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Harmonized time model of the Entenschnabel region

Documentation

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GENERAL INTRODUCTION

The GeoERA research project "3D Geomodeling for Europe (3DGEO-EU)" aims to show on the example of cross-border pilot areas (work packages 1 - 3) how harmonization across the borders can be established and maintained with the progress of the national models. The pilot area of work package 3 (WP3) spans thereby the offshore cross-border North Sea area between the Netherlands, Germany and Denmark. In this region, the partners the Netherlands Organization for Applied Scientific Research (TNO, NL), the Geological Survey of Denmark and Greenland (GEUS, DK) and the Federal Institute for Geosciences and Natural Resources (BGR, GER) intent to integrate existing national (and regional) geomodels into a harmonized, consistent cross-border geomodel of the North Sea area.

The following report is a documentation of the harmonization work conducted in order to create a harmonized time model of the Entenschnabel region. The harmonized time model incorporates 8 key stratigraphic horizons from the base of the Zechstein to the Cenozoic and covers the northwestern part of the German North Sea sector and the adjacent areas in Denmark and the Netherlands. The challenges and problems encountered with the harmonization as well as the revisions made to harmonize the national time horizon models across the borders are described in detail.

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1 INTRODUCTION

Work package 3 (WP3) of the GeoERA research project "3D Geomodeling for Europe (3DGEO-EU)" aims to integrate existing national (and regional) geomodels into a harmonized, consistent cross-border geomodel of the North Sea area between the Netherlands, Germany and Denmark. For the planned cross-border harmonization, three working areas have been initially defined as shown in Figure 1. These areas comprise the cross-border area of the Danish, German and Dutch Central Graben in the central North Sea, a small stripe along the NL-GER border and the area of the Horn Graben.

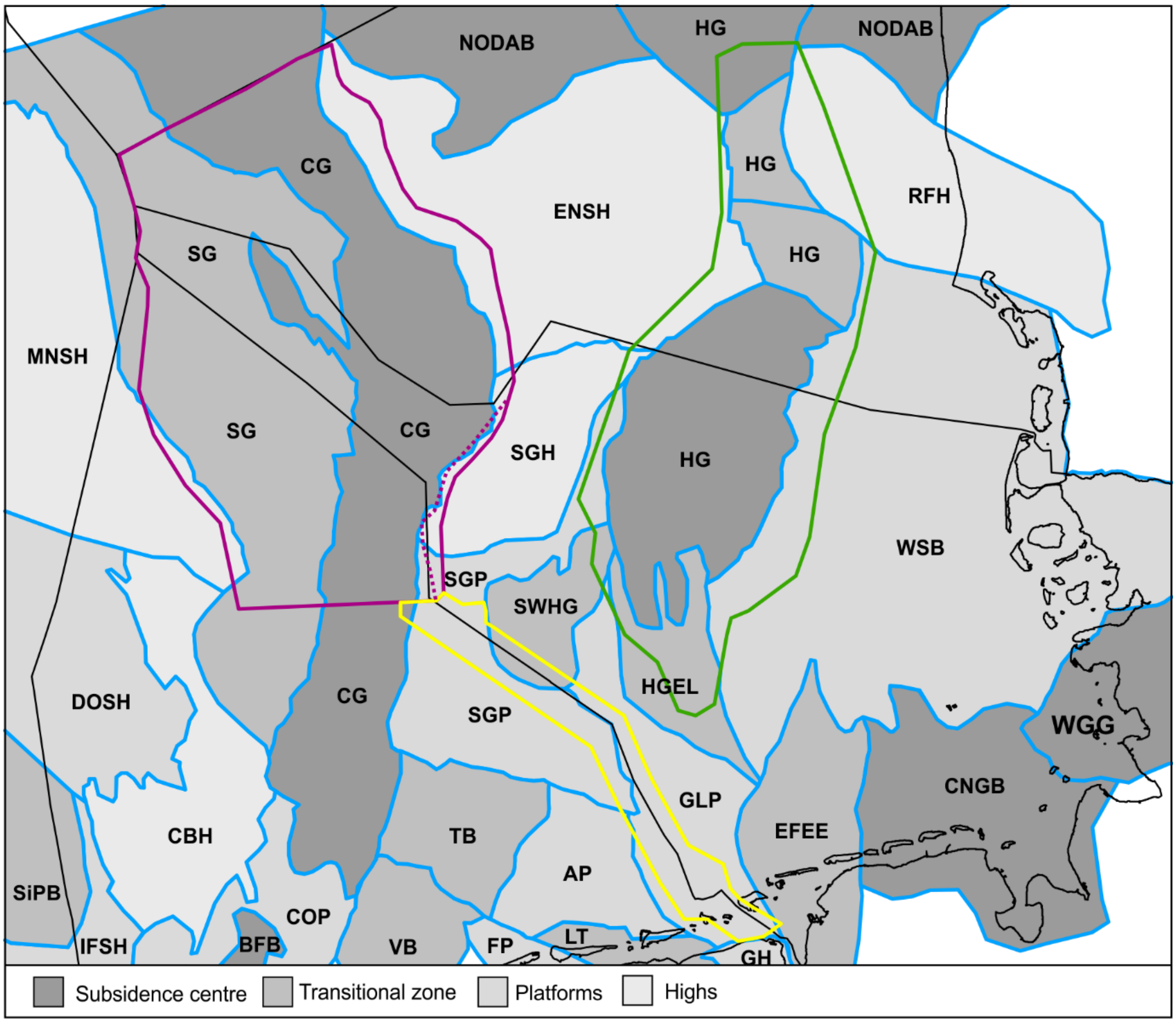


Figure 1: Preliminary map of main structural elements in the area of the Dutch, German and Danish North Sea sectors showing the location of the working areas defined in the North Sea for 3DGEO-EU WP3 (yellow= NL-GER offshore border area / purple = Entenschnabel region / green = Horn Graben region). Note that the areal extent of the harmonized time model of the Entenschnabel region was slightly extended compared to the initial GARAH model (dotted purple line) and covers now further parts of the German Schillgrund High/Platform.

Main structural elements: SG = Step Graben / CG = Central Graben / ENSH = East North Sea High / HG = Horn Graben / RFH = Ringkøbing-Fyn High / MNSH = Mid North Sea High / SGH = Schillgrund High / SGP = Schillgrund Platform / SWHG = southwestern branch Horn Graben / HGEL = southern branch Horn Graben – Ems Lineament / WSB : West Schleswig Block / GLP = G- and L-Platform / EFEE = East Frisia – Ems Estuary Region / CNGB = NW part of the Central North German Basin / WGG – Western branch Glückstadt Graben / DOSH = Dogger Shelf / CBH = Cleaver Bank High / COP = Central offshore Platform / VB = Vlieland Basin / TB = Terschelling Basin / BFB = Broad Fourteens Basin / FP = Friesland Platform / AP = Ameland Platform / LT = Lauwerszee Trough / GH = Groningen High / SIPB = Silver Pit Basin / IFSH = Indefatigable Shelf / NODAB = Norwegian-Danish Basin.

In an initial phase of the project, TWT (Two-Way Travel time) horizon grids of various model sources were provided by the participating GSOs for the working areas referred to as the "Entenschnabel region" and the "NL-GER offshore border area" (Figure 1). The aim was to compare the national horizon models and to identify possible cross-border discrepancies in the nationally mapped horizons. The input models and their horizons were presented and discussed in detail in Deliverable D3.1 ("State of the Art Report"). For the working area defined by the Horn Graben, no time horizons grids were initially provided and compared, since no recent horizon model existed for the Danish part of the Horn Graben. However, within the framework of the GeoERA project, GEUS started a seismic re-interpretation of the Danish Horn Graben and in this context it was possible to develop a harmonized seismic stratigraphic concept for the Horn Graben together with BGR (see for details Deliverable D3.5).

During the initial comparison of the shared horizon models, major discrepancies in distribution and thickness of certain stratigraphic intervals became apparent within the Entenschnabel region, whereas the differences in the national horizon models within the NL-GER offshore border area were usually negligible and rely mainly on slightly different interpretations in the vicinity of salt dome flanks and tops (see appendix of Deliverable D3.1). Since most discrepancies in the national horizon models were within the Entenschnabel region and their removal within this structurally complex region proved to be very time consuming, the project partners decided to focus their cross-border harmonization of exiting geomodels on the Entenschnabel region. The challenges and problems encountered with this harmonization as well as the revisions made to harmonize the national time horizon models in the Entenschnabel region are described in the following sections.

2 HARMONIZED TIME MODEL (ENTENSCHNABEL REGION)

2.1 Model area and selected stratigraphic horizons

The working area, here referred to as Entenschnabel region, covers the northwestern part of the German North Sea sector and the adjacent areas in Denmark and the Netherlands (Figure 1). The region is characterized by a complex rift-dominated structural pattern, with the Central Graben as the main structure, forming in general a half-graben system (Møller & Rasmussen, 2003). For this structural complex region, a first 3D model was built during July 2018 to March 2019 in WP3 based on the initially provided time horizon grids and was needed as input model within the GARAH-project. Eight key stratigraphic horizons from the base of the Zechstein to the Cenozoic were selected for this generalized model (Table 1) and time-depth converted by a first developed cross-border velocity model for this region (see Deliverable D3.2). Cross-border discrepancies observed in the national horizon models, however, were not removed in this initial model. The harmonized time model presented here for the Entenschnabel region incorporates the same horizons selected for the GARAH model (Table 1). The area of the harmonized time model was, however, slightly extended compared to the initial GARAH model and now covers further parts of the German Schillgrund High & Platform (Figure 1).

Table 1: Key stratigraphic horizons selected for harmonization of the time model in the Entenschnabel region.

No	Horizon
1	Near Mid Miocene Unconformity
2	Near base Cenozoic
3	Base Upper Cretaceous
4	Near base Lower Cretaceous
5	Near base Upper Jurassic
6	Near base Lower Jurassic
7	Near base Lower Triassic
8	Base Zechstein

2.2 Harmonization challenges and problems – DK/GER border

Harmonizing the Danish time horizon grids with those of the German North Sea proved to be a challenging task due to various aspects. In the following, the challenges and problems encountered with the harmonization as well as the approaches used to solve them will be briefly outlined. A detail description of the revisions made to harmonize the national horizons is given later in chapter 2.4.

2.2.1 Geometrical inconsistencies in the national horizon models

Contrary to the Dutch and German input models and their horizons, the time horizon grids initially provided by GEUS for the Entenschnabel region were taken from different projects and are not the result from a specific seismic mapping campaign where horizon grids are generally aligned to each other (see for details Deliverable D3.1). Some of the Danish horizons, for example, evolved from three major multi-client projects recently conducted in the Danish North Sea sector:

- The Jurassic Petroleum System in the Danish Central Graben (PETSYS) project
- The Cretaceous Petroleum System in the Danish Central Graben (CRETSYS) project
- The Cenozoic Petroleum Potential in the Danish North Sea (CENSYS)

Within these projects, GEUS has generated comprehensive 3D structural models of the Jurassic, Cretaceous and the Cenozoic based on extensive 2D and 3D seismic data. For the pre-Jurassic succession in the Danish Central Graben area, however, no comparable work has been carried out recently, and the time horizon grids initially provided by GEUS for this interval were derived from older seismic mapping studies. The Top pre-Zechstein surface provided at the beginning of the project, for example, is derived from Vejbaek and Britze (1994). A problem that arises from the fact that the Danish horizon grids have emerged from various projects and different data sets is that the time grids provided are often not aligned and therefore partly intersect each other. Especially the older interpretations of the Danish Top Zechstein and Top pre-Zechstein surfaces, which are mainly based on sparse 2D seismic data, intersect considerably with the more recently mapped horizons, as illustrated in Figure 2. These geometrical inconsistencies in the national horizons, which of course also existed along the Danish-German border (Figure 2), made cross-border harmonization rather difficult at first, or even impossible for certain horizons.

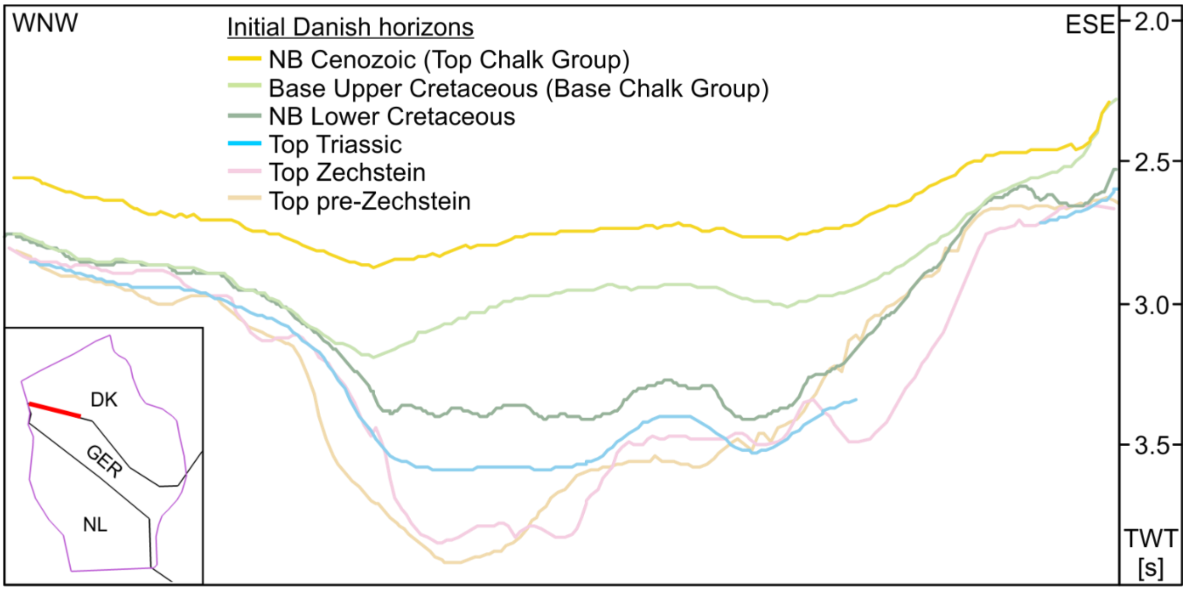


Figure 2: Cross-section through the time horizon grids initially provided for the Danish North Sector in the Entenschnabel region. The cross-section runs along the Danish-German border in the area of the Outer Rough Basin (see red line in the embedded map). Note the considerable horizon intersections in the initial time horizon model and that most of the Danish horizons were mapped as top surfaces.

2.2.2 Differences in the seismic picking concept

Besides the geometrical inconsistencies in the national horizons, harmonization along the Danish-German border was further hampered by differences in the seismic interpretation concepts. In general, the boundary of a stratigraphic unit may be represented by top horizons or base horizons. For the planned cross-border harmonization in 3DGEO-EU WP3, it was decided by the project partners to harmonize the bases of key stratigraphic intervals (Table 1). The horizons of the Dutch and German models provided for harmonization were generally mapped as base surfaces, whereas in the Danish North Sea the boundaries of certain stratigraphic units are traditionally represented by top surfaces. This circumstance complicates harmonization across borders, as the horizons mapped according to the different interpretational concepts (base vs. top) may differ to some extent, as illustrated in Figure 3. For example, the base of the Upper Jurassic corresponds here in areas where Lower and Middle Jurassic is preserved to the Top Middle Jurassic reflector, whereas in areas without these strata the Base Upper Jurassic is equivalent to the horizon mapped as Top Triassic.

The different interpretation philosophies applied mainly affected the harmonization of the horizons below the Near base Lower Cretaceous. For younger Mesozoic to Cenozoic intervals, the different concepts had only a minor impact on the harmonization. This is because the younger units are generally distributed throughout the study area without major gaps and, accordingly, differences between top and base surfaces are often negligible. For example, the top of the Chalk Group provided for the Danish North Sea is broadly comparable to the Near base Cenozoic horizons mapped in the Dutch and German North Sea sectors. In contrast, the top surfaces of the Middle Jurassic, Triassic, Zechstein and pre-Zechstein mapped in the pre-Cretaceous succession of the Danish North Sea and provided by GEUS for harmonization purposes in 3DGEO-EU WP3 are only regionally comparable with the base horizons selected for harmonization. Most striking is this for the Base Upper Jurassic. Depending on the underlying stratigraphy, the base horizon is formed in the Danish North Sea by either the Top Middle Jurassic, Top Triassic, Top Zechstein, or even where Mesozoic deposits are absent, by the Top pre-Zechstein surface. The fact that the base horizons in the German North Sea may coincide with different Danish top surfaces along the border further complicated the harmonization work.

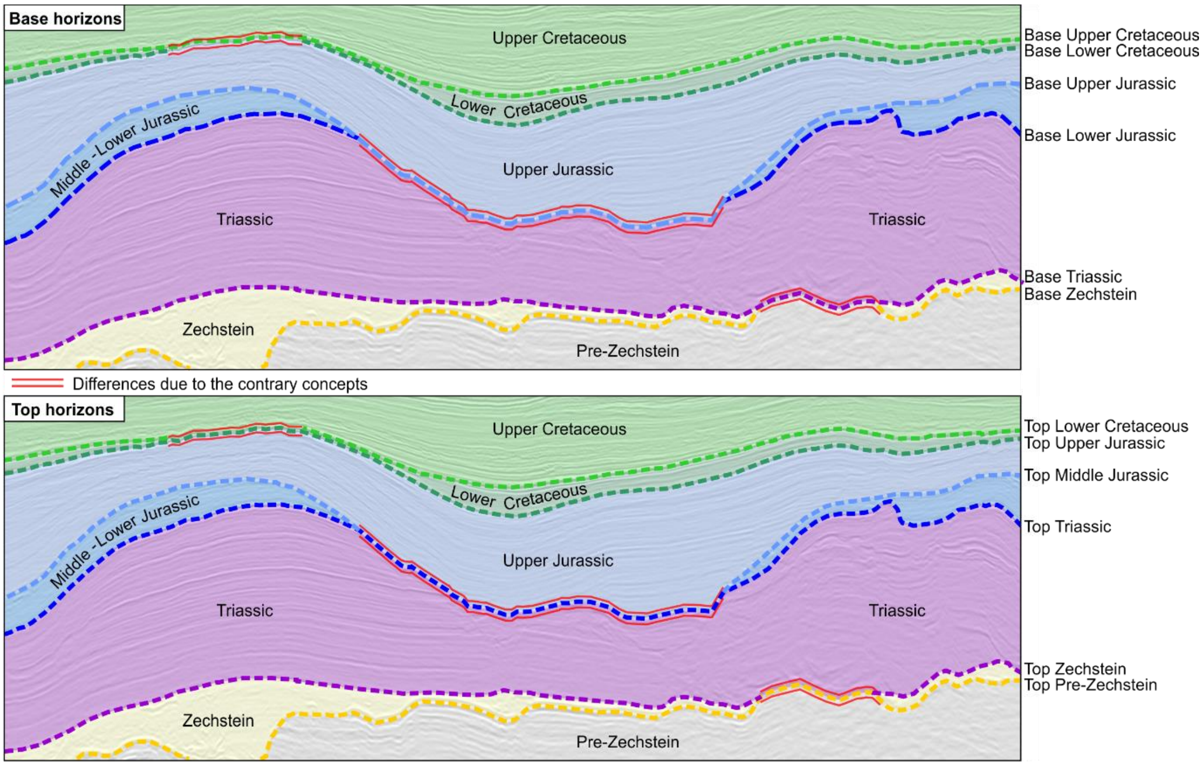


Figure 3: Seismic sections illustrating the difference of horizons mapped as basal or top surfaces. Differences are marked in red.

2.2.3 Horizon adaptions required for harmonization

In view of the problems discussed above, it was necessary to adapt the Danish horizon model to a certain extent in order to enable cross-border harmonization along the German-Danish border. The adaptations conducted are briefly described below:

<u>Removal of horizon intersections:</u>

In general, horizon intersections can be easily eliminated by grid mathematics and the software packages used in the project (e.g. Emerson Paradigm©) have corresponding functions by default. However, since the older interpretations of the Danish Top Zechstein and Top pre-Zechstein intersect considerably, especially with the newer interpretations, and these overlaps may reach several 100 ms [TWT] (Figures 2 and 4A), it was not advisable to adapt these horizons accordingly. Instead, GEUS re-interpreted their Top Zechstein and Top pre-Zechstein horizons in the area of the Danish Central Graben based on 2D and 3D seismic data currently available. The re-interpretations intersected much less frequently with the other horizons than it was the case before. However, especially in structurally complex regions, intersections between the different Danish horizons still existed, as illustrated in Figure 4B. These intersections were removed using simple grid mathematics, employing the new Top pre-Zechstein surface and the Danish Base Upper Cretaceous as reference horizons. A more detailed evaluation of these intersections was not carried out due to time constraints.

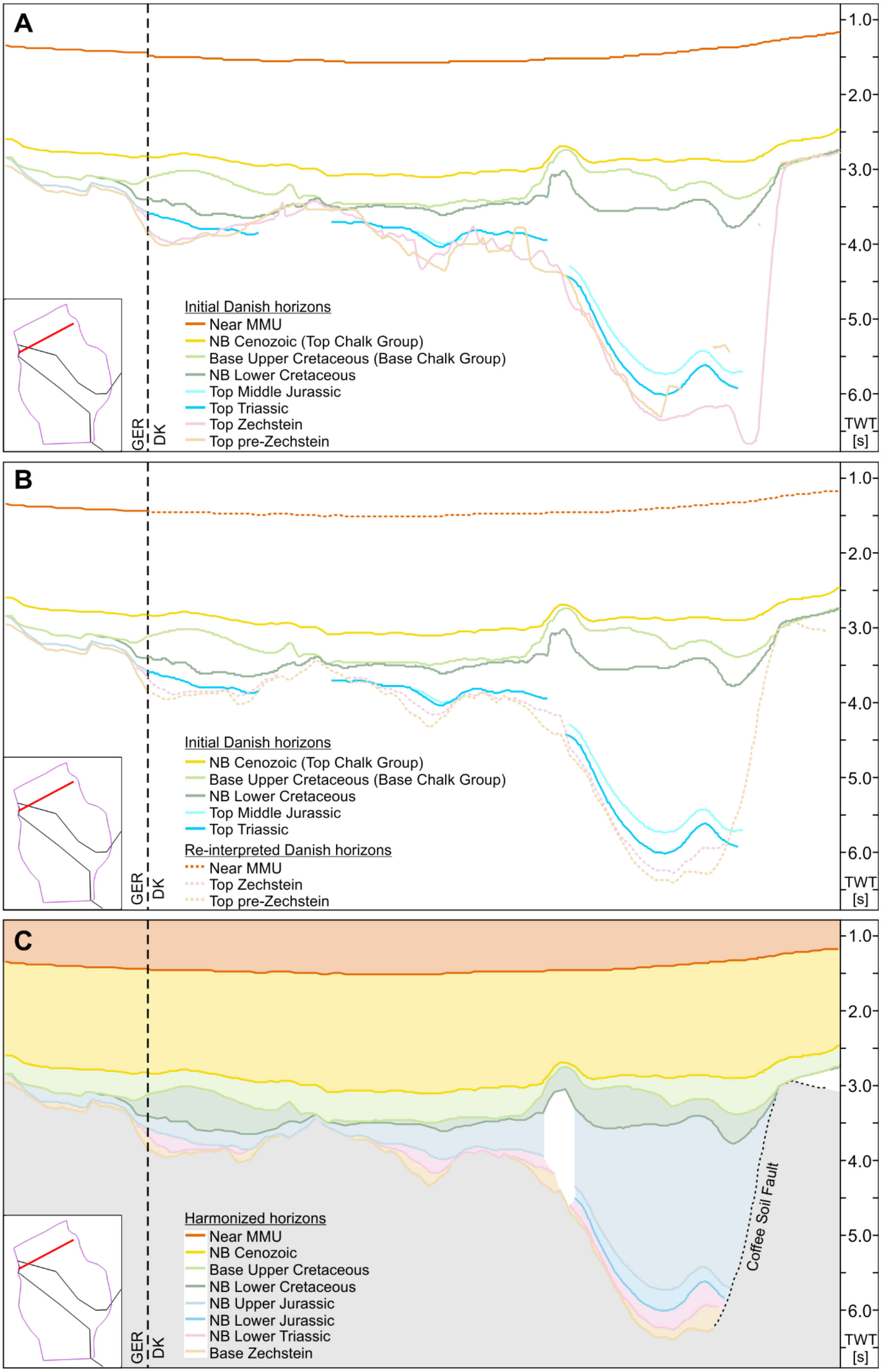


Figure 4: (see next page)

Figure 4 (previous page): (A) Cross-section through the Danish part of the Entenschnabel region showing the time horizon grids initially provided by GEUS for harmonization purposes. Note the considerable horizon intersections in the initial time horizon model and that some of the horizons provided were mapped as top surfaces. The location of the cross section is indicated by the red line on the embedded map. (B) Same cross section with the Danish re-interpretation of the Top Zechstein and Top Pre-Zechstein, which became necessary because of the marked horizon intersections of the initially provided time grids. Note that the re-interpretations intersect much less frequently with the other horizons than it was the case before. (C) Same cross section as in (A) and (B) but with Danish top horizons converted to base horizons, allowing harmonization with German horizons.

<u>Converting top horizons into base horizons:</u>

The fact that the base horizons selected for harmonization (Table 1) can be composed of different Danish top surfaces, it was necessary to convert the Danish horizons mapped as top surfaces into base surfaces prior to the cross-border harmonization. The procedure to convert the horizons is described in the following for the Near base Upper Jurassic.

As described before, the Near base Upper Jurassic is formed by either the Top Middle Jurassic, Top Triassic, Top Zechstein or Top pre-Zechstein in the Danish North Sea, depending on the underlying stratigraphy. In order to generate a Base Upper Jurassic horizon for the Danish North Sea, a combined surface was first created from the top surfaces mentioned above. The horizons were combined by using the smallest available value (i.e. shallowest) at a location. Afterwards, the combined surface and a closed grid of the Near base Lower Cretaceous were used to determine the thickness of the Upper Jurassic. In areas where no Upper Jurassic were present (zero thickness), the combined horizon was then deleted. The base horizons of the Lower Jurassic, Lower Triassic and Zechstein were created accordingly. Finally, the horizon model created in this way was checked for local geological plausibility along numerous cross-sections and, if necessary, adjustments were made to the horizons. For example, owing to the grid mathematics performed, the generated horizons partially coincided with fault planes. Along prominent fault zones such as the Coffee Soil Fault, the horizons were removed in these areas, as illustrated in Figure 4C.

2.3 Harmonization challenges and problems – NL/GER border

The challenges and problems encountered in harmonizing the Dutch and German horizon models were different from those along the Danish-German border. In general, the reasons for the discrepancies observed along the border were not always immediately obvious and may have been caused by a combination of independent factors. A closer evaluation of these discrepancies and their causes was therefore an important step in the process towards a harmonized, consistent cross-border geomodel along the Dutch-German border.

The horizon models provided for harmonization are generally based on the interpretation of 2D and 3D seismic data, supplemented by well information. In Deliverable D3.5, the seismic stratigraphic interpretation concepts applied by the participating GSOs in the North Sea region were compared in detail for the first time. Along several cross-border seismic sections and synthetic seismics, the nationally mapped stratigraphic horizons and their seismic polarity were depicted in great detail. One intent was to understand whether the disparities in the nationally mapped horizons may arise from differences in the seismic stratigraphic interpretation concepts or whether others reasons play a role. In this context, it could be shown that the nationally mapped seismic reflectors generally differ only slightly from each other, often only by one reflector (see for details Deliverable D3.5). One exception was the Near base Lower

Cretaceous in the Central Graben. Here, the seismic reflector mapped initially in the Dutch sector lies about 150 ms [TWT] above the German interpretation. After a re-evaluation of well and seismic data, however, the Dutch interpretation was revised following the interpretation in the German offshore sector (see Figure 16 in chapter 2.4.3).

Although the seismic reflectors mapped in the Dutch and German North Sea generally differed only slightly, marked cross-border discrepancies were locally evident in the time horizon grids initially provided by TNO and BGR (Figure 5). For the area of the Central Graben, it became clear in Deliverable D3.5 that the horizon disparities observed here in the pre-Cretaceous horizons are not caused by different seismic interpretation concepts, but rather are related to low significance of the seismic data sets used for the interpretation. In the German sector, the interpretation was largely based on 3D seismic data (Arfai et al., 2014), whereas in the area where discrepancies occurred, the Dutch horizons were mapped based on sparse 2D seismic lines (Kombrink et al., 2012; Figure 6). In order to remove the cross-border disparities and to harmonize the nationally mapped horizons, the pre-Cretaceous horizons were re-interpreted in the northern Dutch Central Graben based on currently available 2D and 3D seismic data (see chapters 2.4.5 – 2.4.8; Figure 5). In the area of the Step Graben, on the other hand, comparable datasets were generally used close to the border, and the differences observed here can be largely explained by misinterpretations of the structural geometries of the region and the small-scale changes in distributional pattern associated with it (see chapters 2.4.4 – 2.4.5, 2.4.7).

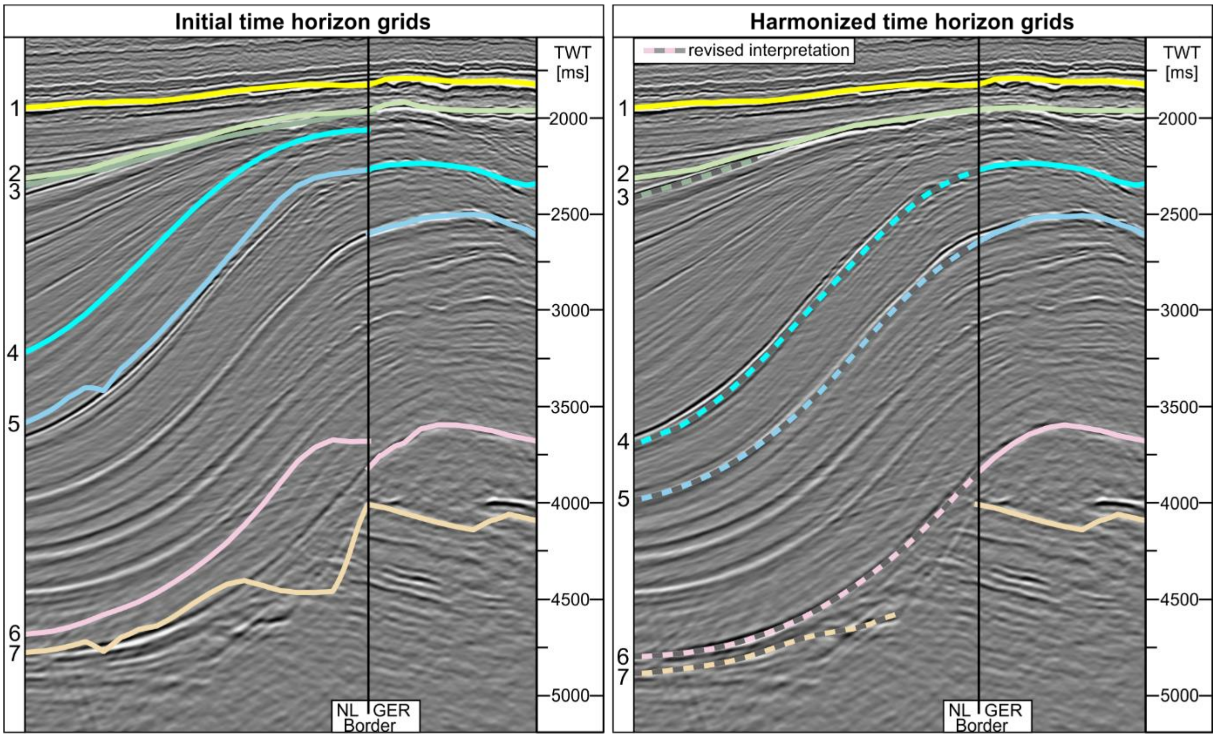


Figure 5: SW-NE orientated seismic section across the Dutch-German border in the area of the Central Graben (see e.g. Figure 20 for location) showing the initial (left) and harmonized (right) time horizon grids. The pre-Cretaceous horizon initially provided for the Dutch sector differ thereby considerably from the German interpretation. In this context, it should be noted that the initial Dutch time horizon grid presented here were interpreted based on sparse 2D seismic data, whereas the seismic section shown was extracted from a 3D seismic survey.

Horizon numbers: (1) Near base Cenozoic, (2) Base Upper Cretaceous, (3) Near base Lower Cretaceous, (4) Near base Upper Jurassic, (5) Near base Lower Jurassic, (6) Near base Lower Triassic and (7) Base Zechstein.

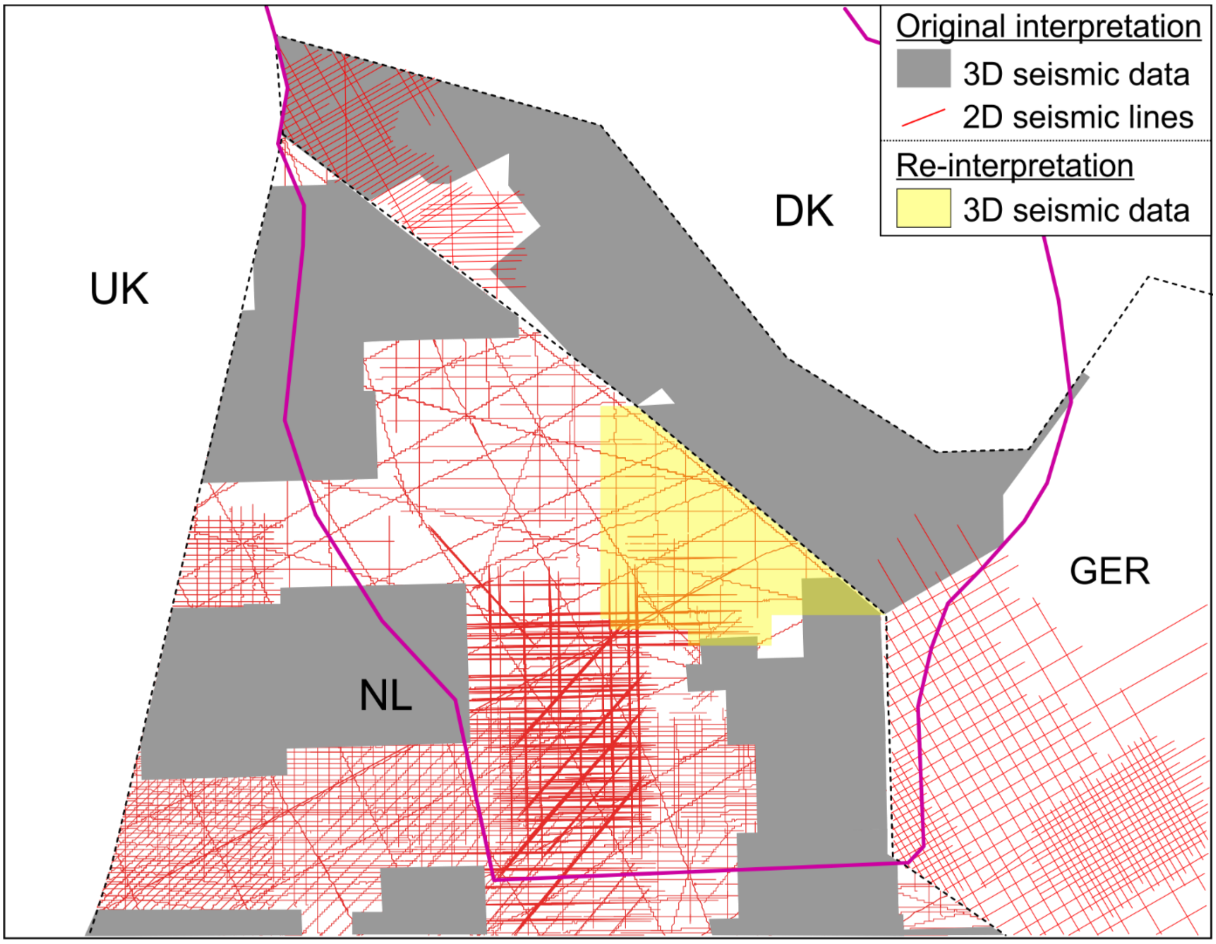


Figure 6: Map showing the seismic data consulted for the original seismic interpretation in the Dutch and German Entenschnabel region (compiled from Kombrink et al., 2012 and Arfai et al., 2014). Note that in the German sector, the initial interpretation was largely based here on 3D seismic data, whereas in the area where discrepancies occurred, the Dutch horizons were mapped based on sparse 2D seismic lines. The 3D seismic survey Z3FUG2002 (NLOG name), which was mainly used to re-interpret the Dutch horizons in the northern part of the Dutch Central Graben, is indicated by the yellow box and the Entenschnabel region by the purple line.

2.4 Harmonization work on the time model

Several discrepancies in distribution and thickness of certain stratigraphic intervals became apparent in the Entenschnabel region during the comparison of the initially shared time horizon grids. In the following section, the revisions made to remove these cross-border disparities in the national horizon models and to harmonize the horizons across the borders are described. For each horizon selected (Table 1), maps showing the initial and harmonized time grids as well the deviation of these grids are presented. In addition, selected seismic sections are shown to illustrate the horizon adaptations made. A detailed description of the (litho-) stratigraphic position and the seismic character of the horizons selected for harmonization, however, is omitted here, and the reader is referred to Deliverable D3.5.

2.4.1 Near Mid Miocene Unconformity

Table 2: Input horizons for the harmonized Near Mid Miocene Unconformity in the Entenschnabel region and summary of revisions made to harmonize the national horizons. For details on the input models see Deliverable D3.1.

Country	Input horizon	Name of provided horizon grid	Grid source
NL	Base of the Upper North Sea Group (NU)	NU_twt_on_offshore_clipped_DGM50_ED50_UTM31	DGM-deep v5.0
Remark:	No revisions		
GER	Mid Miocene Unconformity / Base of the “Eridanos delta”	01_tmiR_MMU	«Eridanos delta» model (GPDN)
Remark:	Local revisions in order to remove horizon intersections		
DK	MMU / Top overpressure	MMU_Top_overpressure_twt_grid	Re-interpretation (3DGEO-EU)
Remark:	Re-interpretation in the area of the Danish Central Graben. The newly mapped horizon coincides here with a transition from overpressured Lower Cenozoic deposits to overlying normal pressured Upper Cenozoic deposits.		

The youngest seismic horizon selected for harmonization is the so-called “Mid Miocene Unconformity (MMU)” which is one of the most prominent seismic features in the Cenozoic sequences of the North Sea Basin. Since the time horizon grids provided for the Dutch and German North Sea matched fairly well along the national border, showing only minor differences of ±15 ms [TWT], an adaption of the MMU was generally not required here (Figure 8). Contrary to this, the time horizon grid initially provided for the Danish North Sea differs partly considerably from the German interpretation, with differences in the horizons of up to 100 ms [TWT] along the national border (Figures 7 and 8). Owing to the condensed nature of overlying sediments, a detailed subdivision of the Cenozoic succession around the MMU is generally difficult to achieve based on seismic data alone, and this circumstance may explain the differences observed. The horizon initially provided for the Danish sector corresponds to the sequence boundary of sequence E of Rasmussen (2017; Figure 7) and is associated with a distinct shift from prograding delta/slope systems to deposition of deeper marine hemipelagic mud. Sequence E represents thereby a condensed section of Middle Miocene deposits and due to its condensed nature the sequence is below seismic resolution in most parts of the North Sea Basin (Rasmussen, 2017). In areas where this is the case, the Danish horizon initially provided for harmonization seismically equates with the base of the Upper Miocene succession and coincides with the seismic reflector mapped in the German North Sea. Here and also in the Dutch North Sea, the MMU corresponds to the lower (seismic) stratigraphic boundary of a westward prograding depositional system (Thöle et al., 2014), often referred to as the 'Eridanos delta' (Overeem et al., 2001). Progradation of the 'Eridanos delta' started in the Late Miocene and developed mainly from the Northeast and East and subsequently from the Southeast leading to deposition of the oldest sequences in the eastern most part of the Danish and German North Sea sectors and increasingly younger sequences towards the west (Thöle et al., 2014).

As sequence E of Rasmussen (2017) is often below seismic resolution and the horizons mapped as MMU in the study area of 3DGEO-EU generally forms the lower seismic stratigraphic boundary of the 'Eridanos delta', the project partners decided to harmonize the base of this prograding depositional system, and to refer the corresponding horizon as Near MMU. In order to remove the initial horizon discrepancies along the Danish-German border, GEUS re-interpreted their horizon in the area of the Danish Central Graben (Figures 8 and 9). Here, the base of the 'Eridanos delta' generally coincides with a transition from overpressured Lower Cenozoic deposits to overlying normal pressured Upper Cenozoic deposits (Figure 7).

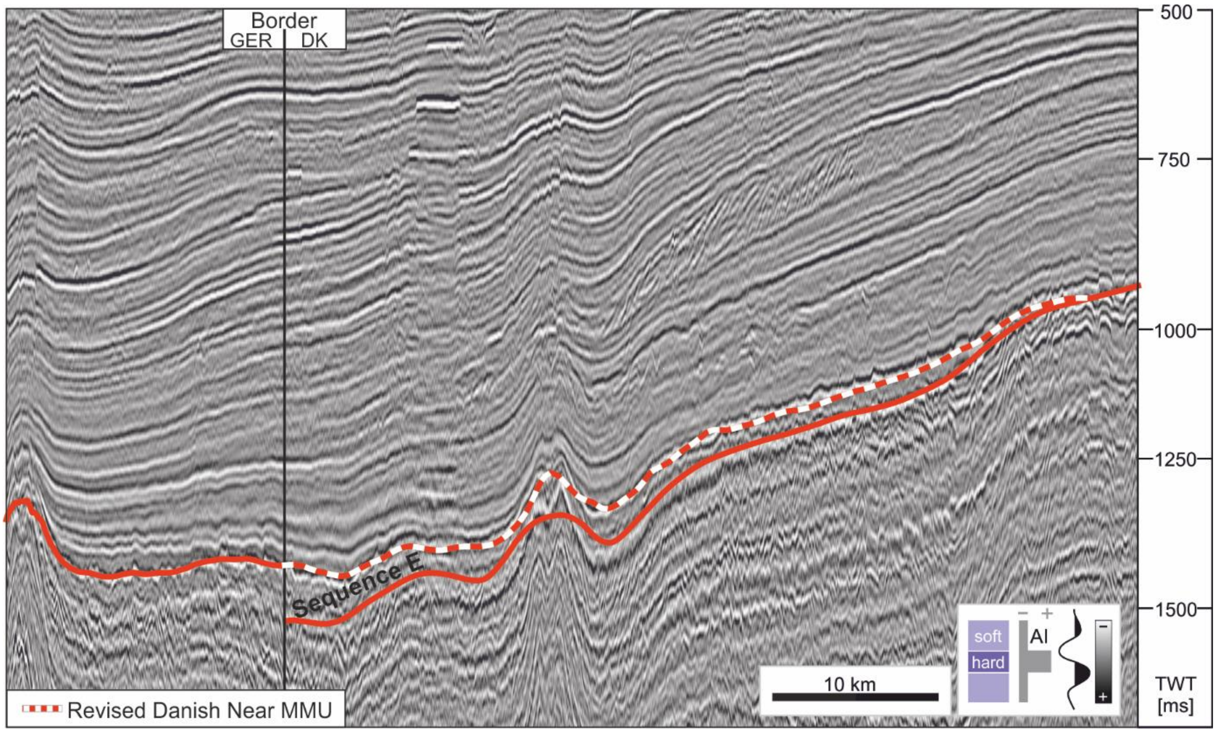


Figure 7: SW-NE orientated seismic section across the Danish-German border (see Figure 8 for location) showing the initial and harmonized interpretations of the Near MMU horizon. Note that the initial Danish grid (red solid line) which corresponds to the sequence boundary of sequence E of Rasmussen (2017) differs considerably from the German interpretation. For harmonization purposes, the Danish horizon was revised and follows now the base of the Upper Miocene-Pliocene 'Eridanos delta' which is associated in the area of the Danish Central Graben with a transition from overpressured Lower Cenozoic deposits to overlying normal pressured Upper Cenozoic deposits.

Near MMU

Initial time horizon grids	Harmonized time horizon grids	Grid deviation (TWT of initial grid – TWT of harmonized grid)

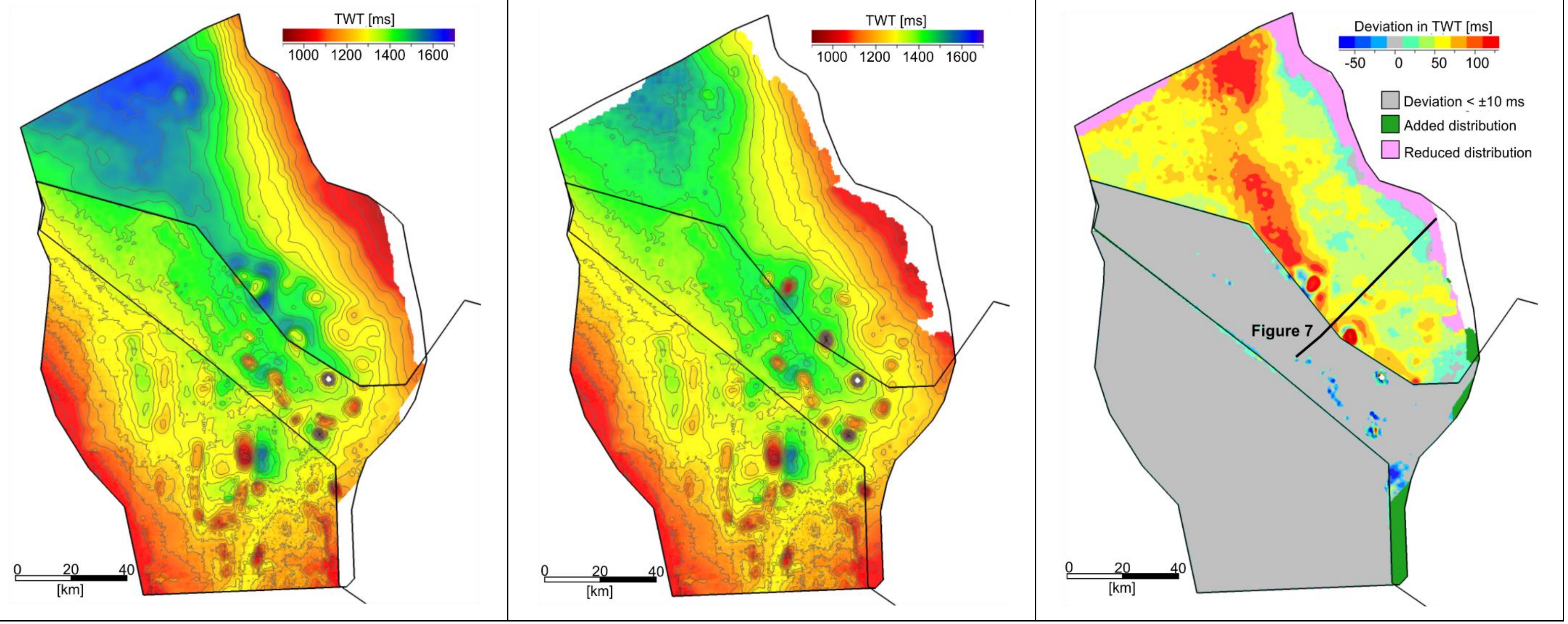
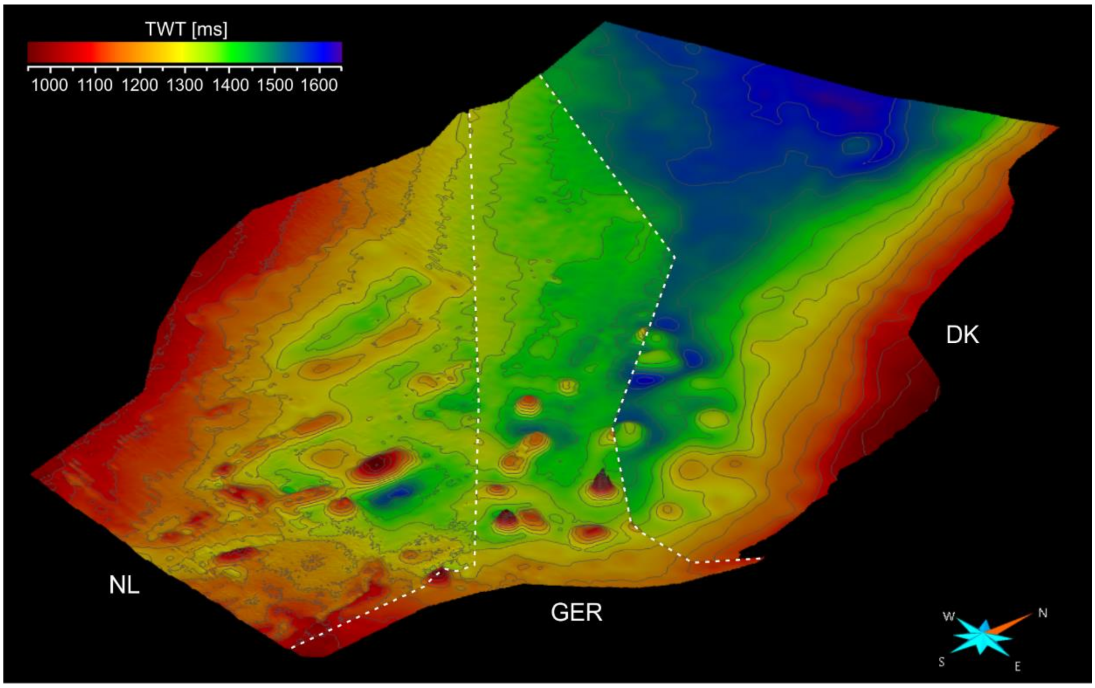


Figure 8: Near MMU maps showing the initial and harmonized time horizon grids as well as the deviation of these grids. Note that the Near MMU was revised for the entire Danish part of the Entenschnabel. The location of the seismic section shown in Figure 7 is indicated by the black line.

Near MMU	3D view

Initial time horizon grids



Harmonized time horizon grids

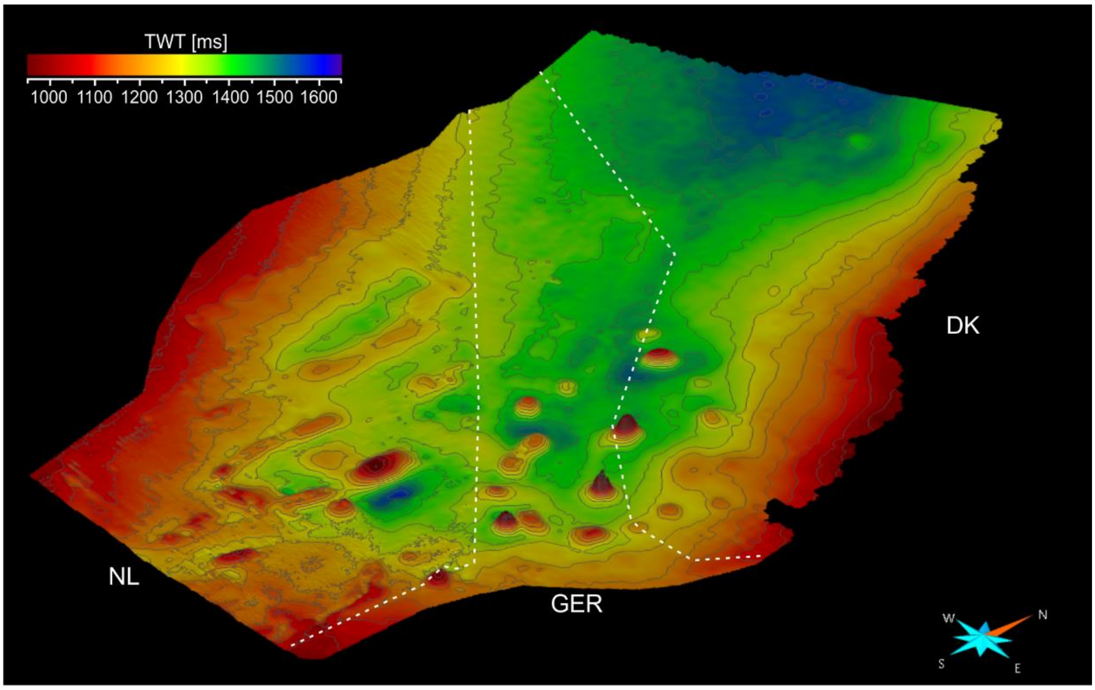


Figure 9: 3D view of the initial and harmonized Near MMU horizon in the Entenschnabel region.

2.4.2 Near base Cenozoic

Table 3: Input horizons for the harmonized Near base Cenozoic horizon in the Entenschnabel region and summary of revisions made to harmonize the national horizons. For details on the input models see Deliverable D3.1.

Country	Input horizon	Name of provided horizon grid	Grid source
NL	Base of the Lower North Sea Group (NL)	NL_twt_on_offshore_clipped_DGM50_ED50_UTM31	DGM-deep v5.0
Remark:	No revisions		
GER	Base Upper Paleocene	05_tpao_T1	3D model Entenschnabel (GPDN)
Remark:	Minor revisions (<20 ms TWT) on the German Schillgrund High and locally along the DK/GER border.		
DK	Top of the Chalk Group	Top_CHALK_TWT_d200_61_60Ma_XYZ	GEUS current structural database
Remark:	No revisions		

The Base Cenozoic horizon represents in all three countries in the presence of concordant layering the top of the Upper Cretaceous/Danian Chalk Group and corresponds in the Dutch and Danish sectors with the top of the Paleocene Ekofisk Formation when present, and is therefore referred here to as Near base Cenozoic. Since the time horizon grids provided for harmonization (Table 3) matched fairly well along the national borders, an adaption of the national horizon grids was generally not required. Only minor revisions (<20 ms TWT) were made on the German Schillgrund High & Platform and locally along the Danish-German border (Figures 10 and 11).

Near base Cenozoic

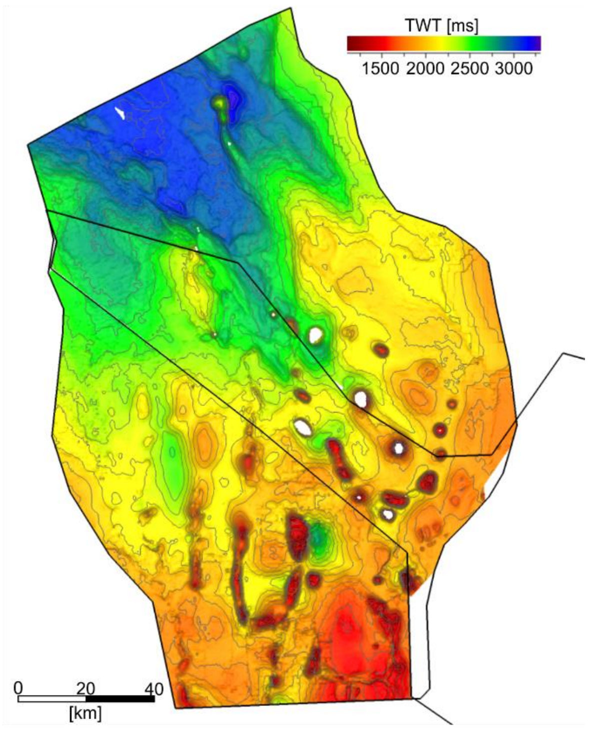
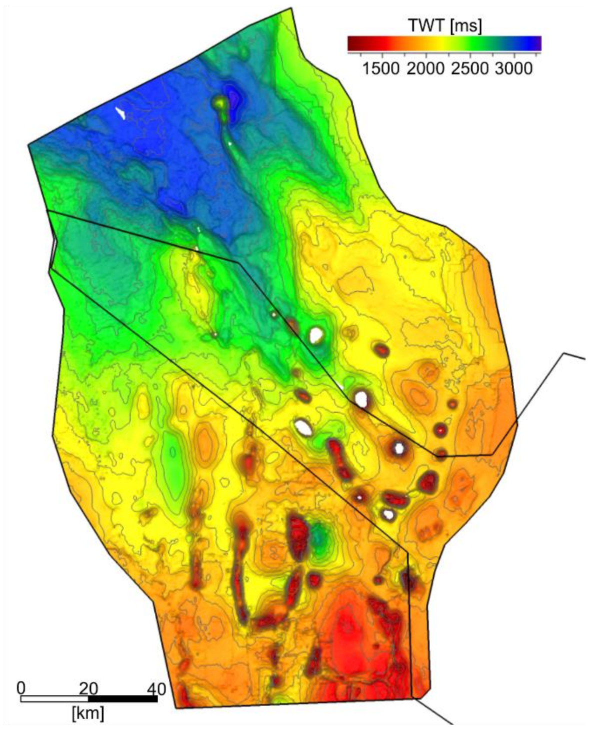
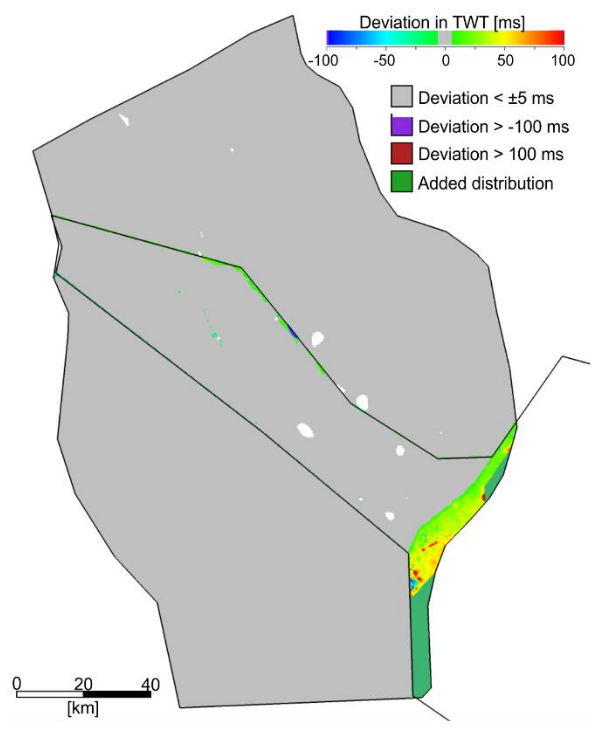
Initial time horizon grids	Harmonized time horizon grids	Grid deviation (TWT of initial grid – TWT of harmonized grid)
		

Figure 10: Near base Cenozoic maps showing the initial and harmonized time horizon grids as well as the deviation of the grids. Note that only minor revisions on the Schillgrund High & Platform and locally along the Danish-German border were required to harmonize the nationally mapped horizons.

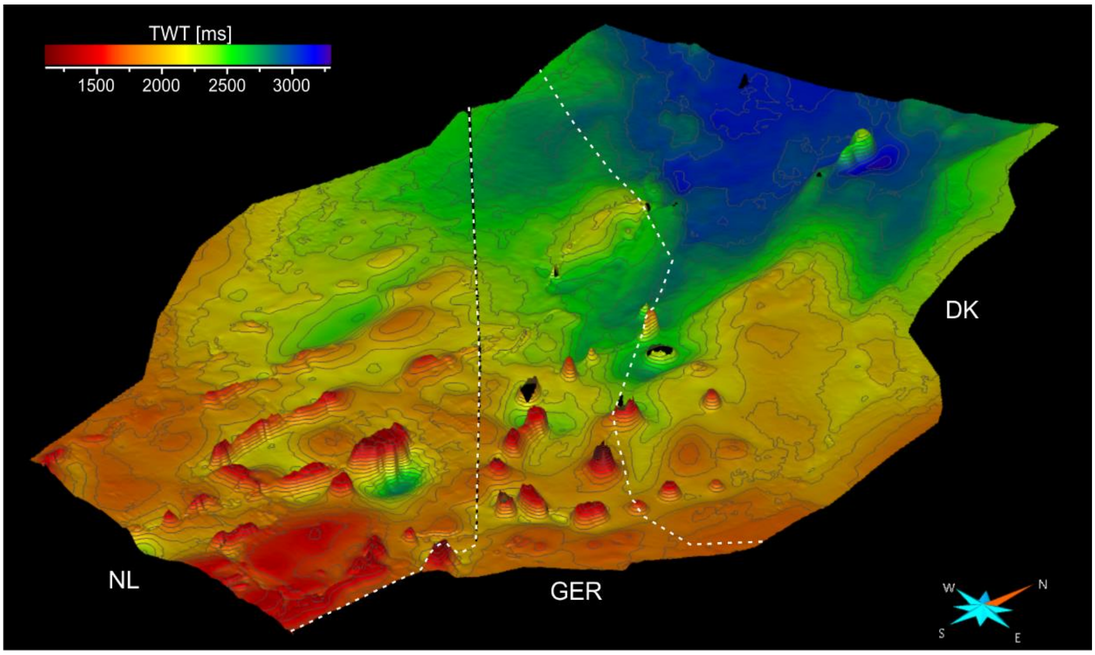
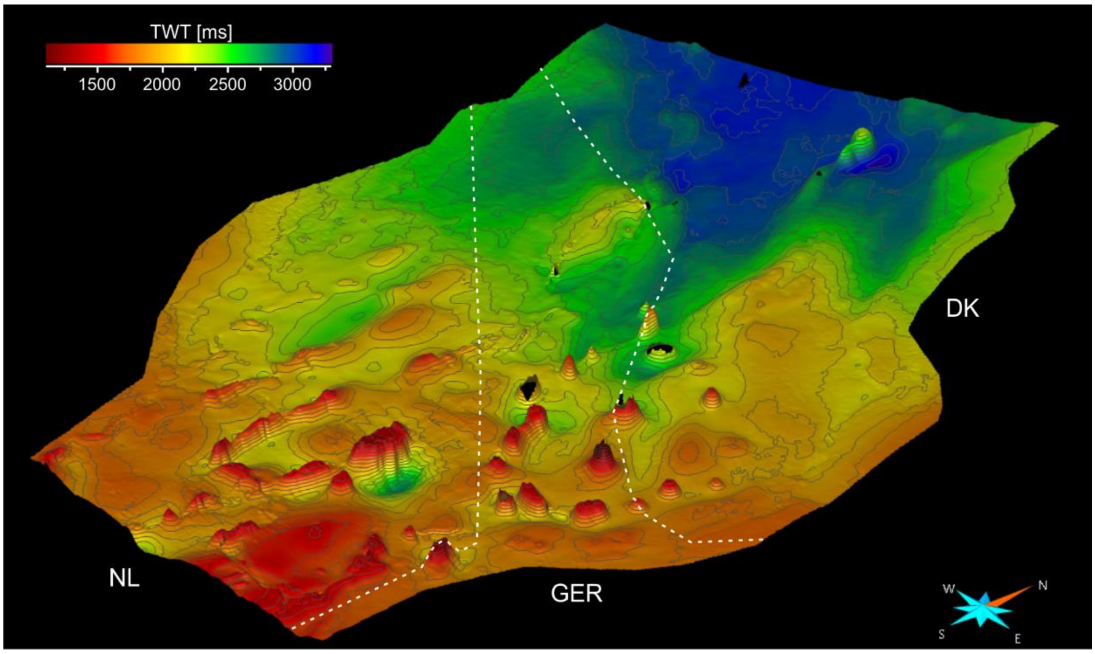
Near base Cenozoic	3D view
Initial time horizon grids	
	
Harmonized time horizon grids	
	

Figure 11: 3D view of the initial and harmonized Near base Cenozoic horizon in the Entenschnabel region.

2.4.3 Base Upper Cretaceous

Table 4: Input horizons for the harmonized Base Upper Cretaceous horizon in the Entenschnabel region and summary of revisions made to harmonize the national horizons. For details on the input models see Deliverable D3.1.

Country	Input horizon	Name of provided horizon grid	Grid source
NL	Base of the Chalk Group (CK)	CK_twt_on_offshore_clipped_DGM50_ED50_UTM31	DGM-deep v5.0
Remark:	Minor changes along the Dutch-German border		
GER	Base Upper Cretaceous	06_kro_Kr2	3D model Entenschnabel (GPDN)
Remark:	Local re-interpretation in the area of the Outer Rough Basin, the Step Graben and on the Schillgrund High/Platform.		
DK	Base of the Chalk Group	Base_CHALK_TWT_d200_100_50Ma_XYZ	GEUS current structural database
Remark:	Minor revisions to remove horizon intersections		

The Base Upper Cretaceous equals in all three countries the base of the Upper Cretaceous/Danian Chalk Group, and except for a few areas, the national time horizon grids provided for harmonization (Table 4) matched fairly well along the national borders (Figures 12 and 14). Local differences in the national horizons that required adaptions occurred, for example, along the Danish-German border in the area of the Outer Rough Basin. Here, the Base Upper Cretaceous mapped so far in the German North Sea sector (Arfai et al., 2014) lies up to 100 ms [TWT] above the Danish interpretation (see e.g. Figure 30 in Deliverable D3.5). Furthermore, in a locally restricted area of the Step Graben, the German Base Upper Cretaceous differed up to 120 ms [TWT] from the Dutch interpretation (Figure 13). After a re-evaluation of well and seismic data, the German interpretation was revised in these areas following the Danish and Dutch interpretations. Further revisions were also made to the Base Upper Cretaceous at the transition from the German Central Graben to the Schillgrund High, as indicated by the deviation map in Figure 12.

Base Upper Cretaceous

Initial time horizon grids	Harmonized time horizon grids	Grid deviation (TWT of initial grid – TWT of harmonized grid)

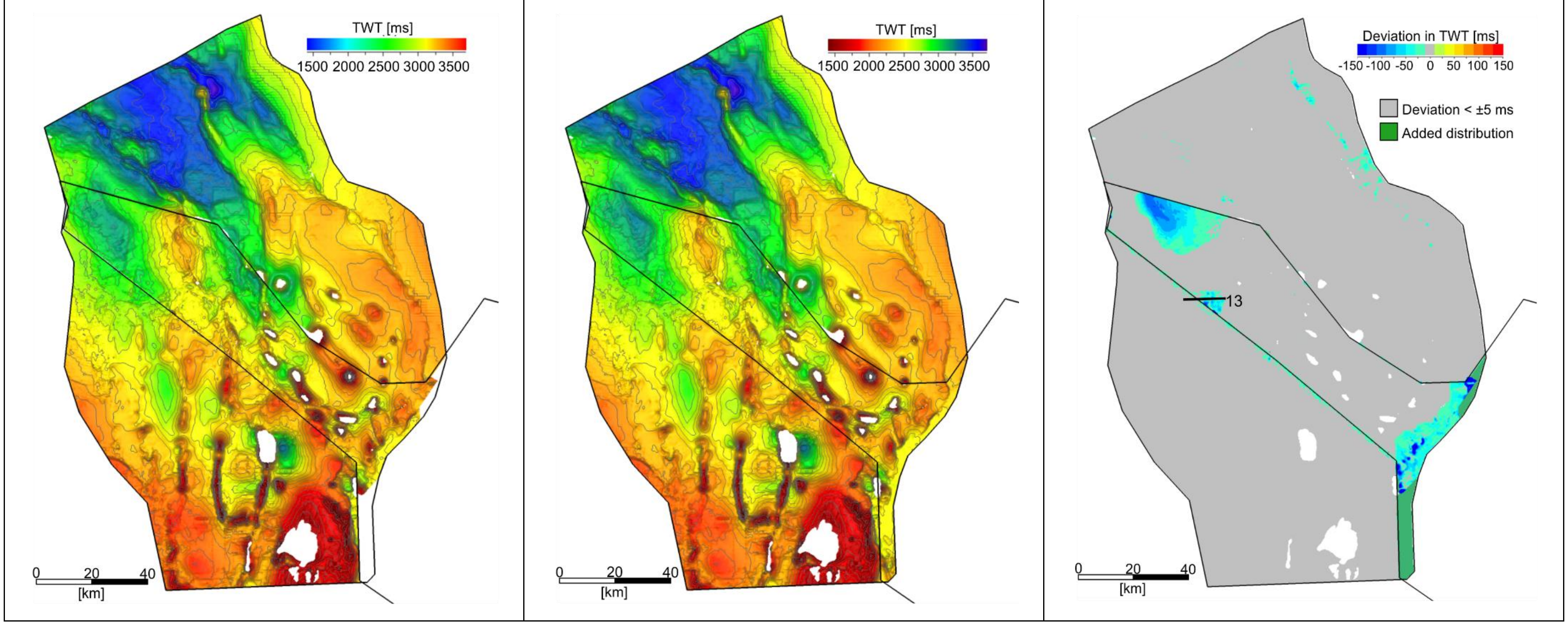


Figure 12: Base Upper Cretaceous maps showing the initial and harmonized time horizon grids as well as the deviation of the grids. Note that the German Base Upper Cretaceous was locally re-interpreted in the area of the Outer Rough Basin, the Step Graben and on the Schillgrund High in order to harmonize the nationally mapped horizons. The seismic section shown in Figure 13 is indicated by the black line.

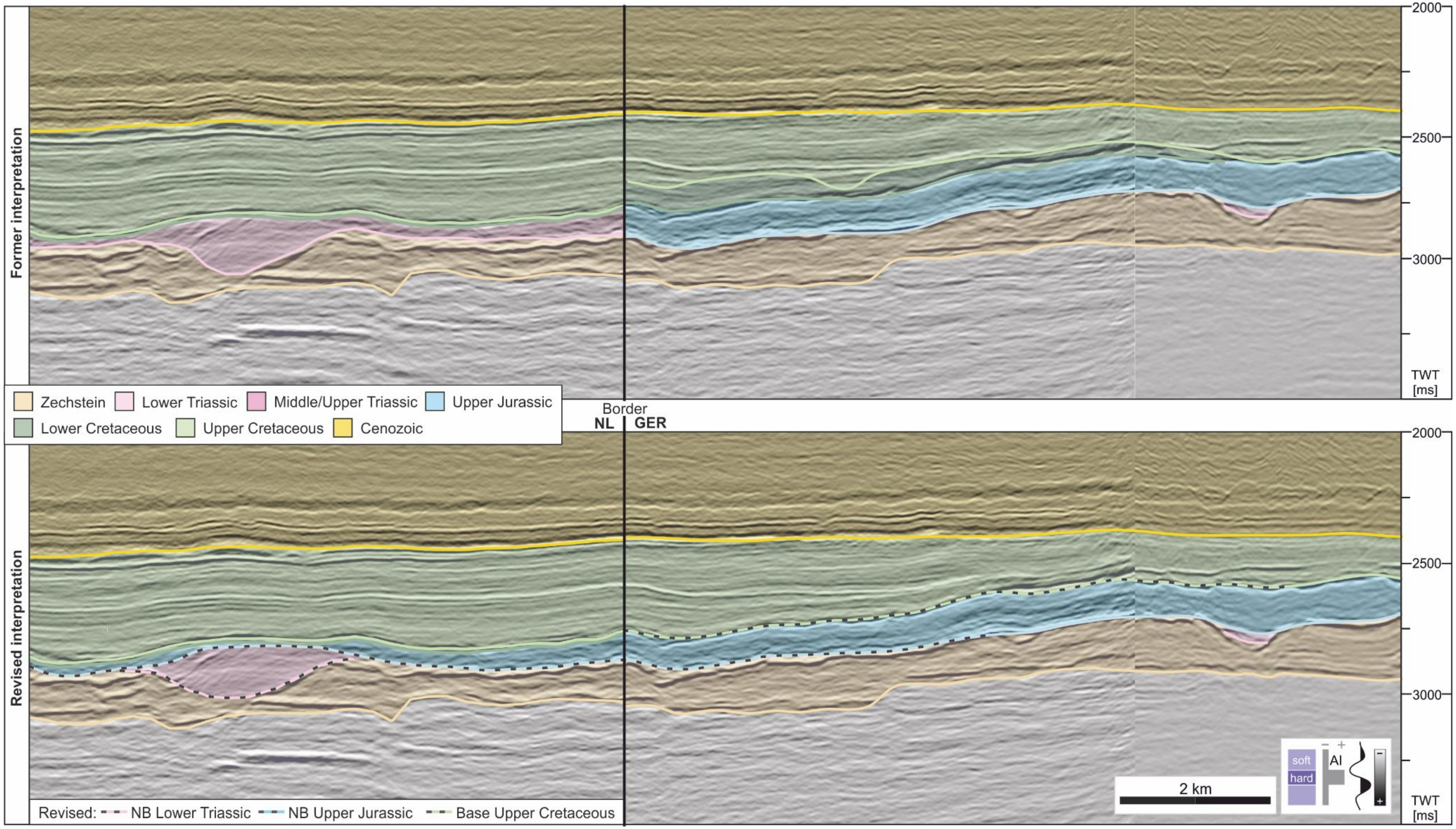
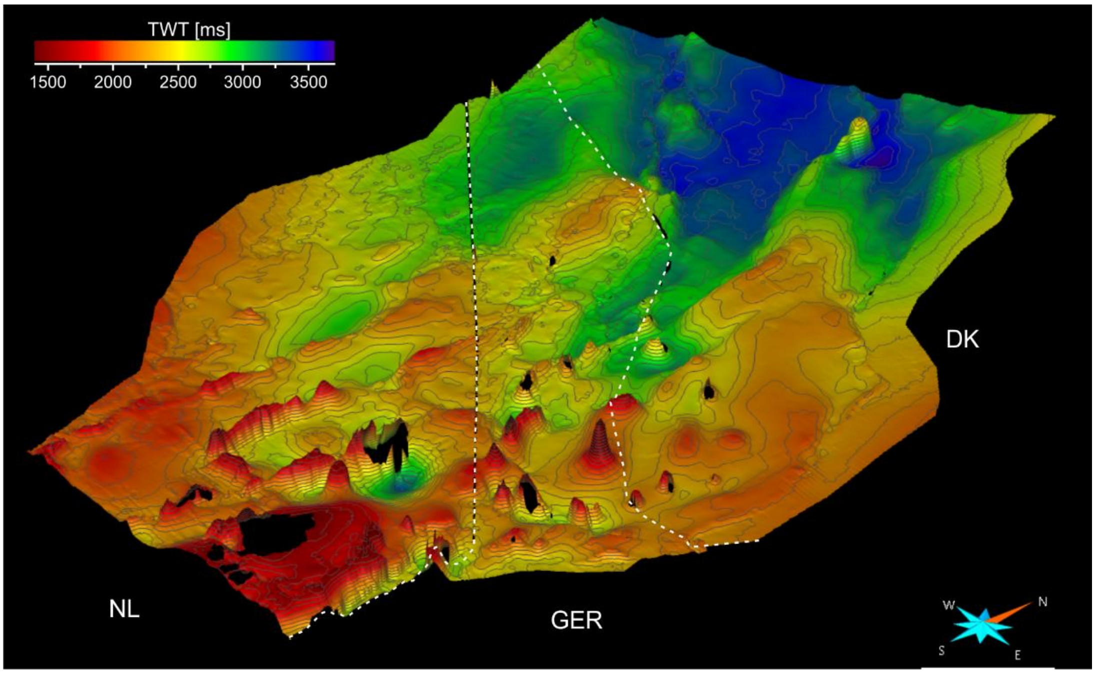


Figure 13: W-E orientated seismic section across the Dutch-German border in the area of the Step Graben (see e.g. Figure 12 for location). Note the considerable cross-border discrepancies of the former interpretations of the Base Upper Cretaceous, Near base Upper Jurassic and the Near base Lower Triassic (upper figure), which have now been revised after a re-evaluation of well and seismic data (lower figure).

Base Upper Cretaceous	3D view

Initial time horizon grids



Harmonized time horizon grids

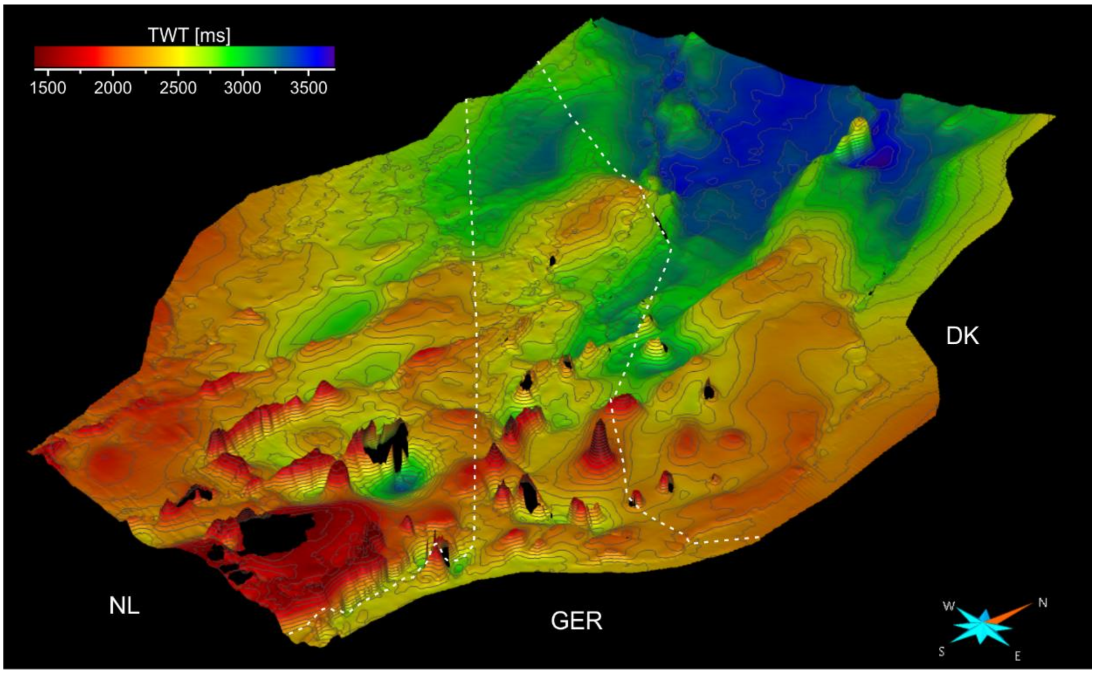


Figure 14: 3D view of the initial and harmonized Base Upper Cretaceous in the Entenschnabel region.

2.4.4 Near base Lower Cretaceous

Table 5: Input horizons for the harmonized Near base Lower Cretaceous horizon in the Entenschnabel region and summary of the revisions made to harmonize the national horizons. For details on the input models see Deliverable D3.1.

Country	Input horizon	Name of provided horizon grid	Grid source
NL	Base of the Rijnland Group (KN)	KN_twt_on_offshore_clipped_DGM50_ED50_UTM31	DGM-deep v5.0
Remark:	Local re-interpretation in the area of the Dutch Central Graben.		
GER	Base Lower Cretaceous	07_kru_Kr1	3D model Entenschnabel (GPDN)
Remark:	Re-interpretation on the German Schillgrund High and locally in the area of the Step Graben.		
DK	Base Cretaceous Unconformity (BCU)	BCU_TWT_d200_140_75Ma_XYZ	GEUS current structural database
Remark:	Local revisions in order to remove horizon intersections.		

When comparing the time horizon grids initially provided for the Near base Lower Cretaceous (Table 5), several cross-border discrepancies in the nationally mapped Near base Lower Cretaceous horizons became apparent. In the Central Graben area, for example, the base reflector mapped so far in the Dutch North Sea lies locally more than 150 ms [TWT] above the German interpretation (Figure 16). After a re-evaluation of well and seismic data, however, the Dutch interpretation was revised and the Near base Lower Cretaceous was re-mapped in the northern part of the Dutch Central Graben based on the 3D seismic survey Z3FUG2002 (NLOG name). The newly mapped horizon lies thereby in some regions more than 250 ms [TWT] below the former interpretation, as indicated by the deviation map in Figure 17. Minor re-interpretations were also made in the area of the German Schillgrund High & Platform and in the Danish sector horizon intersections were removed in order to harmonize the nationally mapped horizons.

Further differences in the nationally mapped horizons, which can be attributed to disparate seismic picking concepts, can be clearly seen when comparing the distributional pattern of the Lower Cretaceous in the German sector with those in the Dutch and Danish North Sea (Figures 17 and 18). Except for the Outer Rough Basin, no Lower Cretaceous is generally present in the northern part of the German Entenschnabel, whereas in the Dutch and Danish sectors Lower Cretaceous is widely distributed. A widespread distribution of Lower Cretaceous deposits, however, cannot be verified by wells in the German Entenschnabel. Furthermore, the Lower Cretaceous is truncated here in many areas by the overlying Upper Cretaceous and seems to be absent or below seismic resolution (see e.g. Figure 25 in Deliverable D3.5). Since the available well information indicate a non-distribution and the Lower Cretaceous is seismically not discernible, no Base Lower Cretaceous was therefore mapped in certain areas of the German sector. However, in the northern Dutch offshore, for example, residual Lower Cretaceous is locally confirmed by wells and it was assumed during the seismic mapping that Lower Cretaceous is at least thinly distributed throughout the area although seismically not discernible. As a consequence, the Base Lower Cretaceous was mapped here in large parts of the northern Dutch offshore sector. Both interpretation approaches can be generally regarded as appropriate, and most likely there is a transitional zone along the border between non- and residual distribution. That the discrepancies in the distributional pattern are primarily related to the different seismic picking concepts applied is also supported by the mapped thickness distribution of the Lower Cretaceous (Figure 15). Considering only thicknesses of more than 25 ms [TWT], the distributional pattern of the Lower Cretaceous is generally in good agreement along the national borders. For this reason, and because both interpretation approaches can be regarded as appropriate, it was decided that these cross-border discrepancies will be left and not harmonized (Figures 17 and 18).

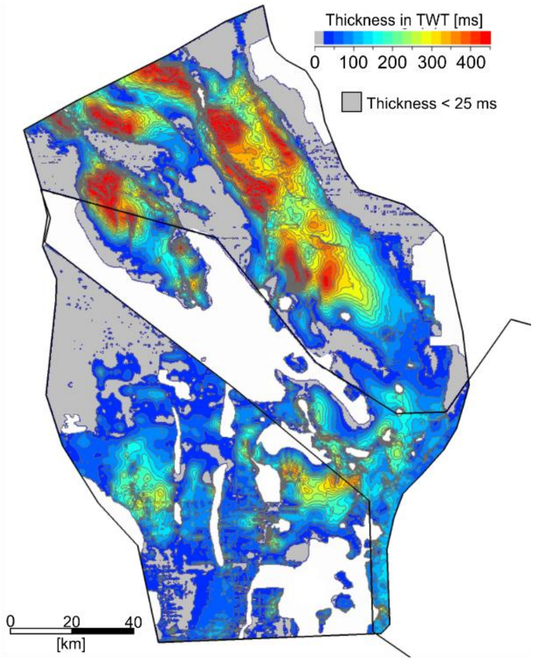


Figure 15: Thickness map of the Lower Cretaceous in the Entenschnabel region. Note that the distributional pattern of the Lower Cretaceous agrees well along the borders when considering only thicknesses of more than 25 ms [TWT].

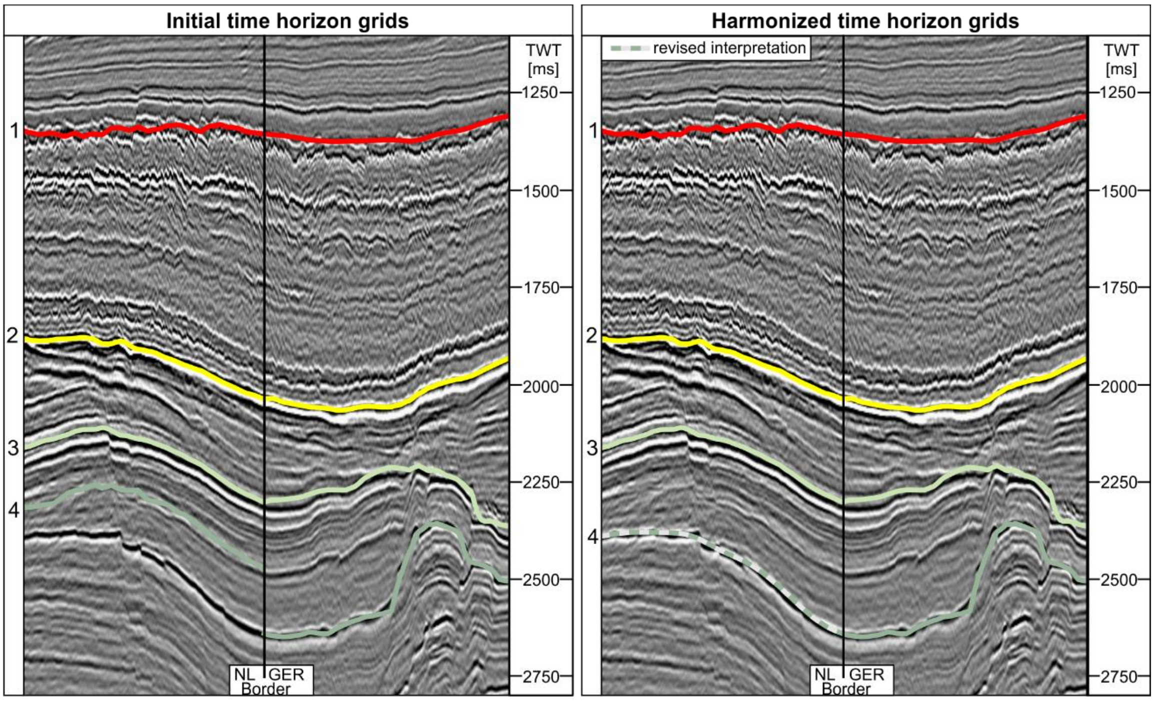
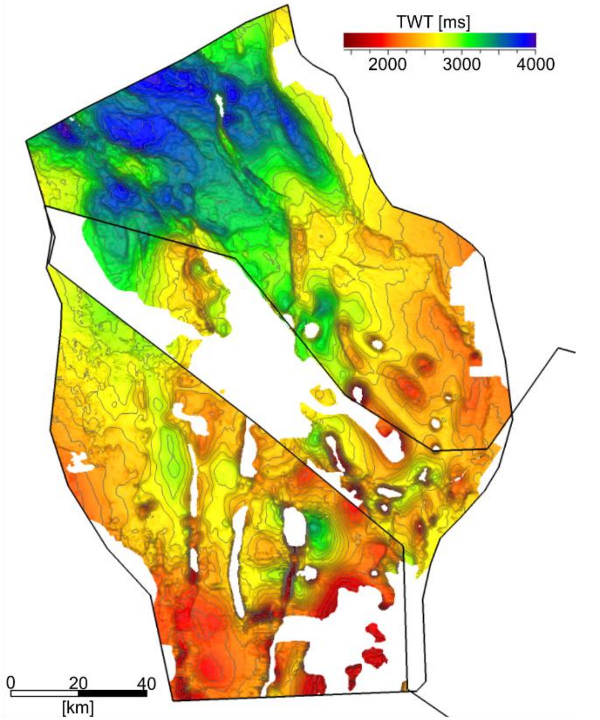
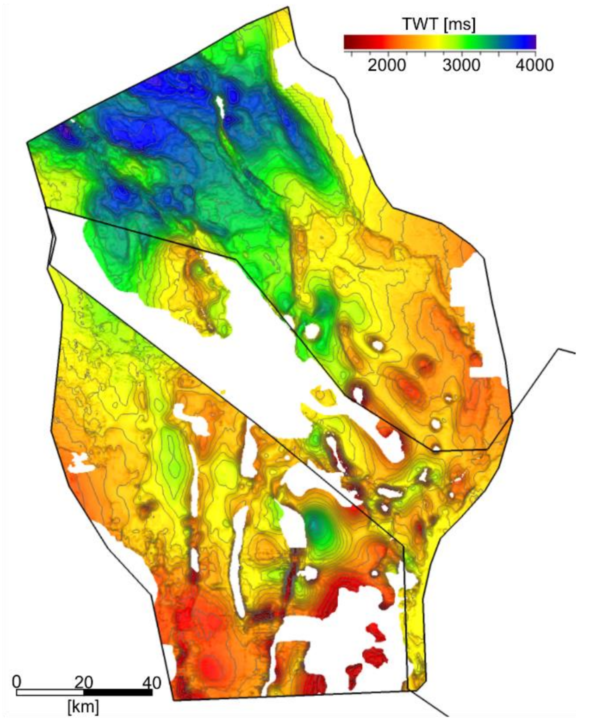


Figure 16: SW-NE orientated seismic section across the Dutch-German border in the area of the Central Graben (see Figure 16 for location). Note that the Near base Lower Cretaceous initially mapped in the Dutch North Sea lies more than 150 ms (TWT) above the German horizon. After a re-evaluation of well and seismic data, the Dutch interpretation was revised following the German interpretation. Horizon numbers: (1) Near MMU, (2) Near base Cenozoic, (3) Base Upper Cretaceous and (4) Near base Lower Cretaceous.

Near base Lower Cretaceous		
Initial time horizon grids	**Harmonized time horizon grids**	**Grid deviation** (TWT of initial grid – TWT of harmonized grid)





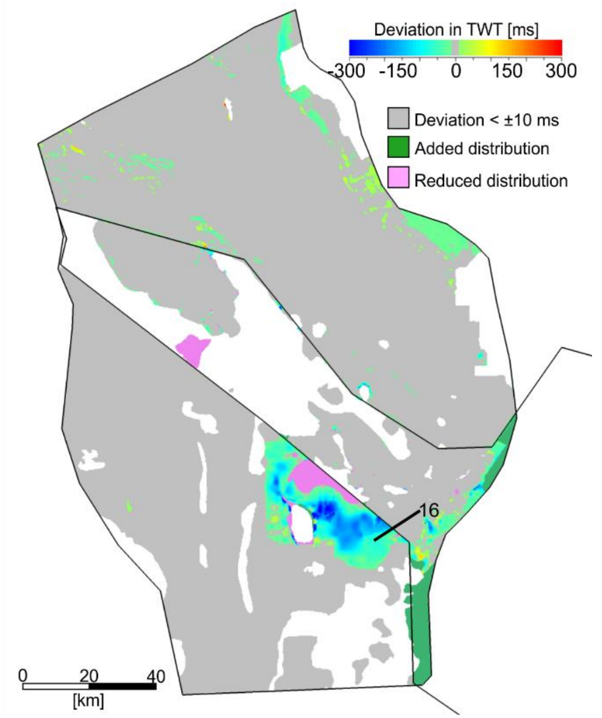
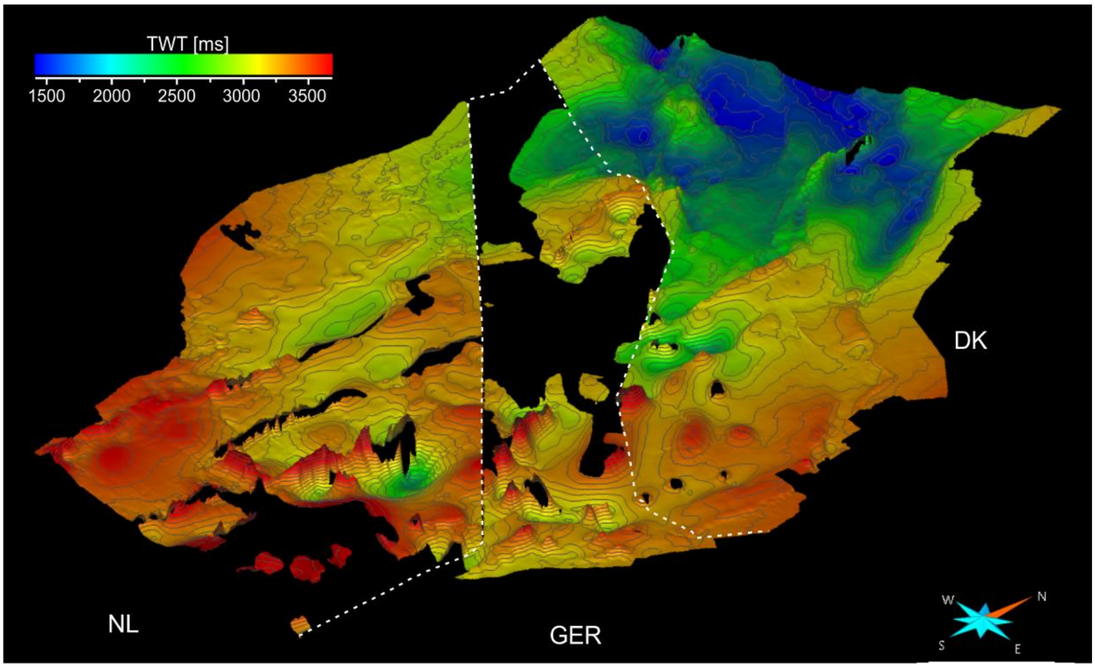


Figure 17: Near base Lower Cretaceous maps showing the initial and harmonized time horizon grids as well as the deviation of these grids. Note that the Near base Lower Cretaceous was locally re-mapped in the northern part of the Dutch Central Graben and in the area of the German Schillgrund High & Platform in order to harmonize the nationally mapped horizons. The seismic section shown in Figure 16 is indicated by the black line.

Near base Lower Cretaceous **3D view**

Initial time horizon grid



Harmonized time horizon grid

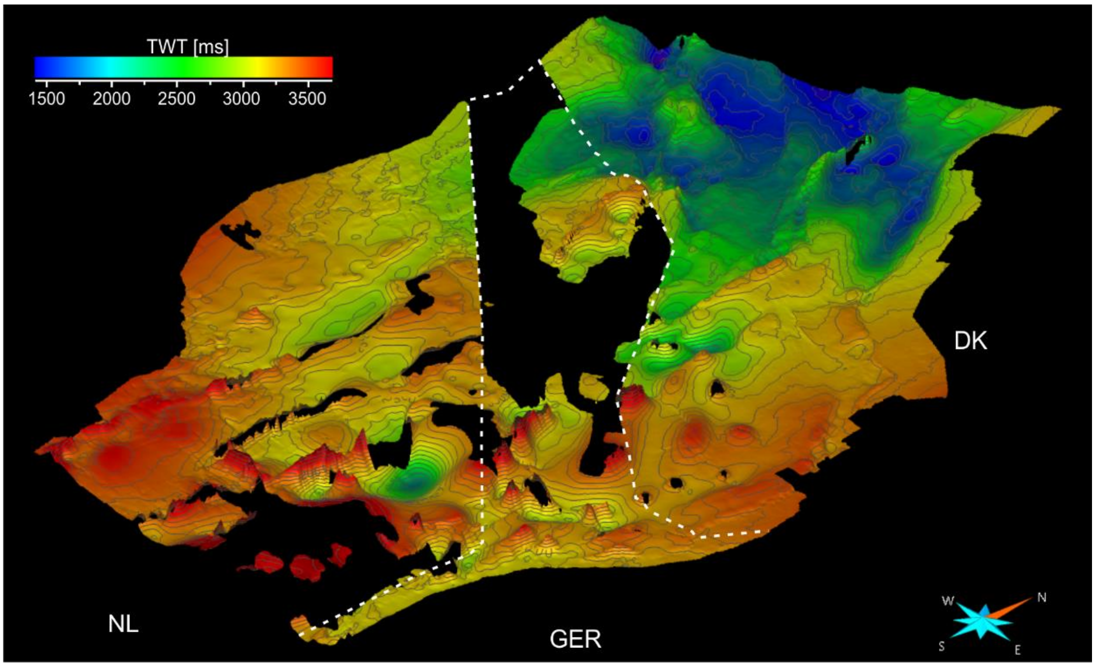


Figure 18: 3D view of the initial and harmonized Near base Lower Cretaceous in the Entenschnabel region. Note the discrepancies between the distributional pattern of the Lower Cretaceous in the German offshore and neighboring countries. These discrepancies can be attributed to disparate seismic picking concepts applied and since each approach can be regarded as appropriate, it was decided that these cross-border discrepancies will be left and not harmonized (see text for details).

2.4.5 Near base Upper Jurassic

Table 6: Input horizons for the harmonized Near base Upper Jurassic horizon in the Entenschnabel region and summary of revisions made to harmonize these horizons. For details on the input models see Deliverable D3.1.

Country	Input horizon	Name of provided horizon grid	Grid source
NL	Base of the Schieland, Scruff and Niedersachsen groups (S)	S_twt_on_offshore_clipped_DGM50_ED50_UTM31	DGM-deep v5.0
Remark:	Re-interpretation in the area of the Step Graben and the northern part of the Dutch Central Graben.		
GER	Base Upper Jurassic	08_jo_J3	3D model Entenschnabel (GPDN)
Remark:	Only minor changes along the border to Denmark and the Netherlands		
DK	1 Top Middle Jurassic	Base_UppJuraPSS_9_TWT_d200_161Ma_XYZ	GEUS current structural database
	2 Top Triassic	Base_Jura_PSS_1_TWT_d200_201Ma_XYZ	
	3 Top Zechstein	3DGEOEU_DK_Top_Zechstein_twt	New interpretation (3DGEO-EU)
	4 Top pre-Zechstein	3DGEOEU_DK_Top_pre_Zechstein_twt	
Remark:	The Near base Upper Jurassic in the Danish sector is constructed based on the Tops of the Middle Jurassic, Triassic, Zechstein and pre-Zechstein (see chapter 2.2.3). The latter two were re-mapped in 3DGEO-EU WP3.		

During the comparison of the initially provided time horizon grids, considerable differences in distribution and thickness of Upper Jurassic strata became apparent in the Entenschnabel region, necessitating extensive adaptations of the national Near base Upper Jurassic horizons.

In the area of the Step Graben, for example, no Upper Jurassic was initially mapped on the Dutch side, whereas in the German sector Upper Jurassic strata is widely distributed (Figures 20 and 21). After a re-evaluation of well and seismic data, the Dutch interpretation was revised and the Base Upper Jurassic was re-mapped in the Dutch North Sea sector in an approximately 15 km wide corridor along the border (Figures 13 and 19). West of the re-mapped area, seismic data indicate that Upper Jurassic may also be present locally in other parts of the Dutch Step Graben (Figure 19). A re-mapping in these regions far from the border was, however, not carried out, because the project focused on cross-border harmonization issues and not on an overall re-interpretation of nationally mapped horizons.

Beside the discrepancies observed in the area of the Step Graben, further differences in the Dutch and German Base Upper Jurassic became evident in the area of the Central Graben. Here, the time horizon grids provided for harmonization partly showed offsets of several 100 ms [TWT] along the Dutch-German border (Figure 5). In Deliverable D3.5, however, it was shown that the seismic reflector mapped as Near base Upper Jurassic generally coincides in both countries, and thus the differences observed in the Central Graben area are not caused by different seismic interpretation concepts. The discrepancies are rather related to the seismic datasets used for the interpretation of the Base Upper Jurassic. In the German sector, the interpretation is largely based on 3D seismic data (Arfai et al., 2014), whereas in the area where discrepancies occurred, the Dutch Base Upper Jurassic was mapped based on sparse 2D seismic lines (Kombrink et al., 2012; Figure 6). A 3D seismic dataset acquired in this area by FUGRO in 2002 (Z3FUG2002 / NLOG webpage) were not considered for interpretations at that time because the data were not publicly available. However, the 3D seismic survey is now released and has been used in the current project to re-interpret the Base Upper Jurassic in the northern part of the Dutch Central Graben (Figure 5). The newly mapped horizon lies partly more than 750 ms [TWT] below the former interpretation, as indicated by the deviation map in Figure 20.

Prior to cross-border harmonization along the Danish-German border, it was necessary to construct a Near base Upper Jurassic horizon for the Danish part of the Entenschnabel region, as described in chapter 2.2. Depending on the underlying stratigraphy, the Near base Upper Jurassic is formed here by either the Top Middle Jurassic, Top Triassic, Top Zechstein or the Top pre-Zechstein (Table 6). Since the initial interpretations of the Danish Top-Zechstein and Top pre-Zechstein intersect considerably, especially with the more recent interpretations of other horizons (Figure 2), GEUS re-interpreted their Top Zechstein and Top pre-Zechstein horizons in the area of the Danish Central Graben based on currently available 2D and 3D seismic data. The Near base Upper Jurassic horizon constructed based on the re-interpretations and existing grids (Table 6) showed along the border a good agreement with the German base horizon, and only minor revisions were locally necessary to harmonize the national horizons, as indicated by the deviation map in Figure 20. A detail description of the harmonization work required to construct the Danish Near base Upper Jurassic horizon is given in Chapter 2.2.

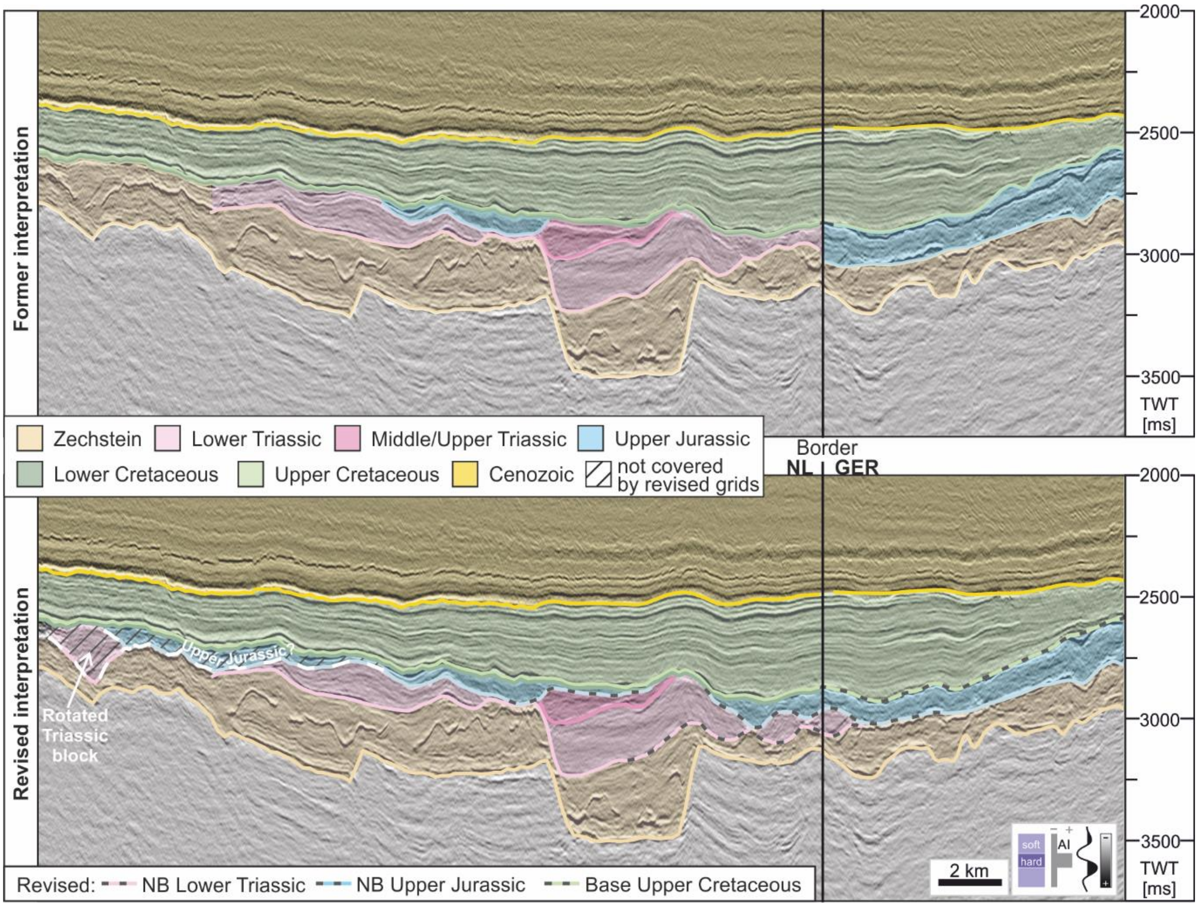
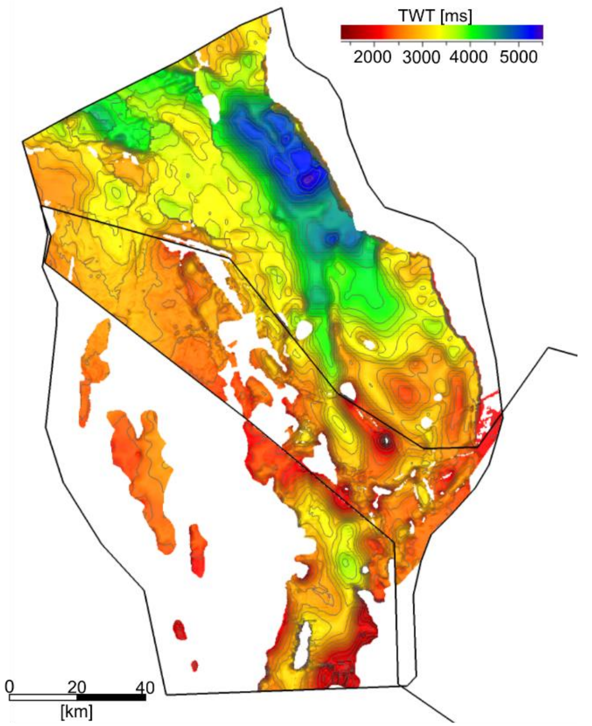
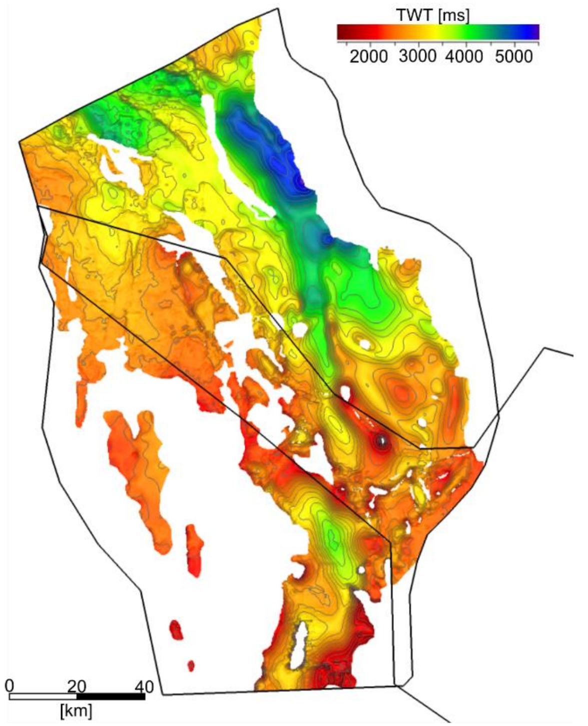


Figure 19: W-E orientated seismic section across the Dutch-German border in the area of the Step Graben (see Figure 20 for location) showing the initial and harmonized time horizon grids for the Dutch and German North Sea sectors. Note the considerable cross-border discrepancies of the former interpretations of the Near base Upper Jurassic and the Near base Lower Triassic (upper figure), which have now been revised after a re-evaluation of well and seismic data (lower figure). Note also that further west of the border, Upper Jurassic may also be present locally in other parts of the Dutch Step Graben, but was not mapped as part of 3DGEO-EU WP3.

Near base Upper Jurassic		
Initial time horizon grids	**Harmonized time horizon grids**	**Grid deviation** (TWT of initial grid – TWT of harmonized grid)





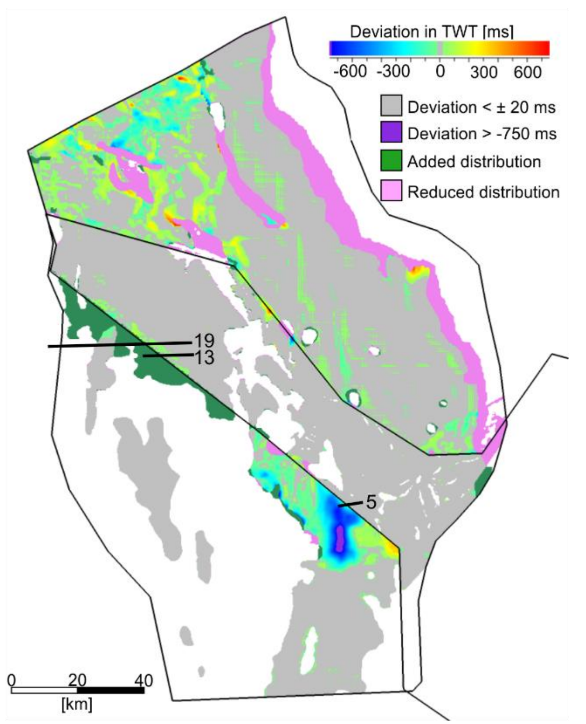
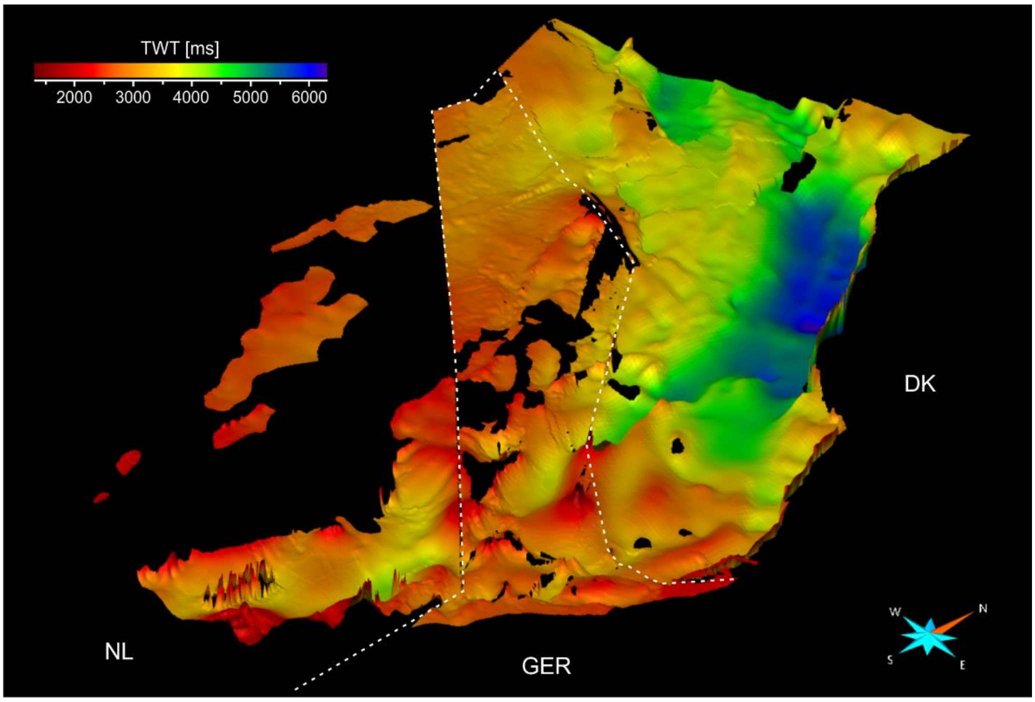


Figure 20: Near base Upper Jurassic maps showing the initial and harmonized time horizon grids as well as the deviation of the grids. Note that the re-interpretation in the northern part of the Dutch Central Graben lies partly more than 750 ms [TWT] below the former interpretation. The seismic sections shown in Figures 5, 13 & 19 are indicated by the black lines and corresponding numbers.

Near base Upper Jurassic	3D view

Initial time horizon grids



Harmonized time horizon grids

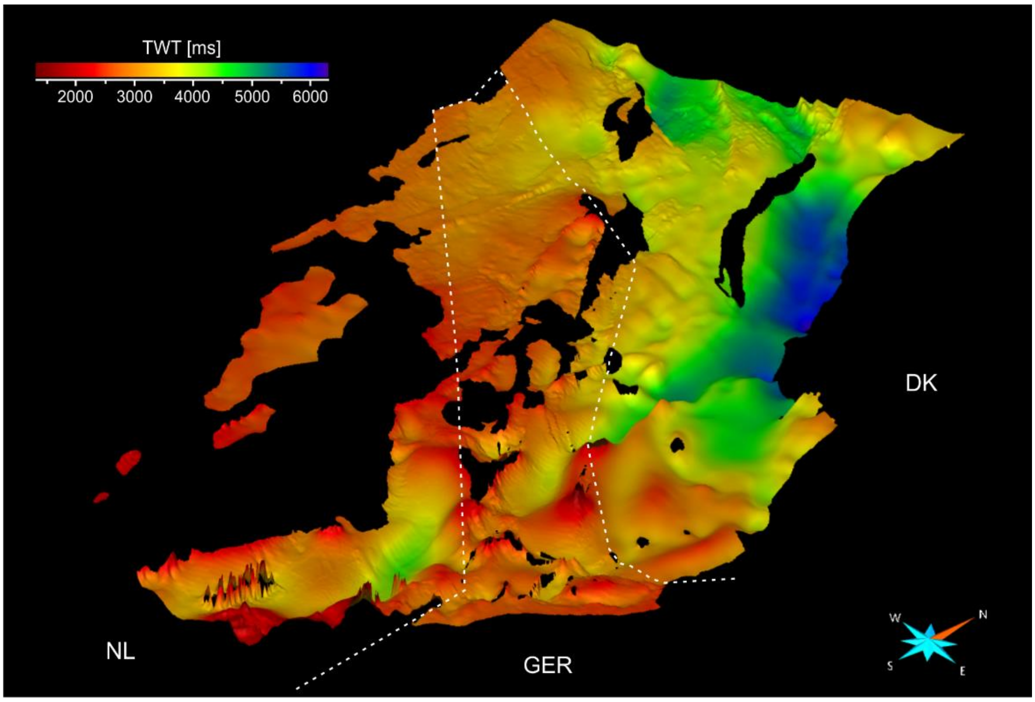


Figure 21: 3D view of the initial and harmonized Near base Upper Jurassic in the Entenschnabel region.

2.4.6 Near base Lower Jurassic

Table 7: Input horizons for the harmonized Near base Lower Jurassic in the Entenschnabel region and summary of revisions made to harmonize these horizons. For details on the input models see deliverable D3.1.

Country	Input horizon	Name of provided horizon grid	Grid source
NL	Base of the Altena Group (AT)	AT_twt_on_offshore_clipped_DGM50_ED50_UTM31	DGM-deep v5.0
Remark:	Re-interpretation in the northern part of the Dutch Central Graben.		
GER	Base Lower Jurassic	10_ju_J1	3D model Entenschnabel (GPDN)
Remark:	Local revisions along the NL/GER border.		
DK	Top Triassic	Base_Jura_PSS_1_TWT_d200_201Ma_XYZ	GEUS current structural database
Remark:	The Near base Lower Jurassic was constructed based on the Top Triassic horizon provided by GEUS (see chapter 2.2.3). Local revisions were required in order to remove horizon intersections.		

Lower Jurassic deposits are in the study area restricted to the area of the Central Graben. Here, the time horizon grid initially provided by TNO for the Near base Lower Jurassic (Table 7) differs partly considerably from the German interpretation, with differences in the horizons of several 100 ms [TWT] along the Dutch-German border (Figures 5 and 22). Similar to the Near base Upper Jurassic, the differences in the nationally mapped horizons are not related to different seismic stratigraphic interpretation concepts (see Deliverable D3.5), but caused by the datasets used for the interpretation. In the German sector, the interpretation is largely based on 3D seismic data (Arfai et al., 2014), whereas in the area where discrepancies occurred, the Dutch Near Base Lower Jurassic was mapped based on sparse 2D seismic lines (Kombrink et al., 2012; Figure 6), as described before. Like the Near base Upper Jurassic, the base of the Lower Jurassic was re-interpreted in the northern part of the Dutch Central Graben (Figure 5) based on the transboundary 3D seismic survey Z3FUG2002 (NLOG name). The re-interpreted horizon lies partly more than 750 ms [TWT] below the former interpretation, as indicated by the deviation map in Figure 22.

A notable difference that complicated the cross-border harmonization along the Danish-German border was that the Near base Lower Jurassic in the Danish sector is actually interpreted as a Top Triassic surface (Table 7). For regional mapping purposes the Base Lower Jurassic was merged here with the Base Upper Jurassic in order to represent a Base Jurassic/Top Triassic map. As a consequence, the Top Triassic surface provided by GEUS for harmonization in 3DGEO-EU WP3 only coincides in areas where Lower Jurassic is preserved to the Base Lower Jurassic reflector (see Figure 3 for illustration). Therefore, prior to cross-border harmonization, it was necessary to construct a Near base Lower Jurassic horizon for the Danish sector, as described in detail in chapter 2.2. The constructed horizon, however, showed generally a good agreement with the German base horizon, and only minor re-interpretations on both sides were necessary to harmonize the nationally mapped horizons in the area of the Central Graben (Figure 22). The slightly different distributional pattern of the Lower Jurassic compared to the initial GARAH model (Figures 22 and 23) result from the harmonization steps described in chapter 2.2 and adaptions made based on well information.

Near base Lower Jurassic

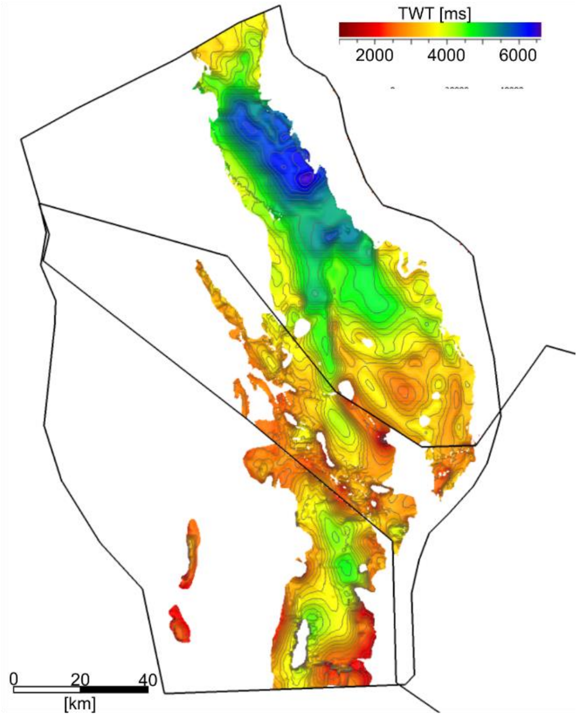
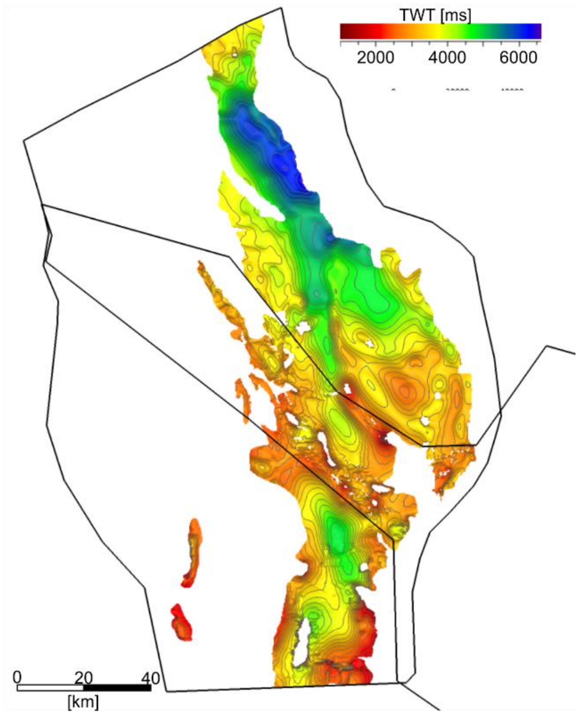
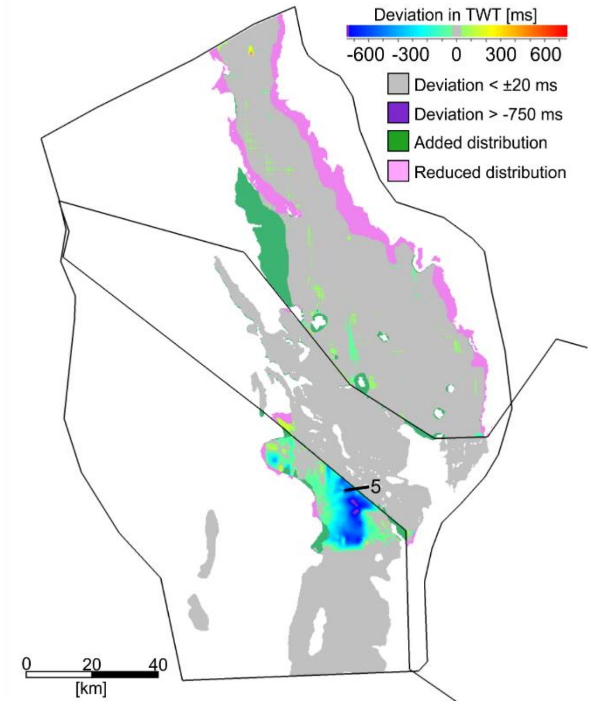
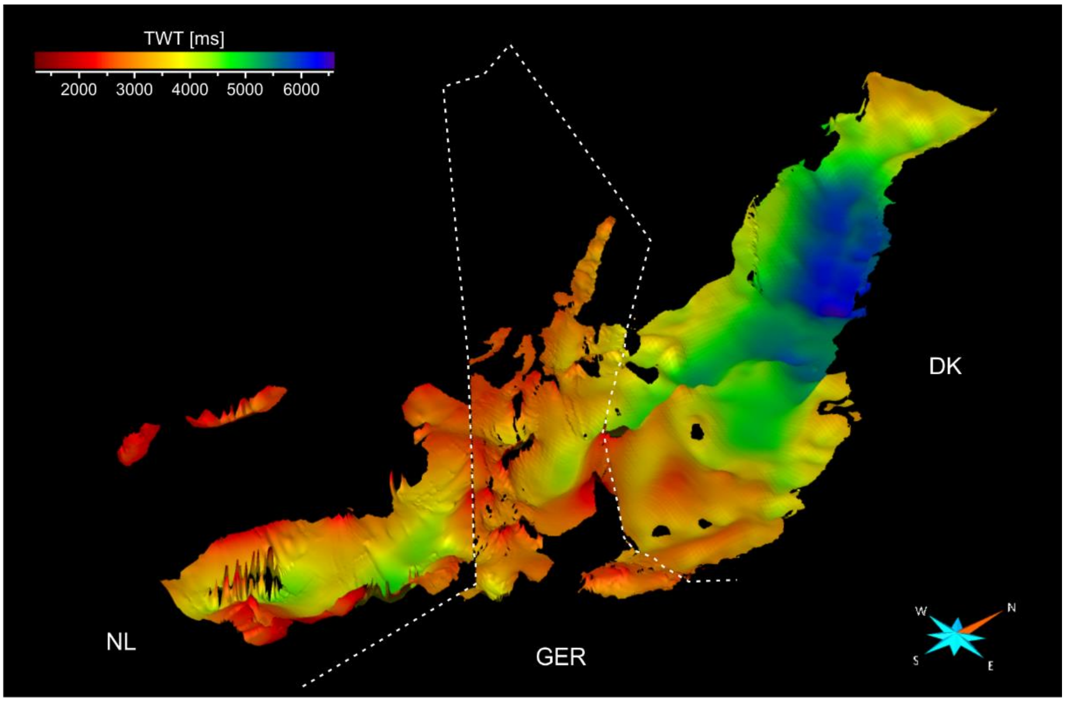
Initial time horizon grids	**Harmonized time horizon grids**	**Grid deviation** (TWT of initial grid – TWT of harmonized grid)
		

Figure 22: Near base Lower Jurassic maps showing the initial and harmonized time horizon grids as well as the deviation of the grids. The initial horizon grid presented here corresponds to the Near base Lower Jurassic horizon constructed for the GARAH model. Note that the GARAH grid was clipped here to Lower Jurassic thicknesses > 0 ms [TWT]. The seismic section shown in Figure 5 is indicated by the black line.

Near base Lower Jurassic	3D view

Initial time horizon grids



Harmonized time horizon grids

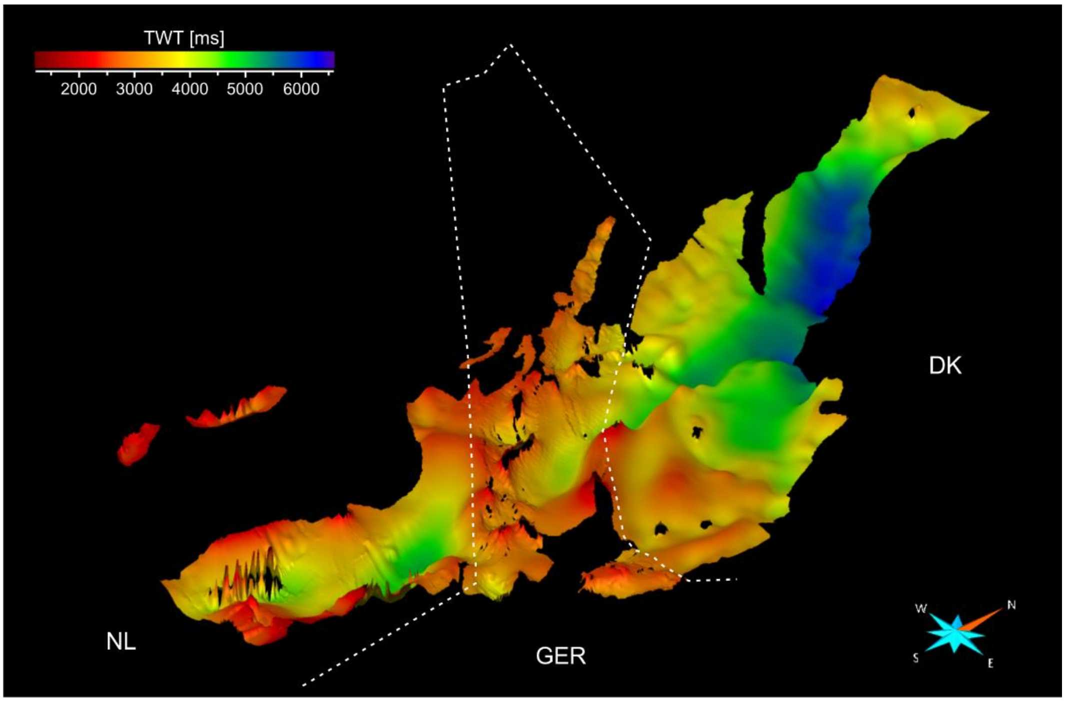


Figure 23: 3D view of the initial and harmonized Near base Lower Jurassic in the Entenschnabel region. The initial horizon grid presented here corresponds to the Near base Lower Jurassic horizon constructed for the GARAH model. Note that the GARAH grid was clipped here to Lower Jurassic thicknesses > 0 ms [TWT].

2.4.7 Near base Lower Triassic

Table 8: Input horizons for the harmonized Near base Lower Triassic horizon in the Entenschnabel region and summary of revisions made to harmonize these horizons. For details on the input models see deliverable D3.1.

Country	Input horizon		Name of provided horizon grid	Grid source
NL	Base of the Lower Germanic Trias Group (RB)		RB_twt_on_offshore_clipped_DGM50_ED50_UTM31	DGM-deep v5.0
Remark:	Re-interpretation in the area of the Step Graben and the northern part of the Dutch Central Graben.			
GER	Base Lower Triassic		Tr1_Base	3D model Entenschnabel (GPDN)
Remark:	Local re-interpretation in the vicinity of the national borders.			
DK	1	Top Zechstein	3DGEOEU_DK_Top_Zechstein_twt	New interpretation (3DGEO-EU)
	2	Top pre-Zechstein	3DGEOEU_DK_Top_pre_Zechstein_twt	
Remark:	The Near base Lower Triassic in the Danish sector is constructed based on the Top Zechstein and locally by the Top pre-Zechstein (see chapter 2.2.3). Both input horizons were re-mapped in 3DGEO-EU WP3.			

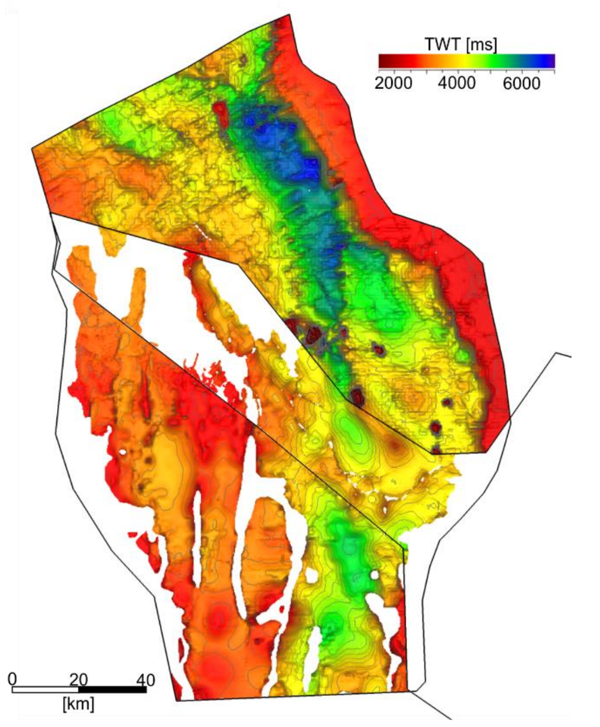
When comparing the time horizon grids initially provided for the Near base Lower Triassic (Table 8), several cross-border discrepancies in the nationally mapped horizons became apparent, necessitating extensive horizon adaptations.

In the area of the Step Graben, for example, Lower Triassic strata is widely distributed in the Dutch North Sea, whereas in the German sector Triassic strata is locally restricted to graben structures or only present as Triassic remnants (Figures 24 and 25). After a re-evaluation of well and seismic data, the Dutch interpretation was revised and re-mapped together with the Base Upper Jurassic in the Dutch North Sea sector within an approximately 15 km wide corridor along the border (Figures 13 and 19), and locally on the German side as indicated by the deviation map in Figure 24. Further differences in the Dutch and German Near base Lower Triassic became evident in the area of the Central Graben. Here, the time horizon grids provided for harmonization showed locally offsets of more than 150 ms [TWT] along the Dutch-German border (Figure 5). Like for the Jurassic horizons, the differences in the nationally mapped horizons are not related to different seismic stratigraphic interpretation concepts (see Deliverable D3.5), but caused by the datasets used for the interpretation. Since the Dutch interpretation was based on sparse 2D seismic data in the area where the discrepancies occurred (Kombrink et al., 2012), the Near base Lower Triassic was re-mapped in the northern part of the Dutch Central Graben (Figure 5) based on currently available 2D and 3D seismic data. The newly mapped horizons lies partly 300 ms [TWT] below the former Dutch interpretation. Minor re-interpretations were also conducted in the southeastern corner of the Entenschnabel region at the transition from the Central Graben to the Schillgrund High/Platform, as illustrated by the deviation map in Figure 24.

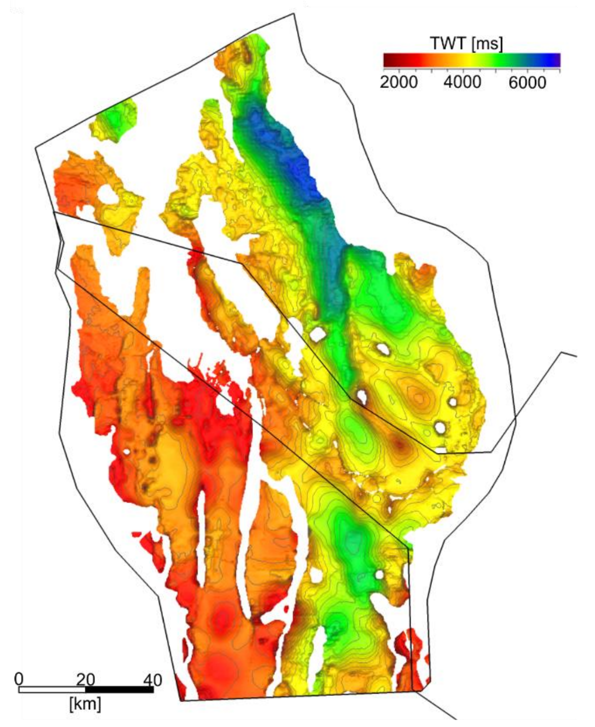
Along the Danish-German border, cross-border harmonization based on the initial provided time horizon grids was at first not feasible for several reasons. The Near base Lower Triassic initially shared for the Danish offshore sector was actually interpreted and mapped as a Top Zechstein surface and was provided as a closed grid (Figures 24 and 25). Furthermore, as described in chapter 2.2., the time horizon grid was derived from an older seismic mapping study and intersected considerably with the other more recent Danish horizons (Figures 2 and 4C). Since the horizon intersections reached locally several 100 ms [TWT], GEUS re-interpreted their Top Zechstein as well as Top pre-Zechstein in the area of the Danish Central Graben. The Near base Lower Triassic horizon constructed based on this re-interpretations (Table 8) showed along the border a good agreement with the German base horizon, and only minor revisions were locally necessary to finalize the cross-border harmonization. A detail description of the harmonization step conducted to construct the Danish Near base Lower Triassic horizon is given in Chapter 2.2, and illustrated in Figure 4.

Near base Lower Triassic

Initial time horizon grids



Harmonized time horizon grids



Grid deviation

(TWT of initial grid – TWT of harmonized grid)

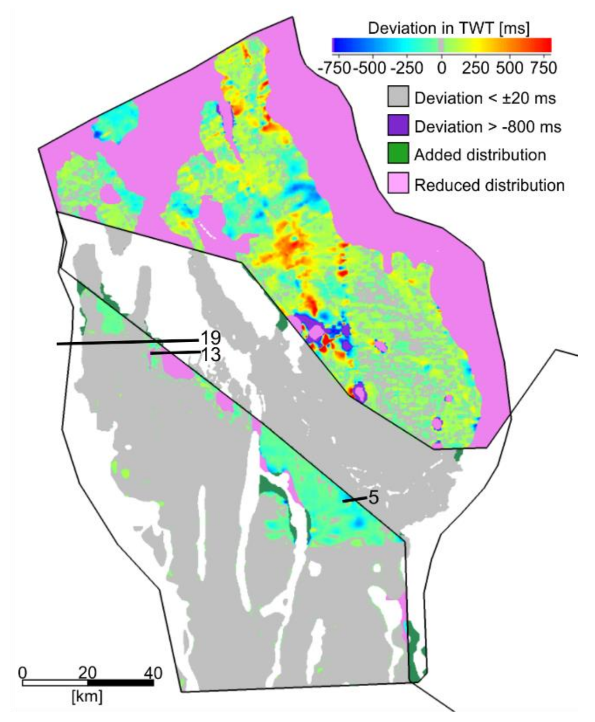
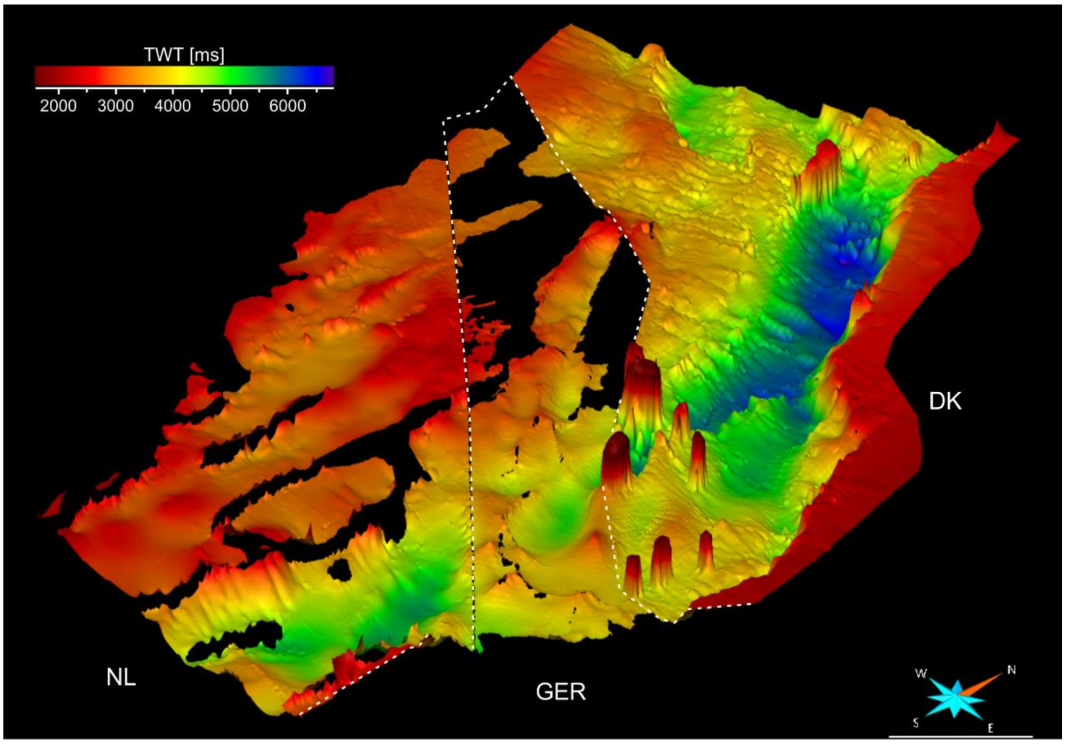


Figure 24: Near base Lower Triassic maps showing the initial and harmonized time horizon grids as well as the deviation of the grids. Note that the Near base Lower Triassic initially shared for the Danish offshore sector was actually interpreted and mapped as a Top Zechstein surface and was provided as a closed grid. The seismic sections shown in Figures 5, 13 & 19 are indicated by the black lines and corresponding numbers.

Near base Lower Triassic	3D view

Initial time grid



Harmonized time grid

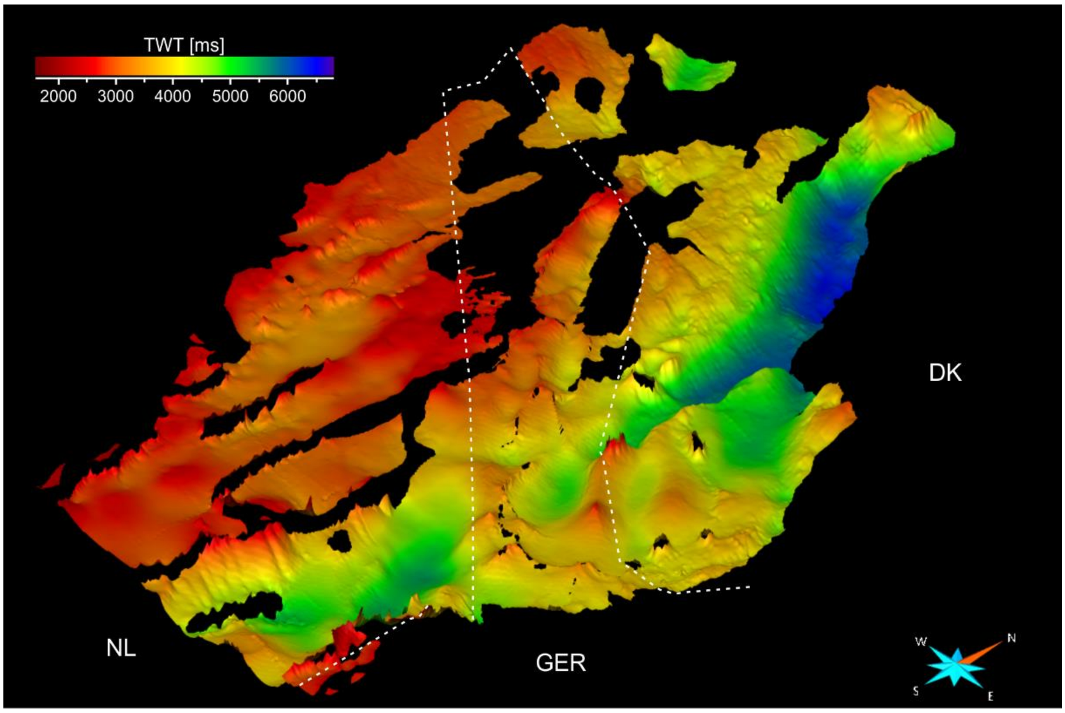


Figure 25: 3D view of the initial and harmonized Near base Lower Triassic in the Entenschnabel region. Note that the Near base Lower Triassic initially shared for the Danish offshore sector was actually interpreted and mapped as a Top Zechstein surface and was provided as a closed grid.

2.4.8 Base Zechstein

Table 9: Input horizons for the harmonized Base Zechstein horizon in the Entenschnabel region and summary of revisions made to harmonize the national horizons. For details on the input models see deliverable D3.1

Country	Input horizon	Name of provided horizon grid	Grid source
NL	Base of the Zechstein Group (ZE)	ZE_twt_on_offshore_clipped_DGM50_ED50_UTM31	DGM-deep v5.0
Remark:	Local re-interpretation in the area of the Dutch Central Graben		
GER	Near base Zechstein	Z_nearbase	3D model Entenschnabel (GPDN)
Remark:	Local revisions on the Outer Rough High in the Step Graben.		
DK	Top pre-Zechstein	3DGEOEU_DK_Top_pre_Zechstein_twt	New interpretation (3DGEO-EU)
Remark:	The Base Zechstein is constructed based on a Top pre-Zechstein surface which was re-interpreted by GEUS in 3DGEO-EU WP3 (see chapter 2.2.3).		

The oldest horizon selected for harmonization in the study area corresponds to the base of the Upper Permian Zechstein Group. In the area of the Step Graben, the time horizon grids initially provided by TNO and BGR for the Base Zechstein matched fairly well along the national border and therefore only minor adaptions of the nationally mapped horizons were generally required here, as indicated by the deviation map in Figure 26. In the Central Graben area, however, the initial Dutch Base Zechstein differs locally more than 400 ms [TWT] from the German interpretation (Figure 26). Like for the other pre-Cretaceous horizons, the differences in the nationally mapped horizons are not related to different seismic stratigraphic interpretation concepts (see Deliverable D3.5), but caused mainly by the datasets used for the interpretation. Given the fact that the Dutch horizon initially provided was based on sparse 2D seismic data in the area where the discrepancies occurred (Kombrink et al., 2012), the Base Zechstein was re-interpreted in the northern Dutch Central Graben (Figure 5) based on currently available 2D and 3D seismic data.

A remarkable difference between the time horizon grids initially shared for the Danish and German North Sea was that the Base Zechstein horizon in the Danish sector actually represents a Top pre-Zechstein surface, and thus is also present in areas where Zechstein is absent. Furthermore, the cross-border harmonization was hampered, as described in chapter 2.2, by the fact that the initial Top pre-Zechstein surface of Vejbaek and Britze (1994) showed considerable horizon intersections with the other more recent Danish horizons (Figures 2 and 4C). Since the horizon intersections reached locally several 100 ms [TWT], GEUS re-interpreted their Top pre-Zechstein in the Danish part of the Entenschnabel region. The newly mapped Top pre-Zechstein surfaces differs thereby considerably from the former interpretation, with differences of more than 500 ms [TWT], as indicated by the deviation map in Figure 26. The Base Zechstein horizon constructed based on this re-interpretation (see chapter 2.2.3 for details) showed along the border a good agreement with the German base horizon, and only minor revisions were locally necessary on the German side to finalize the cross-border harmonization. The German Base Zechstein, for example, was locally removed on the Outer Rough High and in the northernmost corner of the German Entenschnabel at the transition to the Mid North Sea High (Figures 26 and 27).

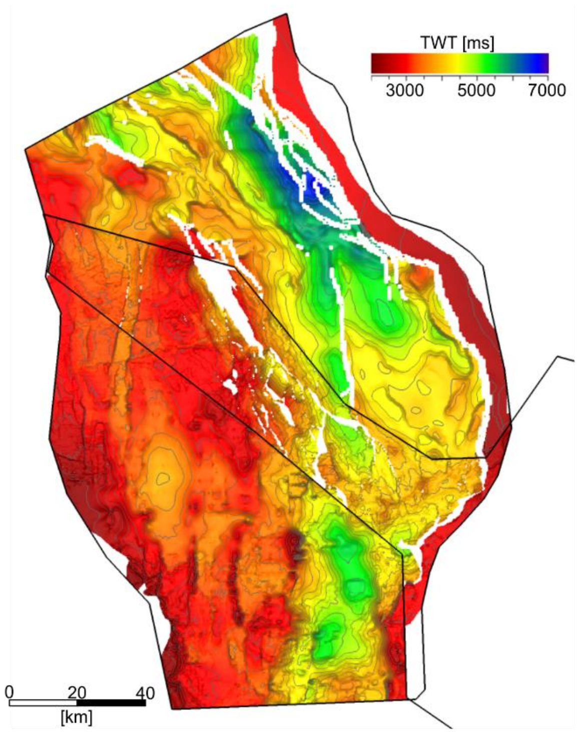
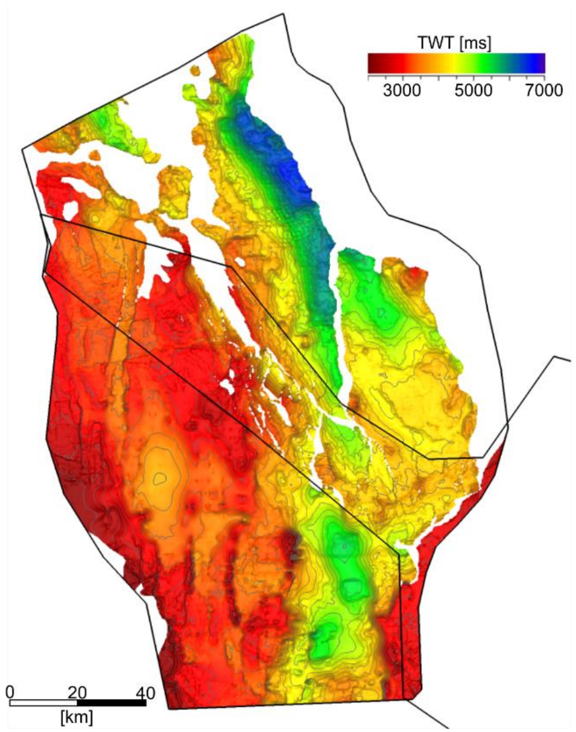
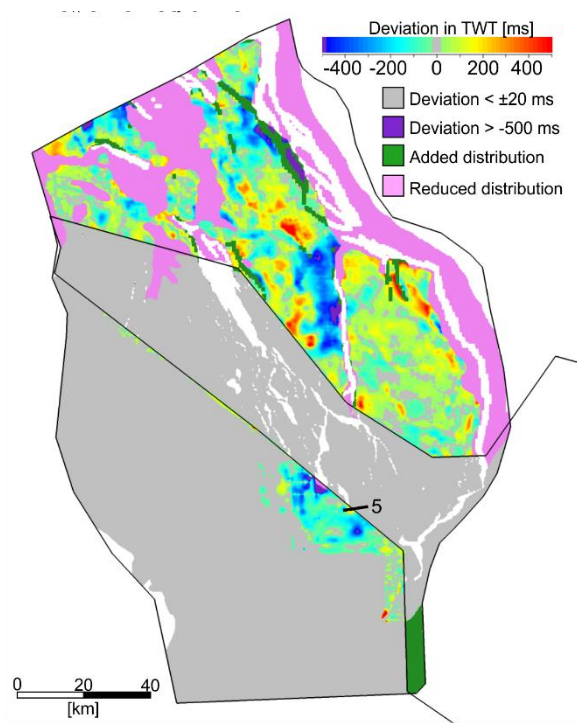
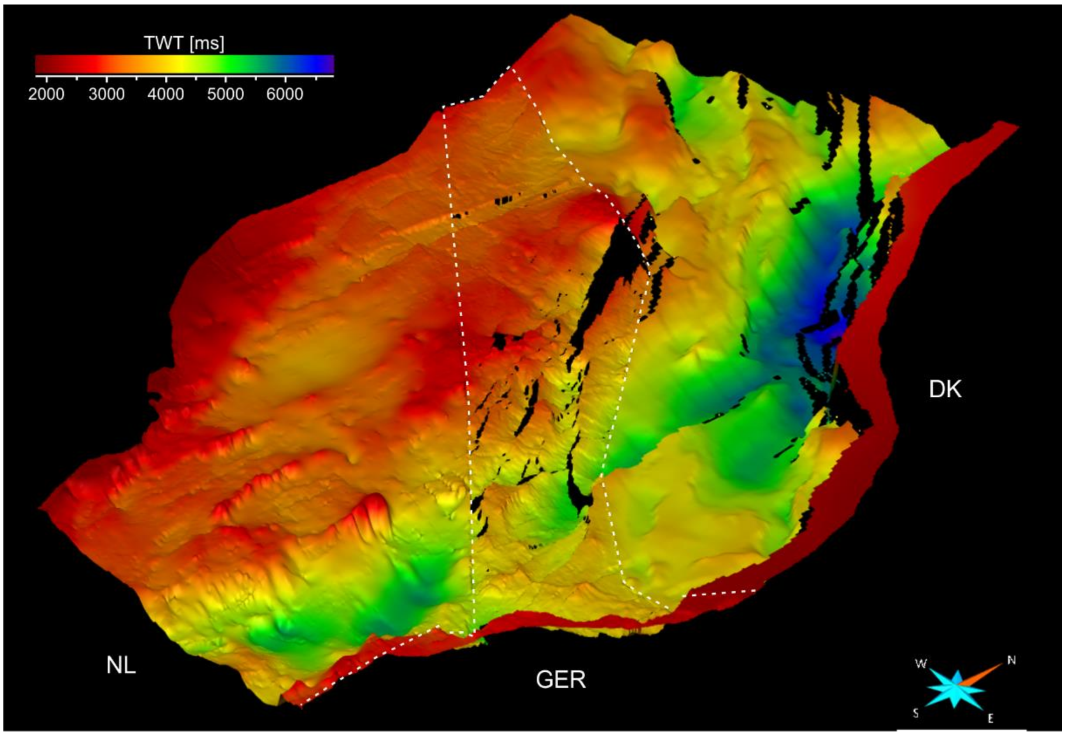
Base Zechstein		
Initial time horizon grids	**Harmonized time horizon grids**	**Grid deviation** (TWT of initial grid – TWT of harmonized grid)
		

Figure 26: Base Zechstein maps showing the initial and harmonized time horizon grids as well as the deviation of the grids. The seismic section shown in Figure 5 is indicated by the black line.

Base Zechstein	3D view

Initial time grid



Harmonized time grid

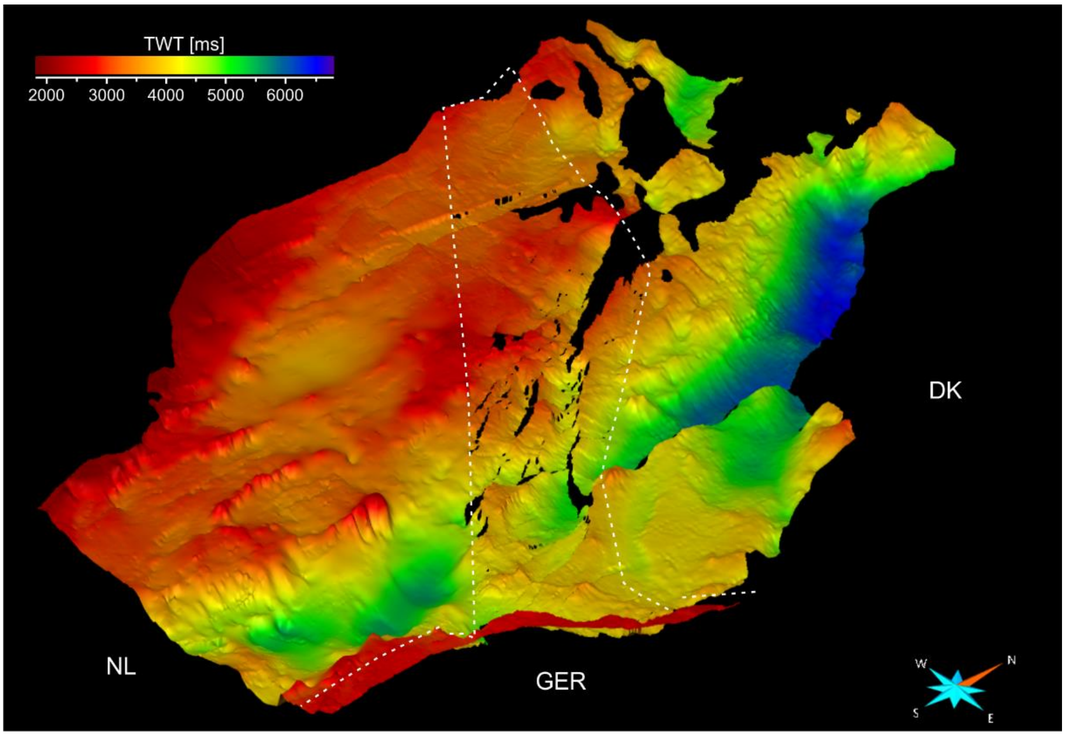


Figure 27: 3D view of the initial and harmonized Base Zechstein in the Entenschnabel.

3 SUMMARY AND CONCLUDING REMARKS

The harmonization work conducted to create a harmonized time model of the Entenschnabel region was described in the present report. The model incorporates eight key stratigraphic horizons from the base of the Zechstein to the Upper Cenozoic (Table 1) and covers the northwestern part of the German North Sea sector and the adjacent areas in Denmark and the Netherlands (Figure 1). Prior to cross-border harmonization, several disparities in the nationally mapped horizons became apparent along the national borders. These discrepancies were largely related to differences in the seismic picking concepts, misinterpretations of structural geometries, or the low significance of seismic data used for the horizon interpretation in certain areas. Most of the discrepancies observed in the time horizon grids initially provided for harmonization were addressed and could be removed within 3DGEO-EU WP3. The deviation of the initial and harmonized time horizon grids are illustrated and summarized in Figure 28a-b. However, there remain disparities in the national horizon models, which could not be resolved in the project so far. In the German horizon model, for example, most faults exhibiting horizon offsets were mapped and are represented by gaps in the current horizon grids. Contrary to this, only major faults, i.e., faults with large offsets and faults that are important for the definition of structural elements, are usually considered in the Danish and Dutch horizon models. Therefore, their horizons partly coincide with fault planes and also locally e.g. with salt dome flanks. A harmonization of fault traces across borders, however, can be time-consuming and is generally hampered by the fact that most faults occur in structurally complex regions, and here the national horizons tend to be highly generalized. In light of this generalization, a re-interpretation of horizons would often be unavoidable to ensure a geologically plausible harmonization, but this is not feasible for the entire study area due to time constraints. A segment of the Coffee Soil Fault (eastern boundary of the Central Graben), however, has been chosen as an example for the harmonization of a main fault zone, and the results will be presented as part of Deliverable D3.8.

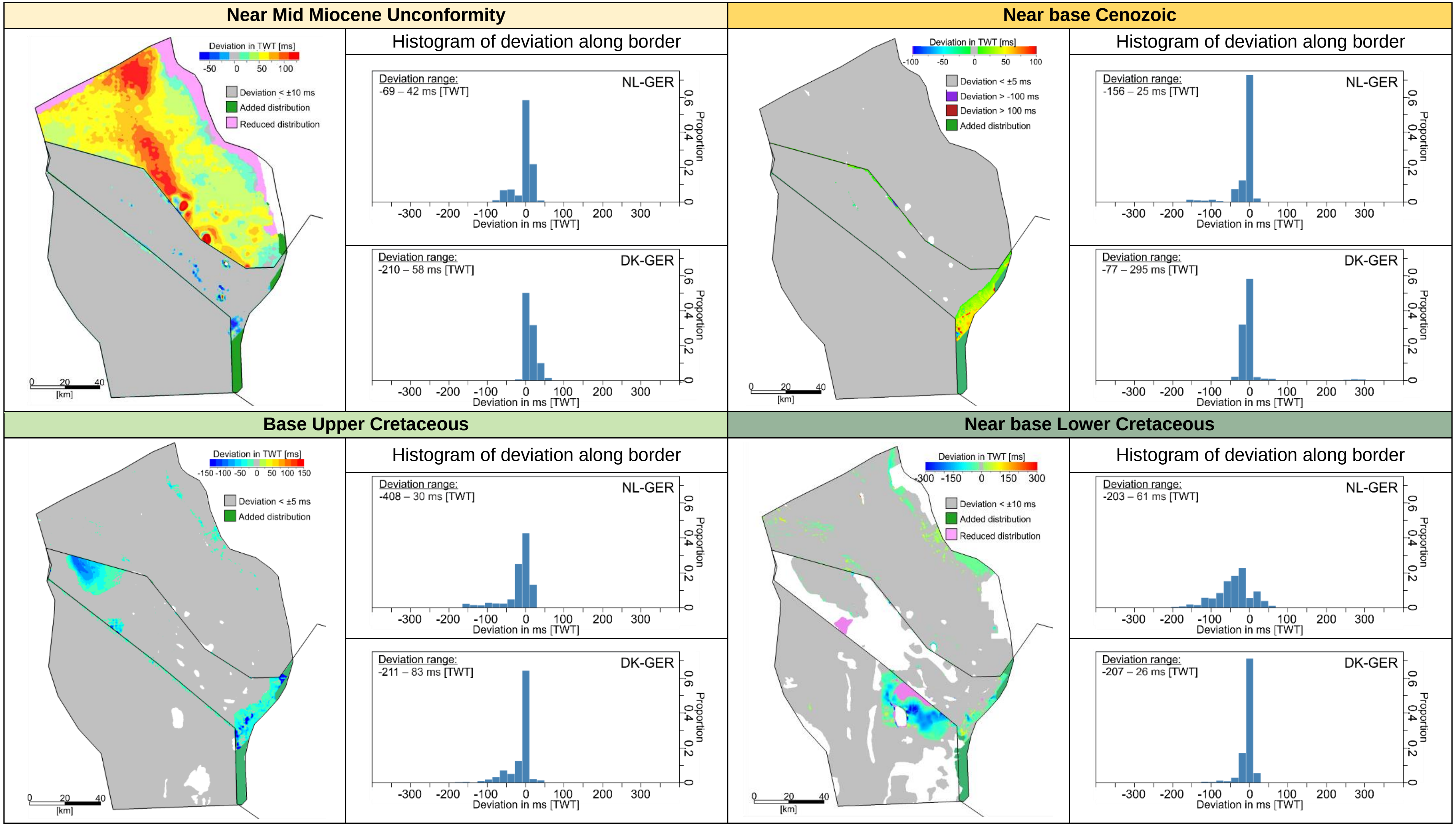


Figure 28a: Maps showing the deviation between the initial and harmonized time horizon grids in the Entenschnabel region and histograms summarizing the deviation (TWT of initial grid – TWT of the harmonized grid) along the national borders. Note that areas with added or removed distribution are not reflected in the histograms and that the axes are fixed to uniform values for better comparability. One histogram bar corresponds to an interval of ~20 ms [TWT].

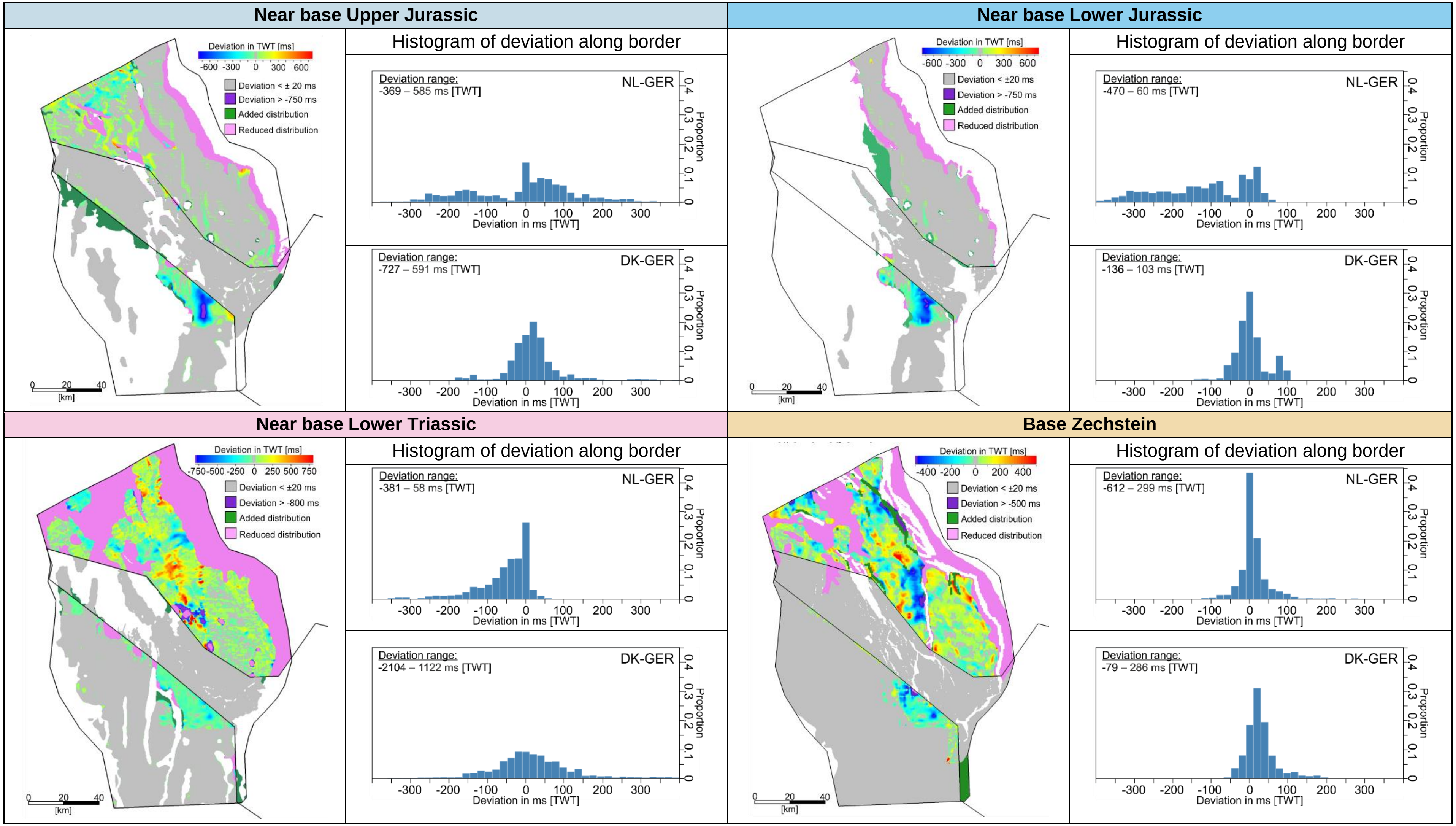


Figure 28b: Maps showing the deviation between the initial and harmonized time horizon grids in the Entenschnabel region and histograms summarizing the deviation (TWT of initial grid – TWT of the harmonized grid) along the national borders. Note that areas with added or removed distribution are not reflected in the histograms and that the axes are fixed to uniform values for better comparability. One histogram bar corresponds to an interval of ~20 ms [TWT].

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