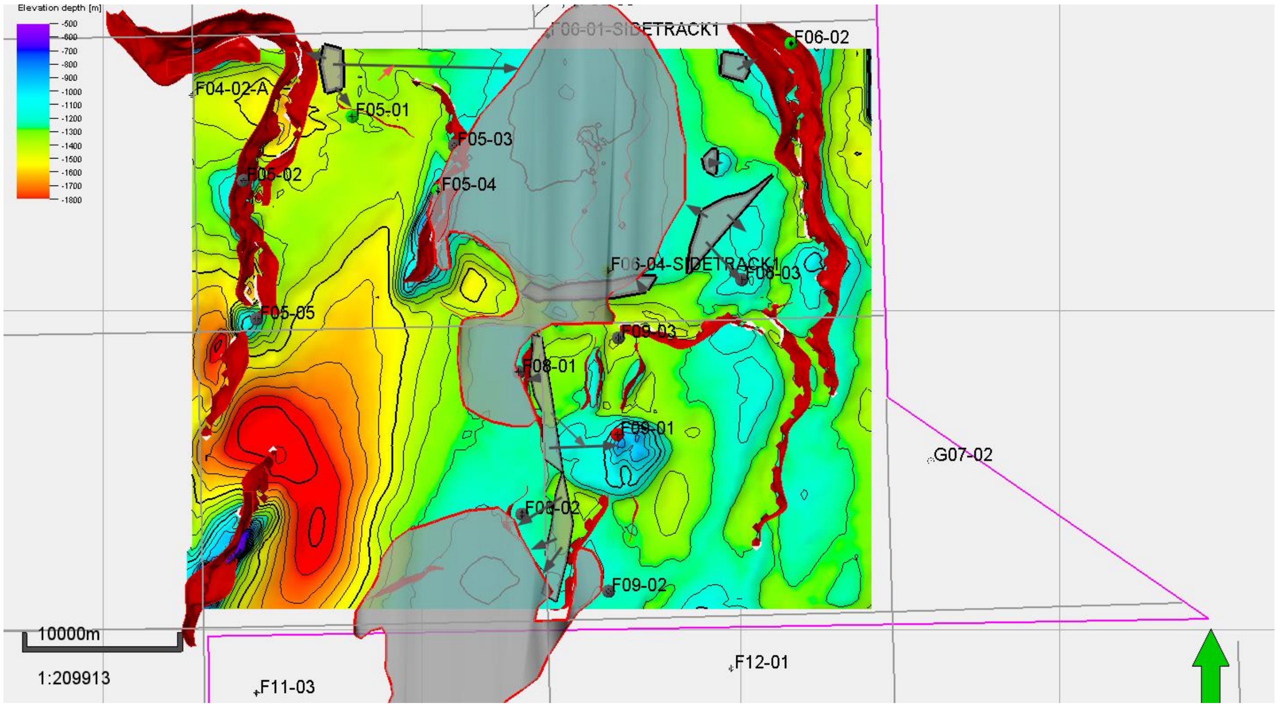


Figure 53: Possible traps in the Chalk (Maastrichtian) during the deposition of TST3 (above) and TST4 (below). The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Maastrichtian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Maastrichtian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).



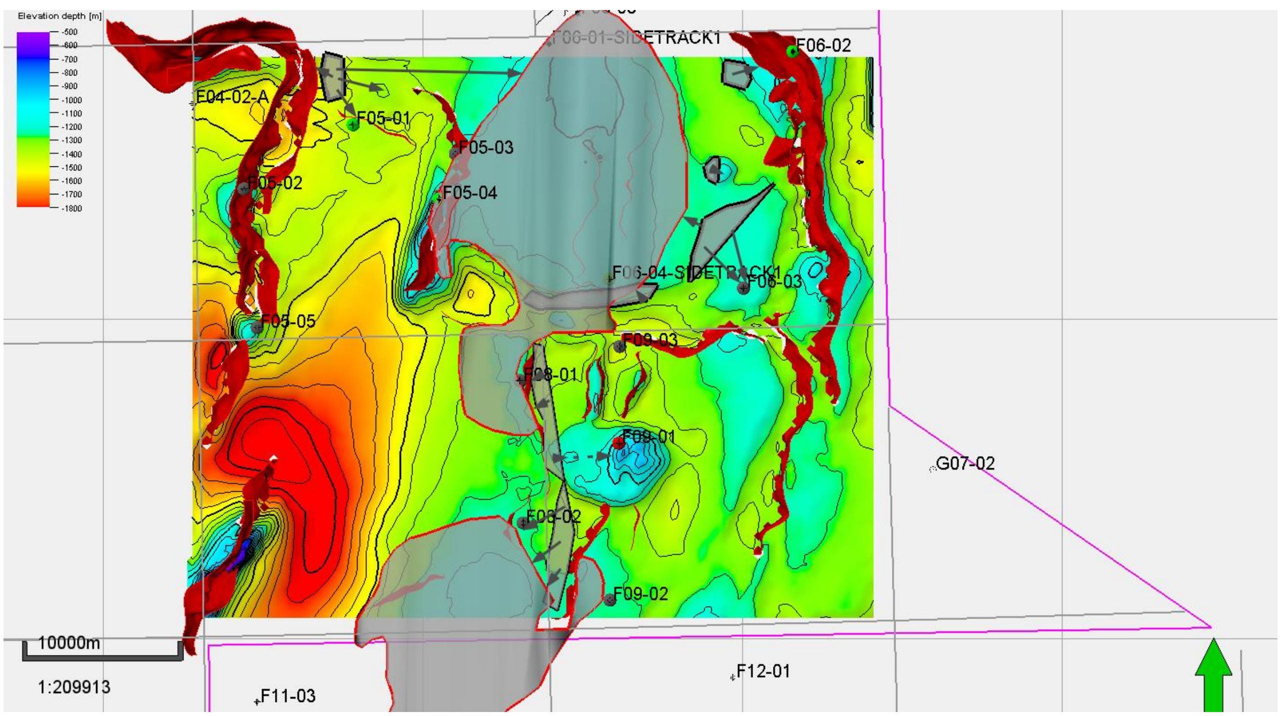


Figure 54: Possible traps in the Chalk (Maastrichtian) during the deposition of HST4 (above) and HST5 (below). The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Maastrichtian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Maastrichtian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).

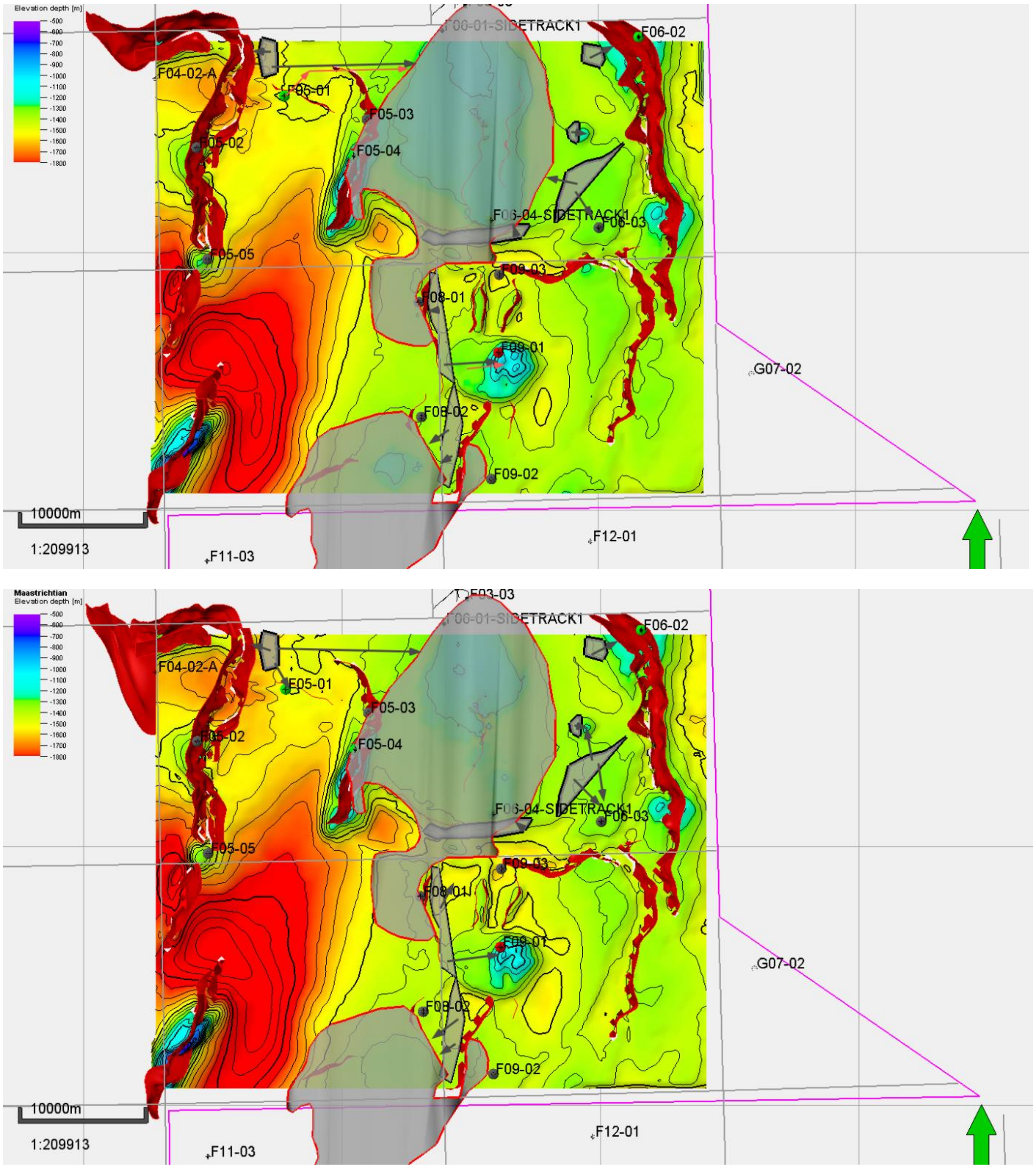


Figure 55: Possible traps in the Chalk (Maastrichtian) during the deposition of S11 (above) and S13 (below). The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Maastrichtian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Maastrichtian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).

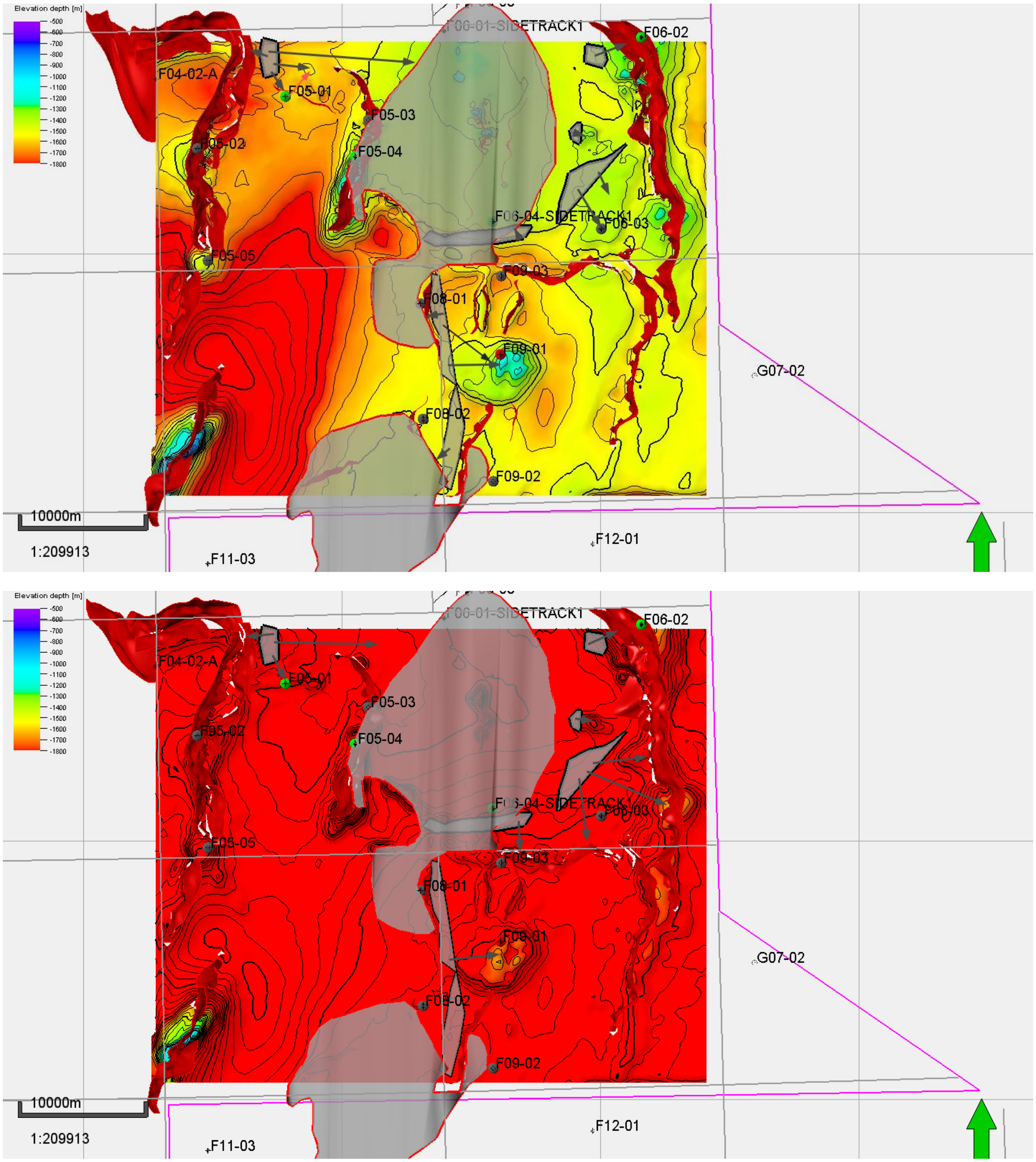


Figure 56: Possible traps in the Chalk (Maastrichtian) during the pre-Elsterian (above) and early Elsterian (below). The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Maastrichtian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Maastrichtian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).

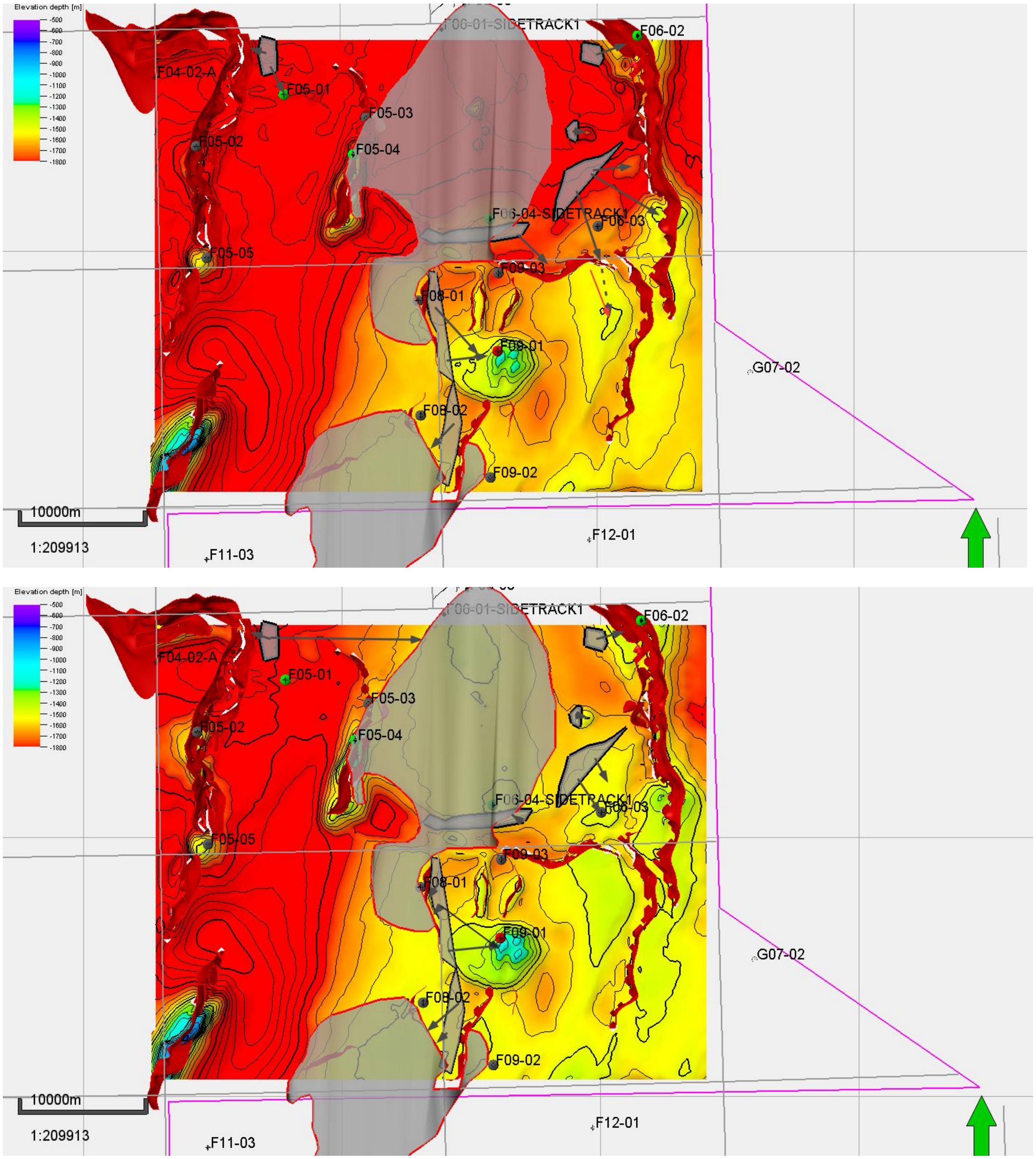


Figure 57: Possible traps in the Chalk (Maastrichtian) during the Late Elsterian (above) and post Elsterian (below). The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Maastrichtian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Maastrichtian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).

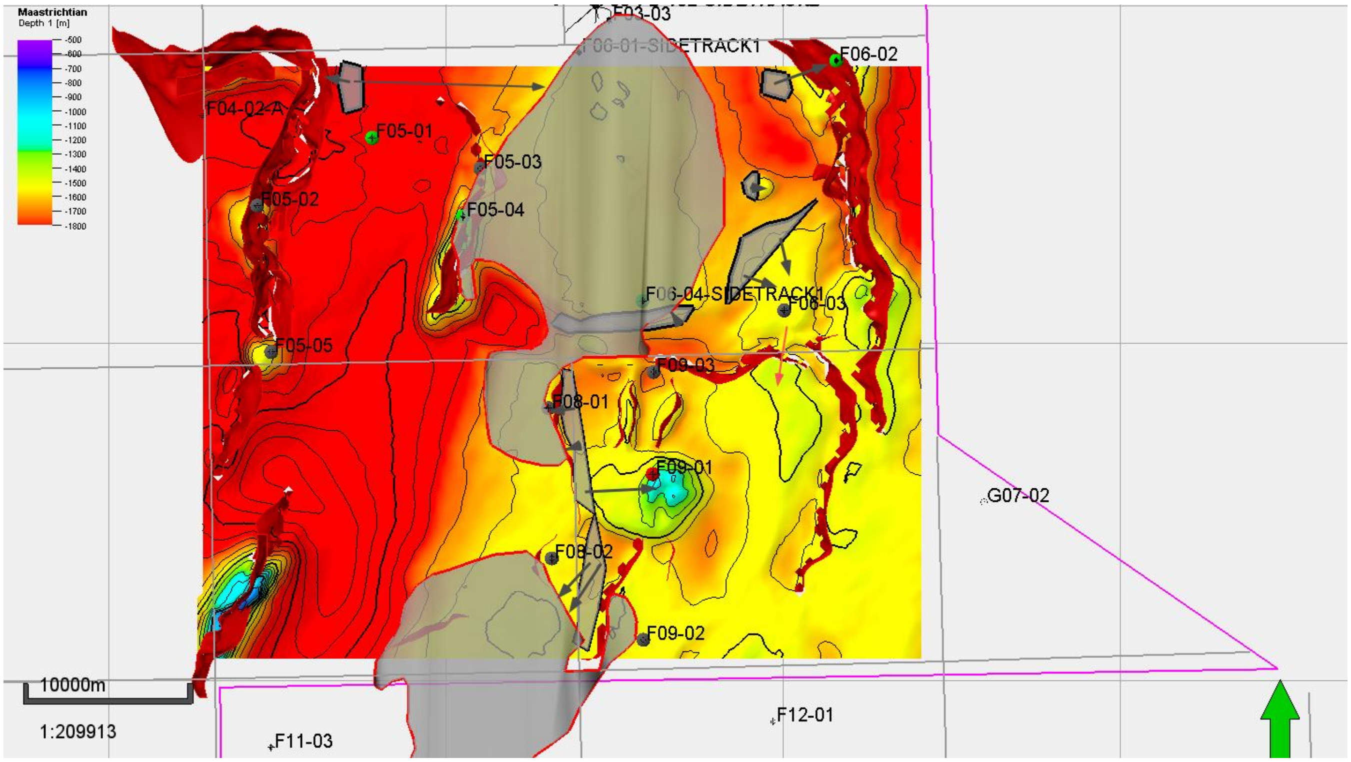


Figure 58: Possible traps in the Chalk (Maastrichtian) during the present. The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Maastrichtian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Maastrichtian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).

Appendix 9 Danian Traps oil bearing

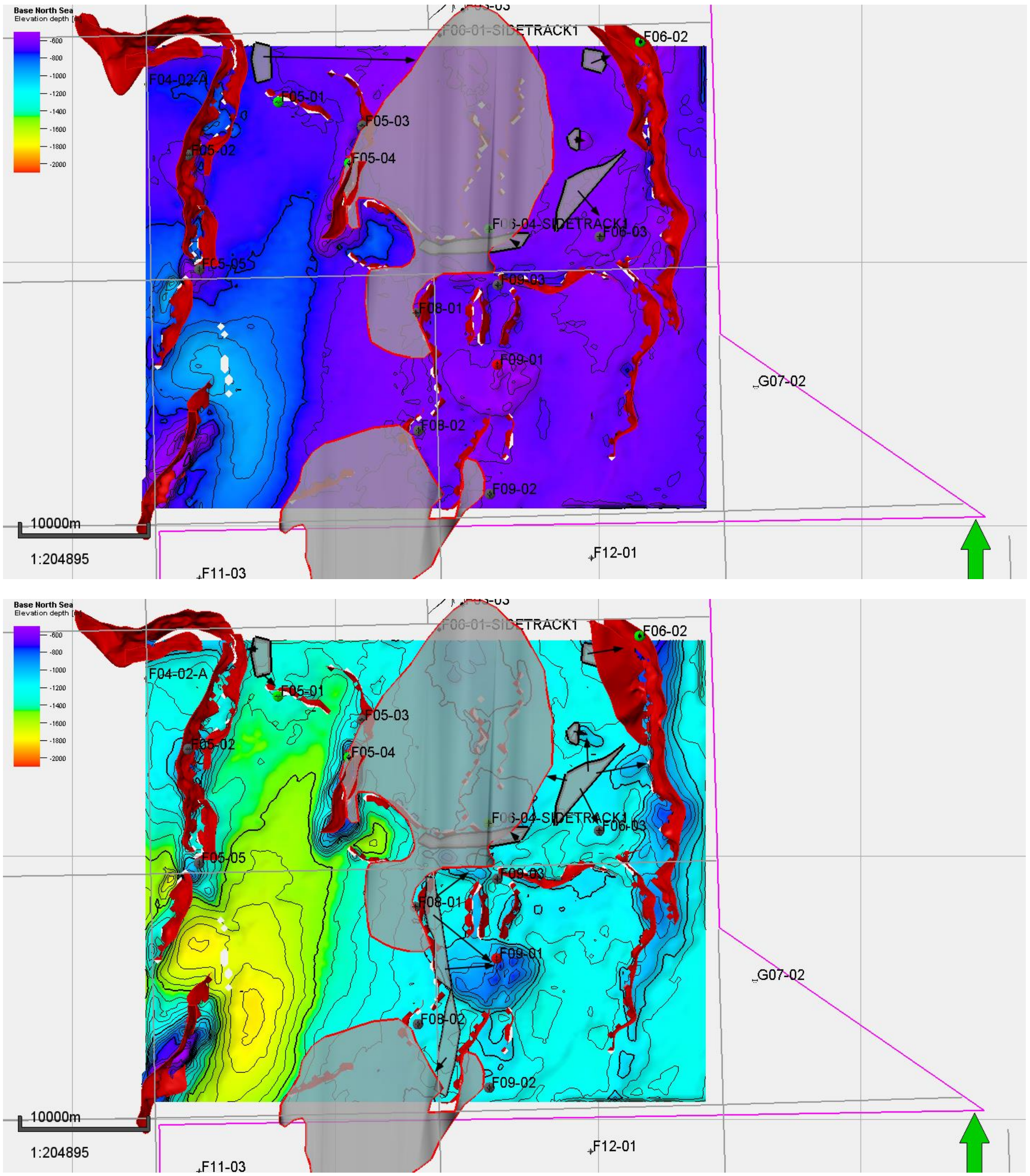


Figure 59: Possible traps in the Chalk (Danian) during the Late Danian (above) and Mid Miocene (below). The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Danian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Danian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).

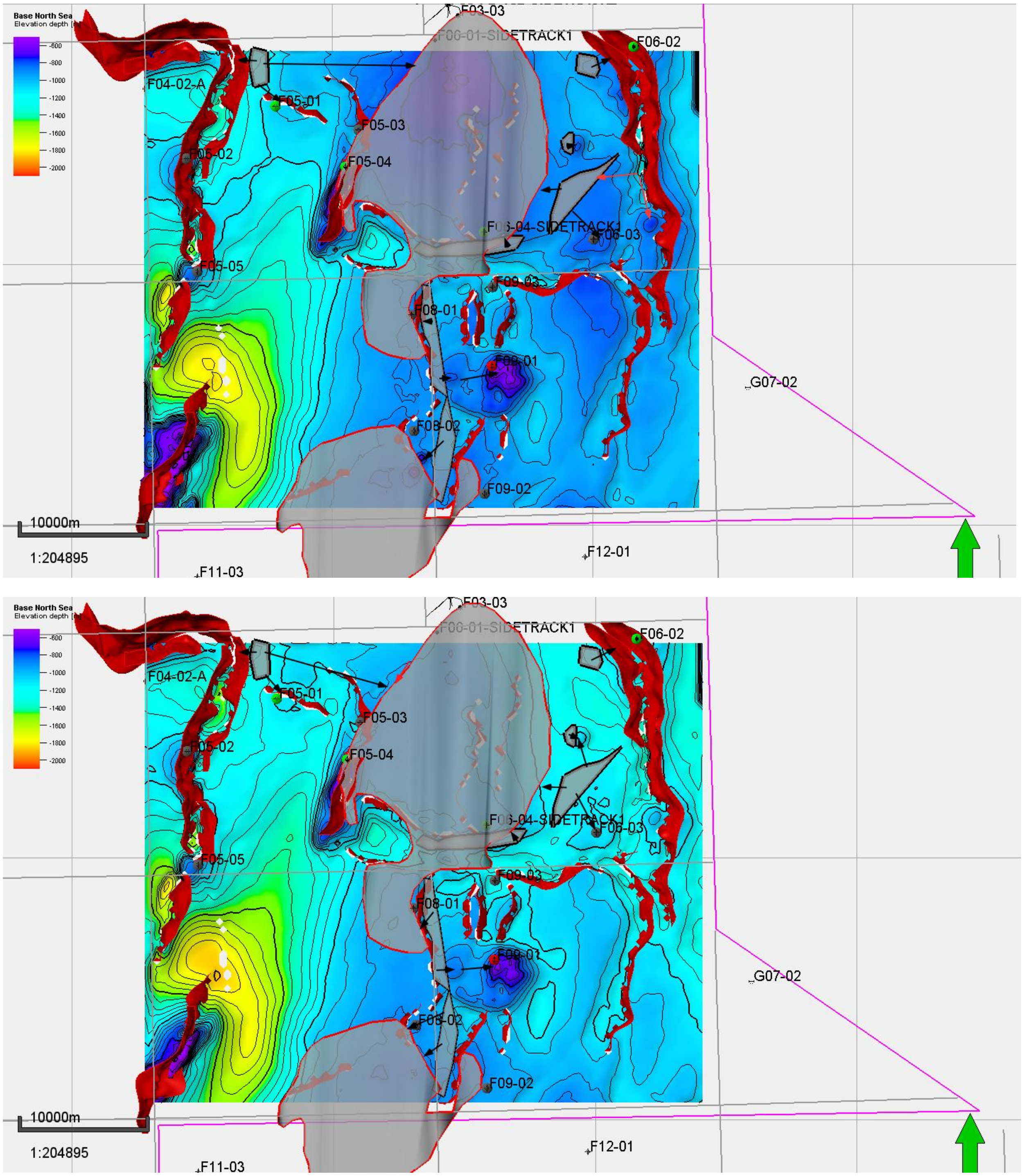
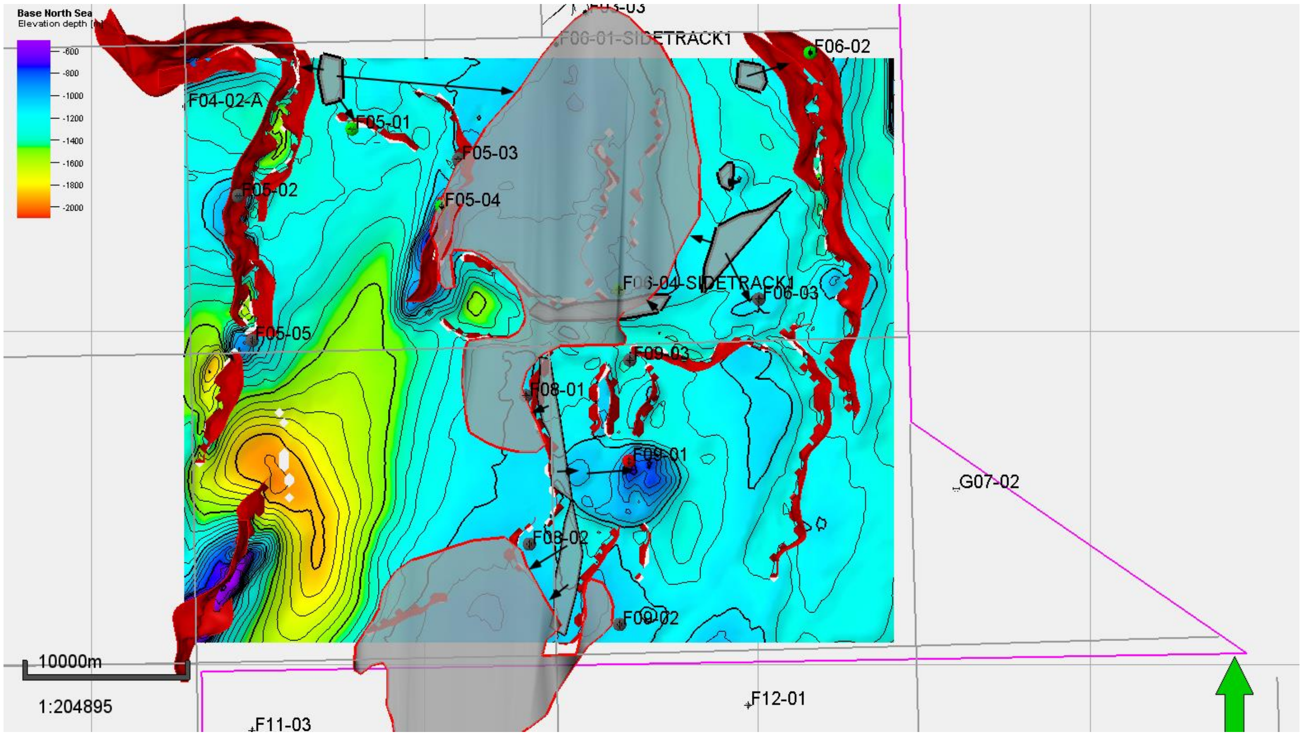


Figure 60: Possible traps in the Chalk (Danian) during the late Mid Miocene (after erosion) (above) and the deposition of TST3 (below). The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Danian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Danian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).



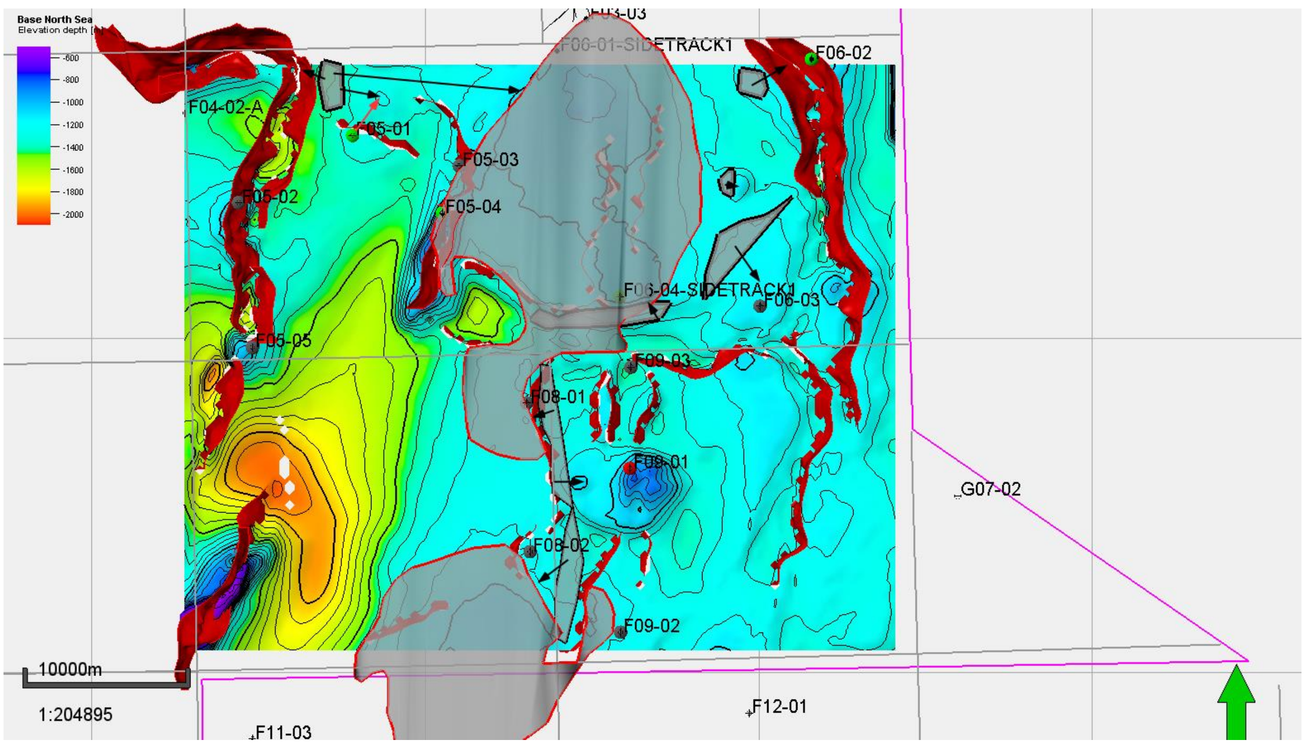
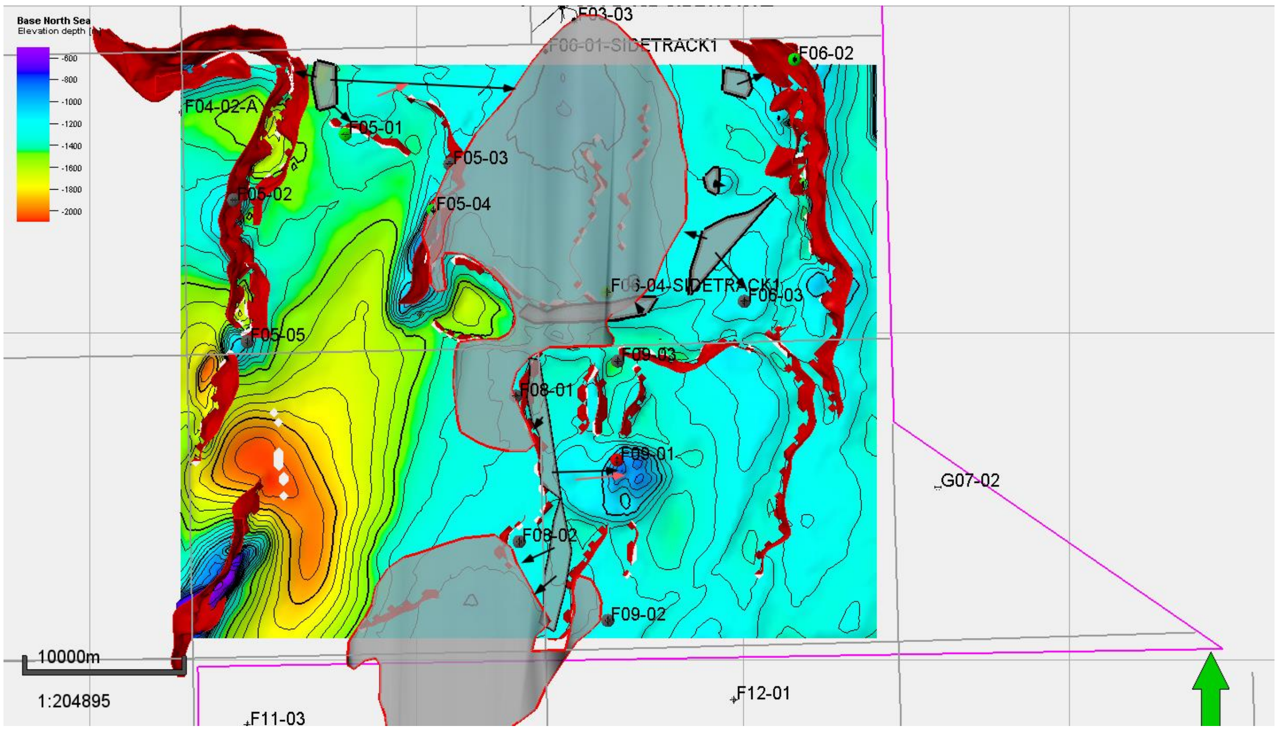


Figure 61: Possible traps in the Chalk (Danian) during the deposition of TST4 (above) and the deposition of HST4 (below). The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Danian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Danian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).



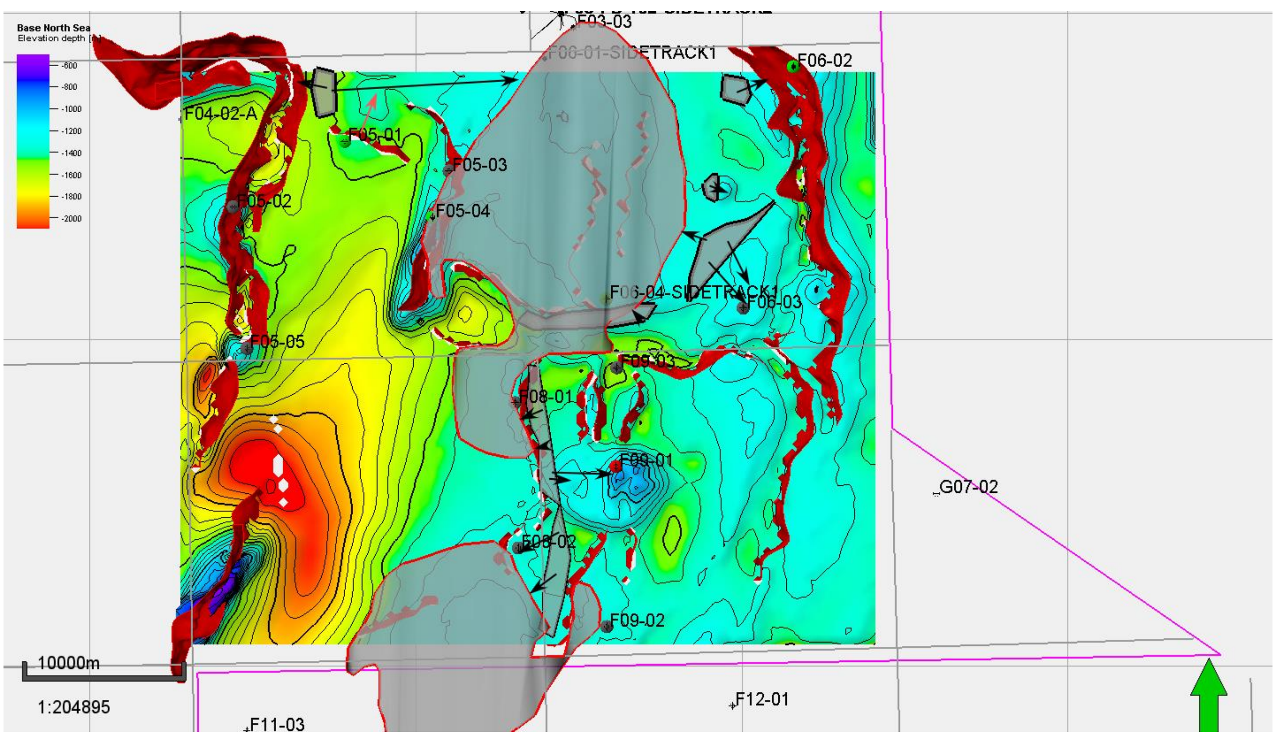


Figure 62: Possible traps in the Chalk (Danian) during the deposition of HST5 (above) and the deposition of S11 (below). The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Danian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Danian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).

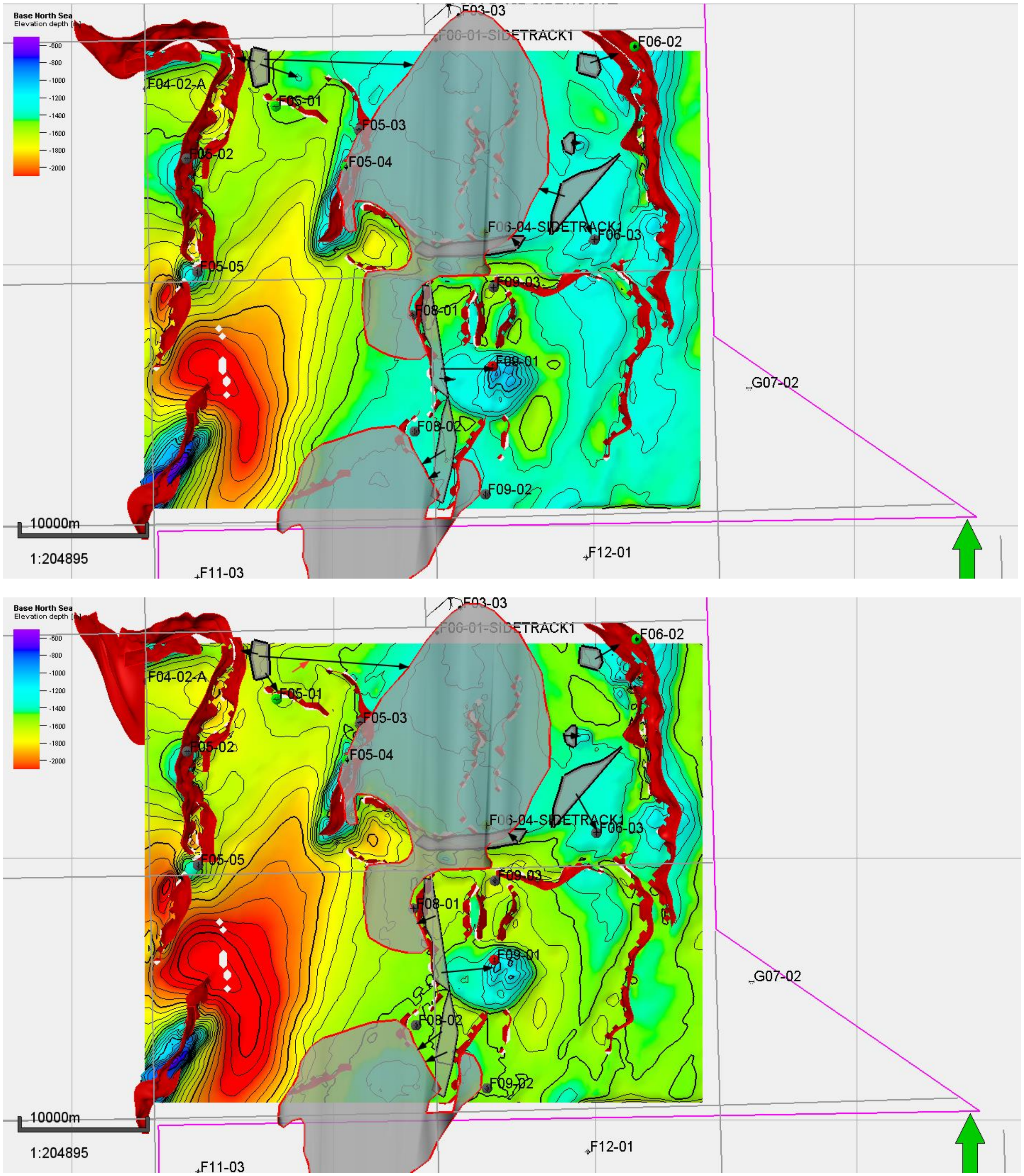


Figure 63: Possible traps in the Chalk (Danian) during the deposition of S13 (above) the pre-Elsterian (below). The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Danian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Danian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).

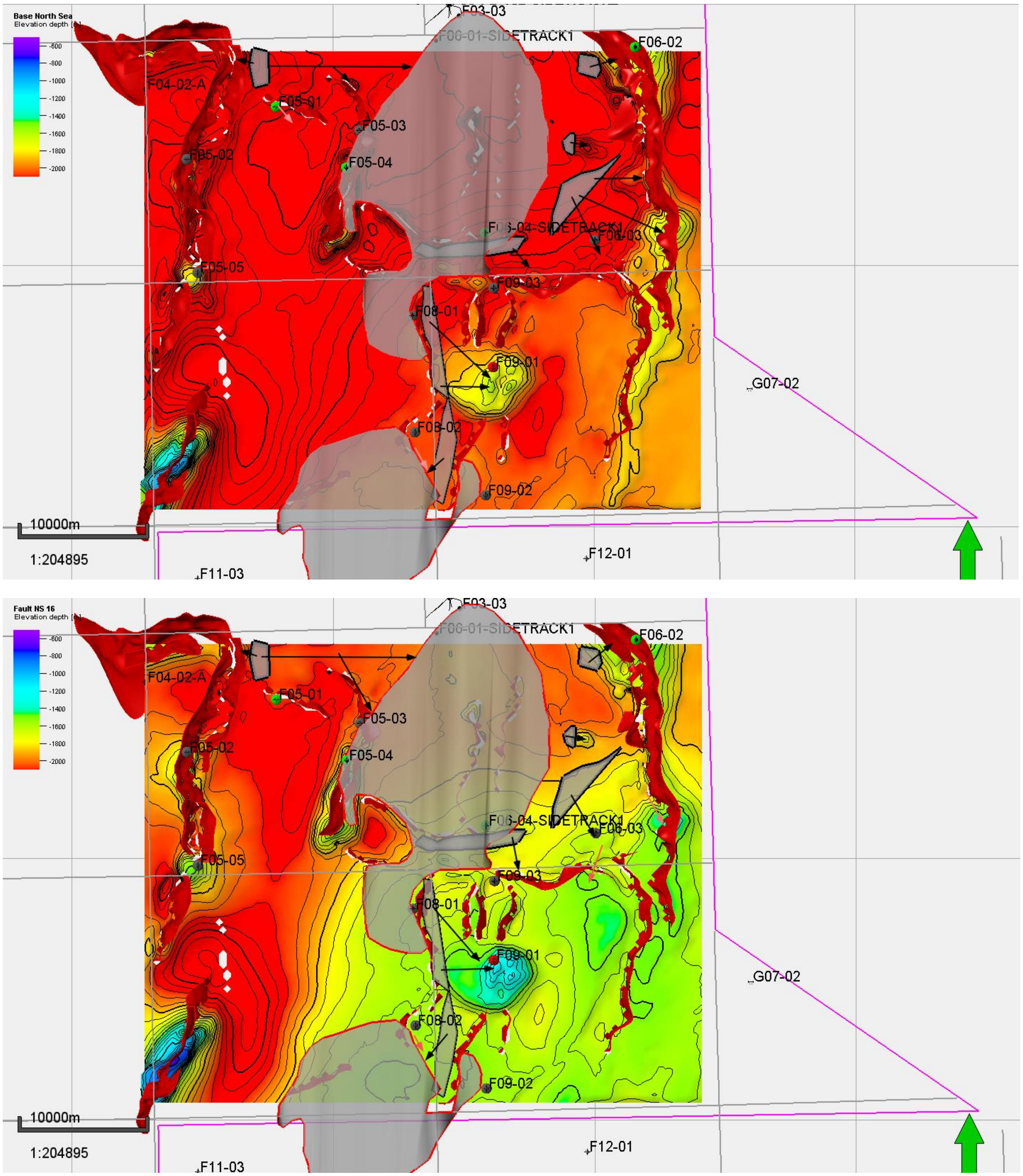


Figure 64: Possible traps in the Chalk (Danian) during early Elsterian (above) and the late Elsterian (below). The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Danian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Danian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).

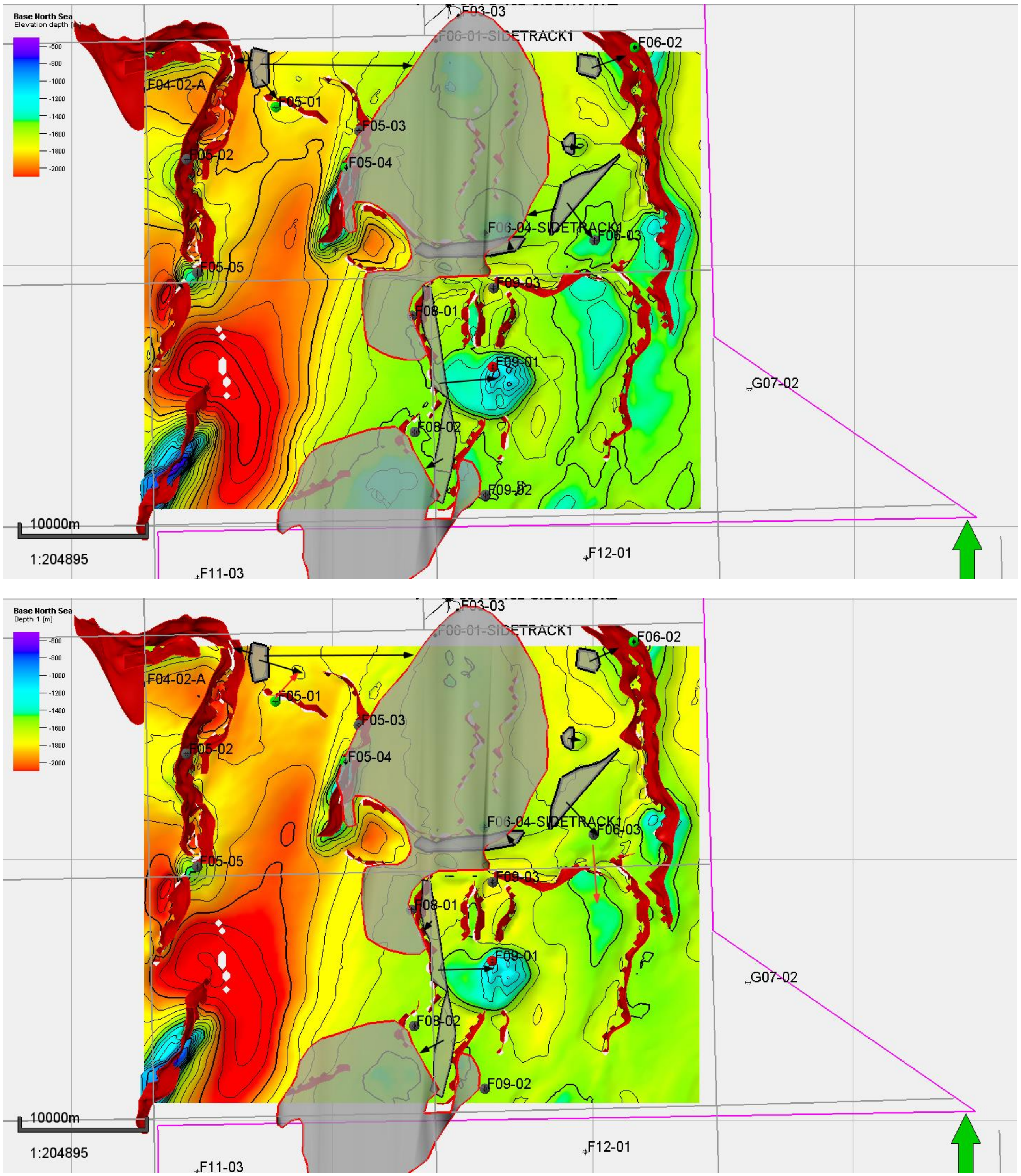


Figure 65: Possible traps in the Chalk (Danian) during the post Elsterian (above) and the Present (below). The grey areas are the areas where the hydrocarbons had migrated to in the Middle Graben Formation. These areas are formed by an angular unconformity between the Middle Graben formation and base Cretaceous. Indicated with arrows are the hydrocarbons migrating through the Danian Chalk into possible traps. The arrows (black =primary, red is secondary) indicate where the hydrocarbons are within the Middle Graben formation during that time and where they migrate to in the Danian Chalk. The red polygons indicate areas where the chalk is absent and the hydrocarbons can get trapped by a stratigraphic trap. The colored dots at the wells indicate oil shows (green), gas shows (red), no shows (grey).

Acknowledgements

I would like to thank Bastiaan Jaarsma for his supervision during this study, his suggestions, and support. Also, I would like to thank Hans de Bresser for his supervision on behalf of Utrecht University. Furthermore, I would like to thank Dana Petroleum Netherlands B.V. for their suggestions concerning the chalk plays. I am grateful to Renaud Bouroullec from TNO for his suggestions about the restoration part of this study. Finally, I would like to thank Nora Heijnen for her help concerning the chalk, and Guido Hoetz for his general suggestions, as well as suggestions about interpretation of well data.

References

Abbink, O. A., Mijnlieff, H. F., Munsterman, D. K., & Verreussel, R. M. C. H. (2006). New stratigraphic insights in the 'Late Jurassic'of the Southern Central North Sea Graben and Terschelling Basin (Dutch Offshore) and related exploration potential. *Netherlands Journal of Geosciences-Geologie en Mijnbouw*, *85*(3), 221-237.

Albertz, M., & Ings, S. J. (2012). Some consequences of mechanical stratification in basin-scale numerical models of passive-margin salt tectonics. *Geological Society, London, Special Publications*, *363*(1), 303-330.

Barton, P., & Wood, R. (1984). Tectonic evolution of the North Sea basin: crustal stretching and subsidence. *Geophysical Journal International*, *79*(3), 987-1022.

Benvenuti, A., Kombrink, H., Ten Veen, J. H., Munsterman, D. K., Bardi, F., & Benvenuti, M. (2012). Late Cenozoic shelf delta development and Mass Transport Deposits in the Dutch offshore area–results of 3D seismic interpretation. *Netherlands Journal of Geosciences*, *91*(04), 591-608.

Buchanan, P. G., Bishop, D. J., & Hood, D. N. (1996). Development of salt-related structures in the Central North Sea: results from section balancing. *Geological Society, London, Special Publications*, *100*(1), 111-128.

Cartwright, J., Stewart, S., & Clark, J. (2001). Salt dissolution and salt-related deformation of the Forth Approaches Basin, UK North Sea. *Marine and Petroleum Geology*, *18*(6), 757-778.

Cartwright, J. A. (1989). The kinematics of inversion in the Danish Central Graben. *Geological Society, London, Special Publications*, *44*(1), 153-175.

Cohen, H. A., & Hardy, S. (1996). Numerical modelling of stratal architectures resulting from differential loading of a mobile substrate. *Geological Society, London, Special Publications*, *100*(1), 265-273.

Clausen, O. R., Nielsen, S. B., Egholm, D. L., & Gołędowski, B. (2012). Cenozoic structures in the eastern North Sea Basin—A case for salt tectonics. *Tectonophysics*, *514*, 156-167.

Van Dalfsen, W., Van Gessel, S. F., & Doornenbal, J. C. (2007). Velmod-2. *Joint Industry Project: TNO-report*.

Davison, I., Alsop, I., Birch, P., Elders, C., Evans, N., Nicholson, H., ... & Young, M. (2000). Geometry and late-stage structural evolution of Central Graben salt diapirs, North Sea. *Marine and Petroleum Geology*, *17*(4), 499-522.

De Bruin, G., Bouroullec, R., Geel, K., Fattah, R.A., van Hoof, T., Ploymaekers, M., van der Belt, F. Vandeweijer, V., Zijp, M. New Petroleum Plays in the Dutch Northern Offshore (2015). *TNO report TNO 2015 R10920.*

De Jager, J. (2003). Inverted basins in the Netherlands, similarities and differences. *Netherlands Journal of Geosciences-Geologie en Mijnbouw*, *82*(4), 339-349.

De Gans, W. (2007). Quaternary. *The geology of the Netherlands*, 173-196.

De Lugt, I. R., Van Wees, J. D., & Wong, T. E. (2003). The tectonic evolution of the southern Dutch North Sea during the Palaeogene: basin inversion in distinct pulses. *Tectonophysics*, *373*(1), 141-159.

EBN (2015) - Multi-target exploration - Combined with minimum facility development, poster presented at Prospex Fair 2015 (http://www.nlog.nl/en/pubs/reports/prospex2015.html)

Ehlers, J., & Gibbard, P. L. (2007). The extent and chronology of Cenozoic global glaciation. *Quaternary International*, *164*, 6-20.

Eidvin, T., Riis, F., & Rundberg, Y. (1999). Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields). *Norsk Geologisk Tidsskrift*, *79*(2), 97-128.

Fattah, R. A., Verweij, J. M., Witmans, N., & Ten Veen, J. H. (2012). Reconstruction of burial history, temperature, source rock maturity and hydrocarbon generation in the northwestern Dutch offshore. *Netherlands Journal of Geosciences*, *91*(04), 535-554.

Ge, H., & Jackson, M. P. (1998). Physical modeling of structures formed by salt withdrawal: implications for deformation caused by salt dissolution. *AAPG bulletin*, *82*(2), 228-250.

Gemmer, L., Huuse, M., Clausen, O. R., & Nielsen, S. B. (2002). Mid-Palaeocene palaeogeography of the eastern North Sea basin: integrating geological evidence and 3D geodynamic modelling. *Basin Research*, *14*(3), 329-346.

Grant, N. T., Middleton, A. J., & Archer, S. (2014). Porosity trends in the Skagerrak Formation, Central Graben, United Kingdom Continental Shelf: The role of compaction and pore pressure history. *AAPG bulletin*, *98*(6), 1111-1143.

Grassmann, S., Cramer, B., Delisle, G., Hantschel, T., Messner, J., & Winsemann, J. (2010). pT-effects of Pleistocene glacial periods on permafrost, gas hydrate stability zones and reservoir of the Mittelplate oil field, northern Germany. *Marine and Petroleum Geology*, *27*(1), 298-306.

Harding, R., & Huuse, M. (2015). Salt on the move: Multi stage evolution of salt diapirs in the Netherlands North Sea. *Marine and Petroleum Geology*, *61*, 39-55.

Hillis, R. R. (1995). Quantification of Tertiary exhumation in the United Kingdom southern North Sea using sonic velocity data. *AAPG bulletin*, *79*(1), 130-152.

Hossack, J. (1995). Geometric rules of section balancing for salt structures.

Hughes, M., & Davison, I. (1993). Geometry and growth kinematics of salt pillows in the southern North Sea. *Tectonophysics*, *228*(3-4), 239-254.

Huuse, M., & Clausen, O. R. (2001). Morphology and origin of major Cenozoic sequence boundaries in the eastern North Sea Basin: top Eocene, near-top Oligocene and the mid-Miocene unconformity. *Basin Research*, *13*(1), 17-41.

Japsen, P. (1998). Regional velocity-depth anomalies, North Sea Chalk: a record of overpressure and Neogene uplift and erosion. *AAPG bulletin*, *82*(11), 2031-2074.

Lang, J., Hampel, A., Brandes, C., & Winsemann, J. (2014). Response of salt structures to ice-sheet loading: implications for ice-marginal and subglacial processes. *Quaternary Science Reviews*, *101*, 217-233.

Mallon, A. J., & Swarbrick, R. E. (2002). A compaction trend for non-reservoir North Sea Chalk. *Marine and Petroleum Geology*, *19*(5), 527-539.

Overeem, I., Weltje, G. J., Bishop-Kay, C., & Kroonenberg, S. B. (2001). The Late Cenozoic Eridanos delta system in the Southern North Sea Basin: a climate signal in sediment supply?. *Basin Research*, *13*(3), 293-312.

Pilcher, R. S., & Blumstein, R. D. (2007). Brine volume and salt dissolution rates in Orca Basin, northeast Gulf of Mexico. *AAPG bulletin*, *91*(6), 823-833.

Rowan, M. G., & Ratliff, R. A. (2012). Cross-section restoration of salt-related deformation: Best practices and potential pitfalls. *Journal of Structural Geology*, *41*, 24-37.

Sclater, J. G., & Christie, P. A. F. (1980). Continental stretching: an explanation of the post-mid-Cretaceous subsidence of the central North Sea basin. *Journal of Geophysical Research*, *85*(B7), 3711-3739.

Sørensen, J. C., Gregersen, U., Breiner, M., & Michelsen, O. (1997). High-frequency sequence stratigraphy of Upper Cenozoic deposits in the central and southeastern North Sea areas. *Marine and Petroleum Geology*, *14*(2), 99-123.

Vackiner, A. A., Antrett, P., Strozyk, F., Back, S., Kukla, P., & Stollhofen, H. (2013). Salt kinematics and regional tectonics across a Permian gas field: a case study from East Frisia, NW Germany. *International Journal of Earth Sciences*, *102*(6), 1701-1716.

Vejbæk, O. V., & Andersen, C. L. A. U. S. (2002). Post mid-Cretaceous inversion tectonics in the Danish Central Graben–regionally synchronous tectonic events. *Bulletin of the Geological Society of Denmark*, *49*(2), 93-204.

Verweij, H. M., Echternach, M. S. C., Witmans, N., & Fattah, R. A. (2012). Reconstruction of basal heat flow, surface temperature, source rock maturity, and hydrocarbon generation in salt-dominated Dutch Basins.

Verweij, J. M., Ten Veen, J. H., De Bruin, G., Nelskamp, S. N., Donders, T., Kunakbayeva, G., & Geel, K. (2012, June). Shallow Gas Migration and Trapping in the Cenozoic Eridanos Delta Deposits, Dutch Offshore. In *74th EAGE Conference and Exhibition incorporating EUROPEC 2012*.

Weisbrod, N., Alon-Mordish, C., Konen, E., & Yechieli, Y. (2012). Dynamic dissolution of halite rock during flow of diluted saline solutions. *Geophysical Research Letters*, *39*(9).

Van Wijhe, D. V. (1987). Structural evolution of inverted basins in the Dutch offshore. *Tectonophysics*, *137*(1-4), 171179185191213-175181187210219.