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Harmonized seismic stratigraphic concepts - A base for consistent structural interpretations

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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 will provide information about seismic stratigraphic definitions on horizons that have been selected by the project partners for harmonization purposes (see D3.1). On the basis of several cross-border seismic sections and synthetic seismics, differences are discussed and solutions for a cross-border harmonization are proposed. The compilation of this information in a clear form should ensure that different interpreters within or outside the geological surveys use the same interpretation concepts, or have a basis for further discussions. The understanding of the seismic stratigraphy concepts presented here should ensure the easy harmonization of existing and future interpretations.

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1 Harmonization of seismic stratigraphic concepts

1.1 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. During an initial cross-border comparison of national horizon models, several discrepancies in distribution and thickness of certain stratigraphic intervals became apparent along the national borders (see for details Deliverable 3.1 “State of the Art Report”). The reasons for such discrepancies are not always obvious and may be caused by a combination of independent factors. In general, the horizon models provided by the participating GSOs are based on the interpretation of 2D and 3D seismic data, supplemented by well information. Discrepancies in the seismic interpretations may arise here from national differences in lithostratigraphic, seismic stratigraphic and interpretational concepts, but they may also depend on the data distribution and quality as well as structural complexity of an analyzed area. A closer evaluation of these discrepancies and their causes is thereby an important step in the process towards a harmonized, consistent cross-border geomodel.

The starting point for any seismic interpretation is the development of a seismic stratigraphic concept for the study area, defining the seismic characteristics of the analyzed stratigraphic intervals and their bounding surfaces. In the North Sea Basin, the seismic mapping concepts applied by the participating GSOs have evolved from regional approaches and reflect the complex basin evolution featuring laterally varying sedimentary cycles. In general, the national concepts differ thereby only slightly on a supra-regional scale with respect to the main stratigraphic boundaries. But when viewed more closely, the interpretations can differ considerably, especially in structurally complex regions or due to small-scale changes in distributional patterns of the lithological units. Here, the thicknesses of individual stratigraphic intervals, for example, may vary heavily and even minor differences in the definition of the nationally-mapped seismic reflectors can cause considerable discrepancies in national interpretations. Finally, this could lead to different conclusions regarding the structural development of a region. The aim of this report is therefore to highlight the differences and similarities in the national seismic stratigraphic concepts and, if possible, to harmonize existing disparities and thus to enable, among other things, more consistent structural interpretations across borders and to provide a basis for future cross-border studies.

1.2 Challenges for harmonization

Cross-border harmonization of seismic stratigraphic interpretation concepts can be a challenging task for several reasons. Differences in the nationally defined lithostratigraphic boundaries, for example, may impede the harmonization process, because as a consequence the respective seismic horizons may also differ. None of these horizons, however, can be regarded easily as incorrect, since they comply with national definitions. At the same time, the mapped seismic horizons may coincide, even if the (litho-)stratigraphic definitions differ considerably. This can be the case, for example, if nationally defined boundaries are not represent by a significant acoustic impedance contrast and therefore a “near base” horizon has been mapped which may coincides with the horizon of the neighboring country.

Further difficulties arise in part from different seismic interpretation concepts that have been applied. In the Dutch and German North Sea, the key stratigraphic horizons selected for harmonization are generally mapped as base surfaces, whereas in Denmark some horizons were mapped as top surfaces. As illustrated in Figure 1, horizons mapped according to the different interpretational concepts (base vs. top) may differ to some extent. For example, the base of the Upper Jurassic corresponds 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. This circumstance must be taken into account when harmonizing and describing the seismic character of a horizon. Different seismic data sets used for the characterization of the seismic horizons, as well lateral changes in depositional facies that may lead to changing acoustic characteristics in neighboring countries, can further complicate the harmonization process.

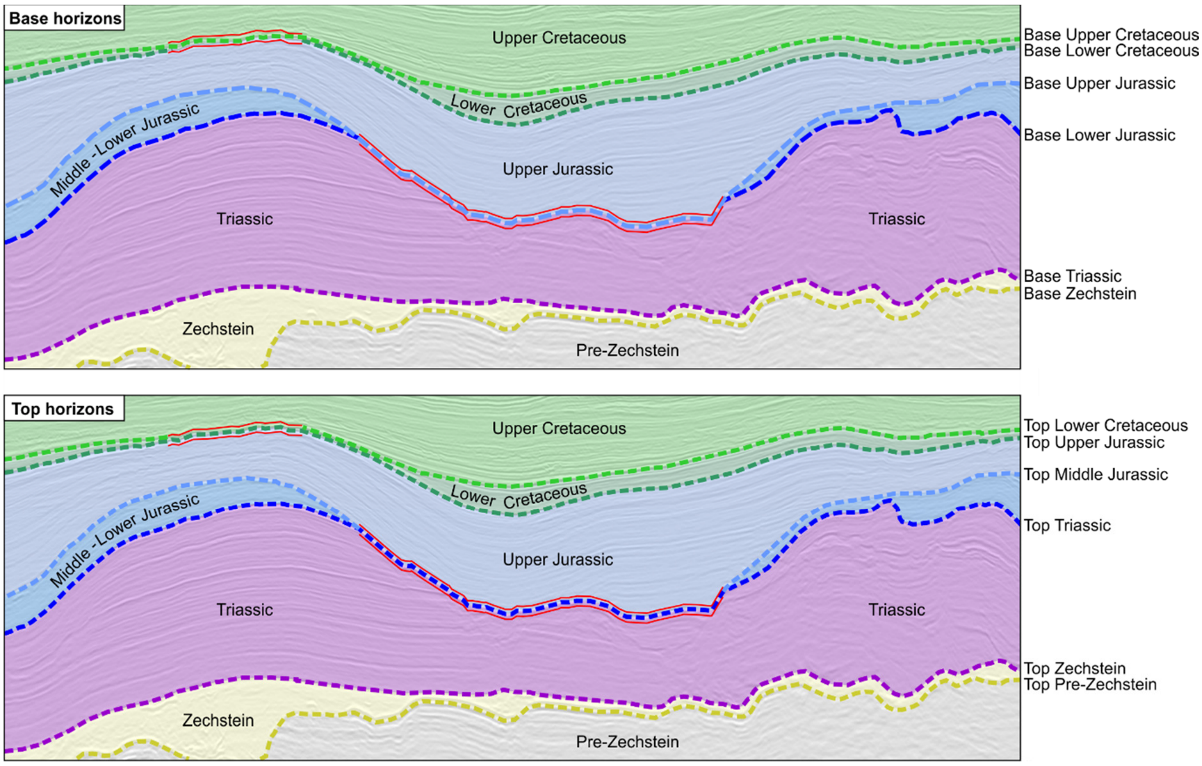

Figure 1: Seismic sections illustrating the difference of horizons mapped as basal or top surfaces. Differences are marked in red.

Another aspect that generally complicates the harmonization of seismic stratigraphic interpretations across national border concerns the shared access to well and seismic information. The disparate legal framework of national data policies especially concerning the provision of industrial data has a strong influence on the availability of this fundamental information and impedes the exchange of data among the participating partner countries. A brief overview of the legal constraints of Germany, The Netherlands and Denmark is given in Thöle et al. (2019). In particular, the data laws that have been valid in Germany until recently have made an exchange rather difficult. On June 30, 2020, however, a new data act (Geologiedatengesetz–GeolDG) was passed in Germany which will simplify data exchange for future cross-border harmonization studies. Most of the seismic-stratigraphic harmonization presented here, however, were still affected by the more restrictive regulations.

1.3 Selected stratigraphic horizons

Eight key stratigraphic horizons have been selected by the project members for the harmonization of the seismic stratigraphy:

- Near Mid Miocene Unconformity (MMU)
- Near base Cenozoic
- Base Upper Cretaceous
- Near base Lower Cretaceous
- Near base Upper Jurassic
- Near base Lower Jurassic
- Near base Lower Triassic
- Base Zechstein

For the Horn Graben region, which is mainly dominated by Triassic clastic strata up to 6 km thick (Kilhams et al., 2018), GEUS and BGR agreed to include additional Triassic horizons to address this fact. The following three horizons were included here:

- Top Grabfeld Formation
- Near base Middle Triassic
- Near base Volpriehausen Formation

1.4 Harmonization approach

For the harmonization of the selected stratigraphic horizons and to address the challenges associated with this, the following working steps were conducted:

(1) Compilation of cross-border seismic sections and synthetics (Chapter 2)

In order to compare the seismic horizons mapped in the Dutch, Danish and German North Sea sectors, several cross-border seismic sections were compiled. These lines were constructed from 2D and 3D seismic data (Table 1) and cover the main structural elements defined for the study area (Figure 3). To achieve the best possible correlation of the nationally mapped horizons, the seismic sections were preferably positioned in areas with little seismic disturbance. All participating project partners transferred their interpretation to these seismic sections and noted the polarity of the mapped seismic reflector. For the display of the seismic the European polarity convention was chosen, in which a positive amplitude (peak) represents a decrease in acoustic impedance and a negative amplitude (trough) an impedance increase (Figure 2).

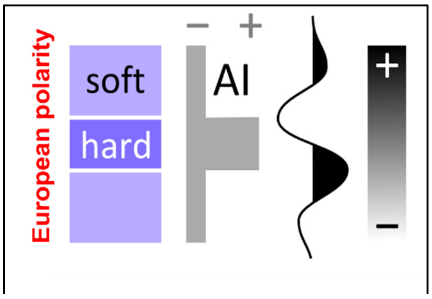

Figure 2: European polarity convention (Brown, 2001)

In order to evaluate the (litho-)stratigraphic position and the seismic character of the mapped seismic horizons, well-to-seismic ties using synthetic seismograms were additionally provided by the project partners for 16 wells. These wells are located on or at a very short distance to one of the cross-border seismic lines (Figure 3).

Table 1: List of the used seismic surveys for the constructions of the cross-border seismic sections. The different working areas are highlighted in colour (yellow = NL-GER offshore border area / blue = Entenschnabel region / green = Horn Graben region)

Figs.		Seismic survey	Figs.		Seismic survey
NL-GER border	4	Z3NAM1994C (seismic traverse)	DK-GER border	18	Entenschnabel 2002 (XL6205)
	7	GR-86 (lines 024 &103)		19	Entenschnabel 2002 (seismic traverse)
	10	G2002 (line 003)		20	GNSC 2001 (seismic traverse)
	11	G2002 (lines 026, 052 & 028a)		23	GNSC 2001 (seismic traverse)
	14	Z3FUG2002A (seismic traverse) [GER: Entenschnabel 2002]		28	Angelina MC3D 2007 (IL15080)
	15	Z3FUG2002A (XL3678) [GER: Entenschnabel 2002]		29	Angelina MC3D 2007 (XL3174)
	24	Z3NAM1993A (seismic traverse)		30	Angelina MC3D 2007 (IL14350)
	25	Amerada Hess 1997, Block A (line 316)		36	Horn Graben 97 (Lines 28, 50, 54, 59, 56 & 82)
				37	HG97 (Lines 38, 42, 54, 129 & 155)

(2) Horizon comparison / harmonization (Chapter 3)

The compiled cross-border seismic sections were used to compare the nationally mapped seismic horizons. The comparison and the subsequent harmonization of the stratigraphic horizons included thereby the following aspects:

- *(Litho-)stratigraphic definitions and their differences*

  The stratigraphic horizons selected for harmonization are often assigned to nationally defined lithostratigraphic boundaries. Differences in these definitions may cause that the respective seismic horizons may also differ. Therefore, a brief outline of the nationally defined horizons and their differences is provided prior to the actual horizon comparison.

- *Comparison of mapped horizon*

  Differences observed in the nationally mapped seismic horizons were briefly described and summarized in tabular form for each cross-border seismic section to provide a quick overview of the discrepancies and similarities.

- *Evaluation of differences and intended harmonization*

  Each project partner provided information that explain their choice of a specific seismic reflector as well as their general mapping concept applied for the respective horizon. This includes particularly information regarding the assumed acoustic impedance contrast along a stratigraphic horizon. Based on this information and by considering the seismic synthetics compiled the differences in the nationally mapped seismic horizons were evaluated and, if possible, existing disparities where harmonized across borders.

2 CROSS-BORDER SEISMIC SECTIONS AND SYNTHETICS

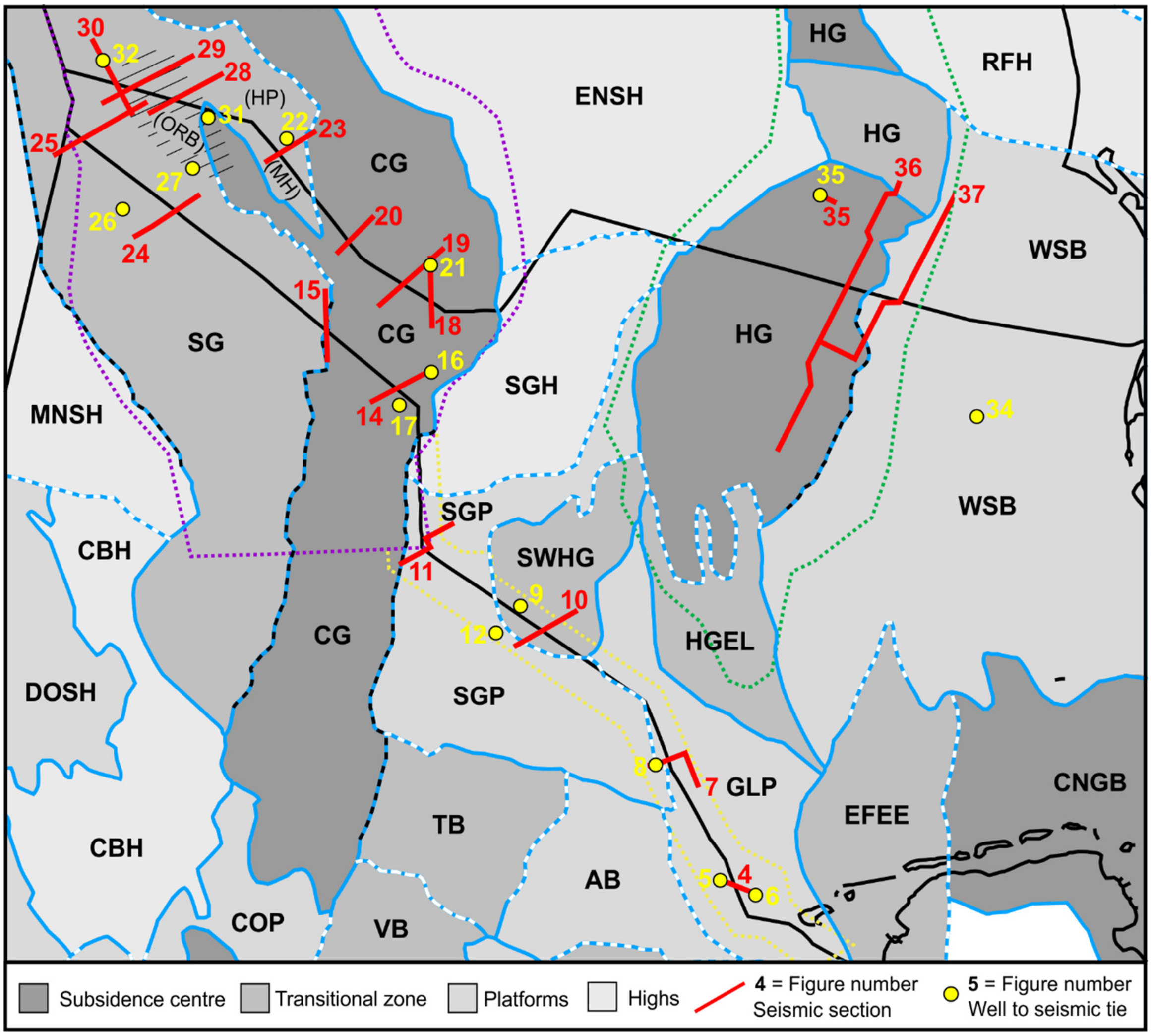

Figure 3: Preliminary map of main structural elements in the area of the Dutch, German and Danish North Sea sectors showing the location of the presented cross-border seismic sections and wells used for generation of synthetic seismic. Working areas defined in the North Sea for 3DGEO-EU WP3 are marked by dotted lines (yellow= NL-GER offshore border area / purple = Entenschnabel region / green = Horn Graben region). Uncertain limits of structural elements which are currently under review in the project (see Deliverable 3.8) are indicated by dashed lines. Blue-black dashed lines: uncertain limits due to differing concepts in defining the boundaries, e.g. according to basement structures or distributional pattern. Blue-white dashed lines: boundaries difficult to define due to e.g. diffuse trends in distributional patterns or no clear basement structures.

Abbreviations of 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 / DOSH = Dogger Shelf / CBH = Cleaver Bank High / COB = Central offshore Platform / VB = Vlieland Basin / TB = Terschelling Basin. Subordinate structural elements: ORB = Outer Rough Basin / MH = Mads High / HP = Heno Plateau.

2.1 Dutch-German offshore border area

Four seismic sections were compiled for the NL-GER offshore border area (Figure 3) covering the different structural elements in the region. These are from southeast to northwest the G- and L- Platform areas (GLP), the Ameland Block (AB), the southwestern branch of the Horn Graben (SWHG), and the Schillgrund Platform/High (SGP/SGH). Jurassic strata is generally absent here due to Mid to Late Jurassic erosion down to the Triassic. Therefore, only six key horizons are present in this working area:

- Near Mid Miocene Unconformity (MMU)
- Near base Cenozoic
- Base Upper Cretaceous
- Near base Lower Cretaceous
- Near base Lower Triassic
- Base Zechstein

Most of the seismic horizons indicated here for the German North Sea are related to recent seismic mapping activities of BGR in the framework of the TUNB project (German acronym for ”Subsurface Potentials for Storage and Economic Use in the North German Basin”). The seismic reflector interpreted as “Near MMU”, however, has been previously mapped by Thöle et al. (2014) within the framework of the GPDN project (German acronym for “Geo-scientific Potentials of the German North Sea”; Reinhardt et al., 2010). For the Dutch North Sea, the seismic interpretation presented here comply with the seismic reflectors mapped for the DGM-deep model (Duin et al., 2006; Kombrink et al., 2012) which is disseminated through the Netherlands Oil and Gas Portal (NLOG).

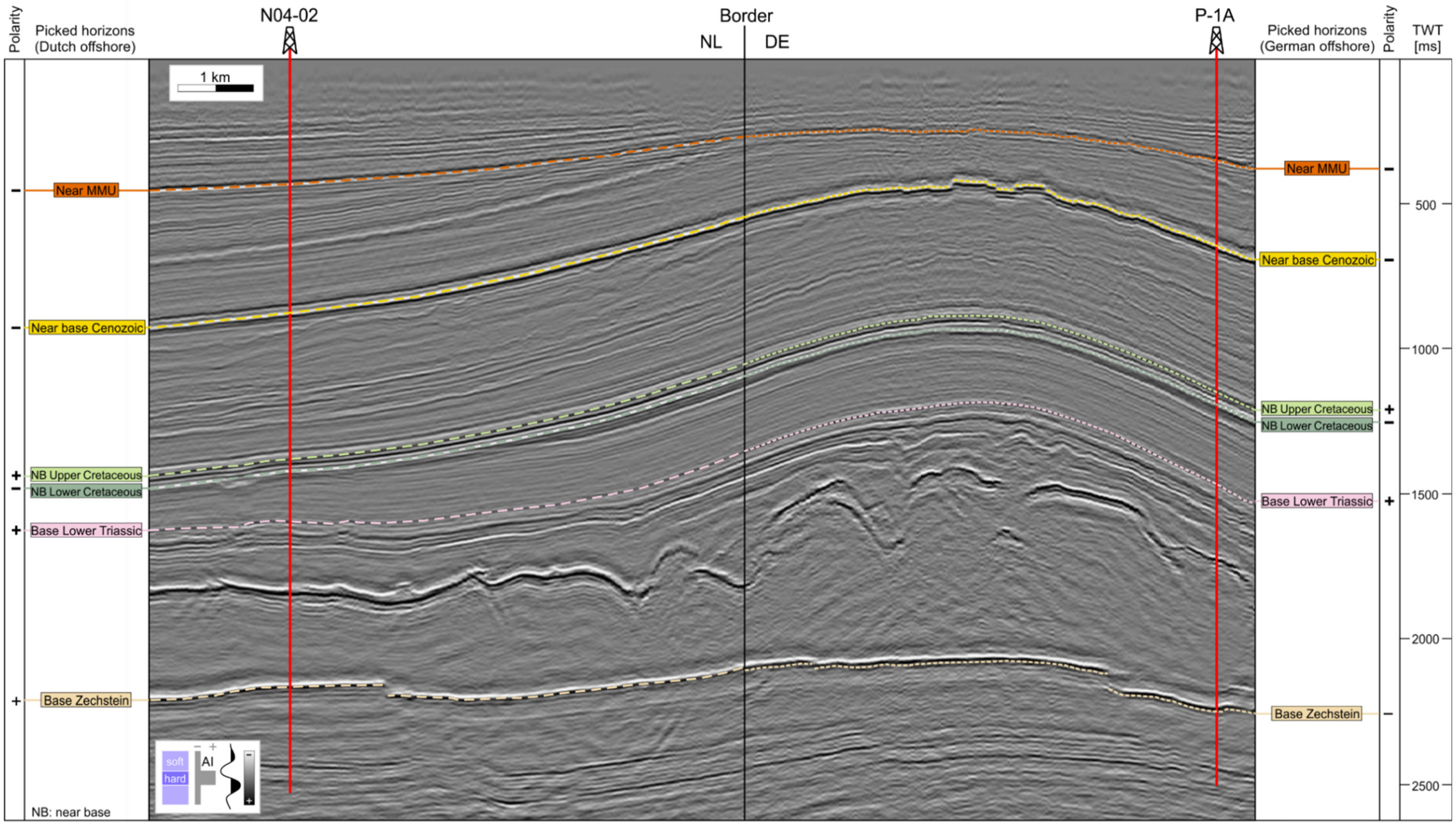

Figure 4: NW-SE oriented seismic section across the G- and L-Platform areas (see Figure 3 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. Red vertical lines show wells for which well-to-seismic ties are provided in the report (Figures 5 and 6). Except for the Base Zechstein, the same reflectors were chosen in this area for the mapping of the key horizons. Abbreviation: NB = Near base.

Dutch well: N04-02

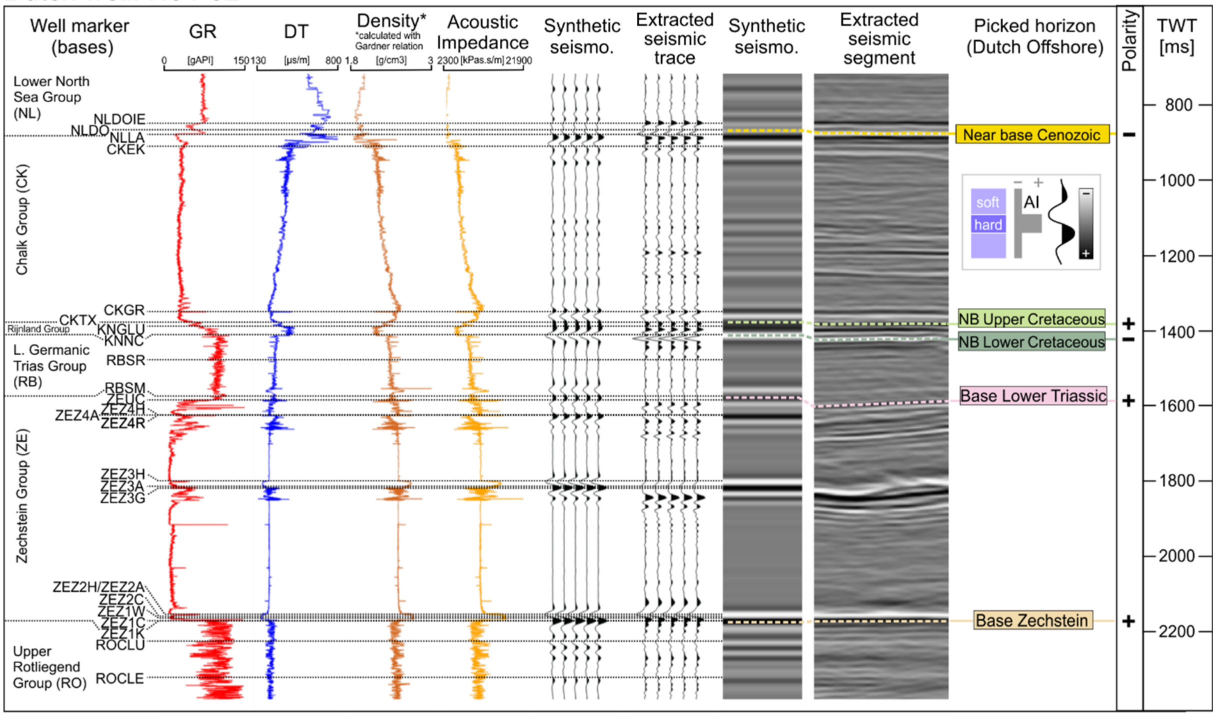

Figure 5: Synthetic seismogram for the Dutch well N04-02 showing the (litho-)stratigraphic position and polarity of horizons mapped in the Dutch North Sea. The well lies on the cross-border seismic section shown in Figure 4. The well-to-seismic tie was provided by TNO. Marker abbreviations are according to the Stratigraphic Nomenclature of the Netherlands (TNO-GSN, 2020).

German well: P1-A

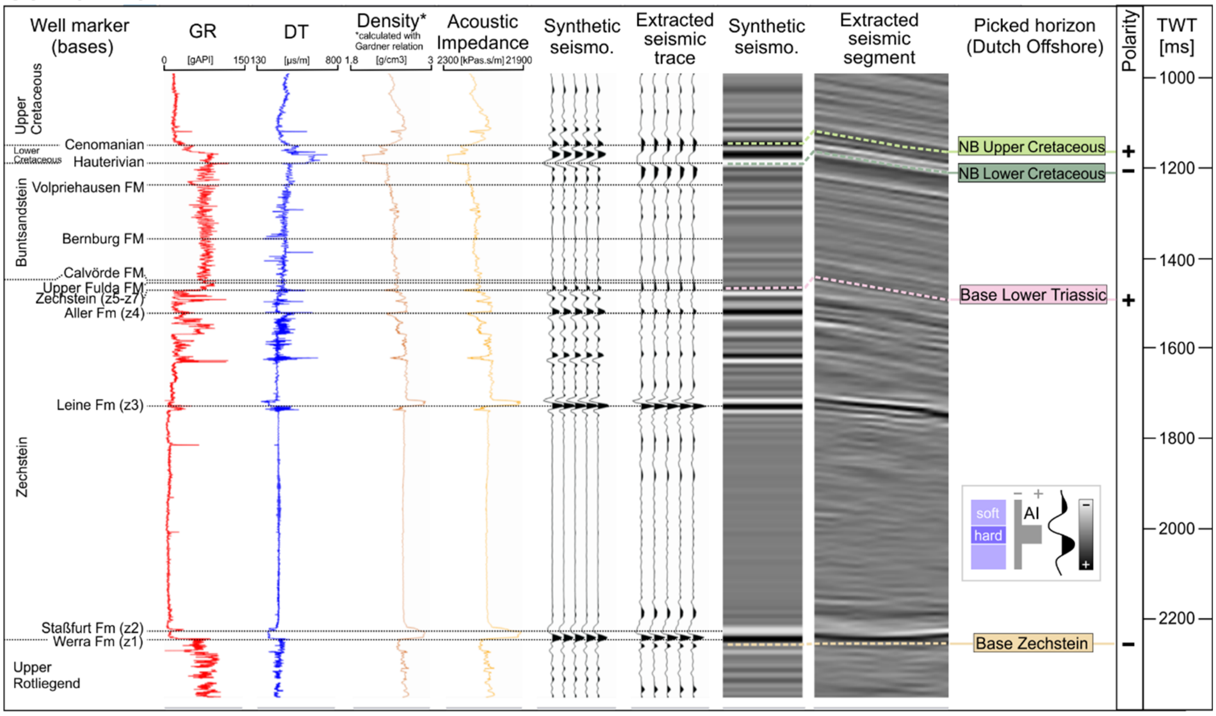

Figure 6: Synthetic seismogram for the German well P1-A showing the (litho-)stratigraphic position and polarity of horizons mapped in the German North Sea. The well lies on the cross-border seismic section shown in Figure 4 and was drilled on behalf of Elwerath Erdgas und Erdöl GmbH in 1966. The well-to-seismic correlation was established by BGR.

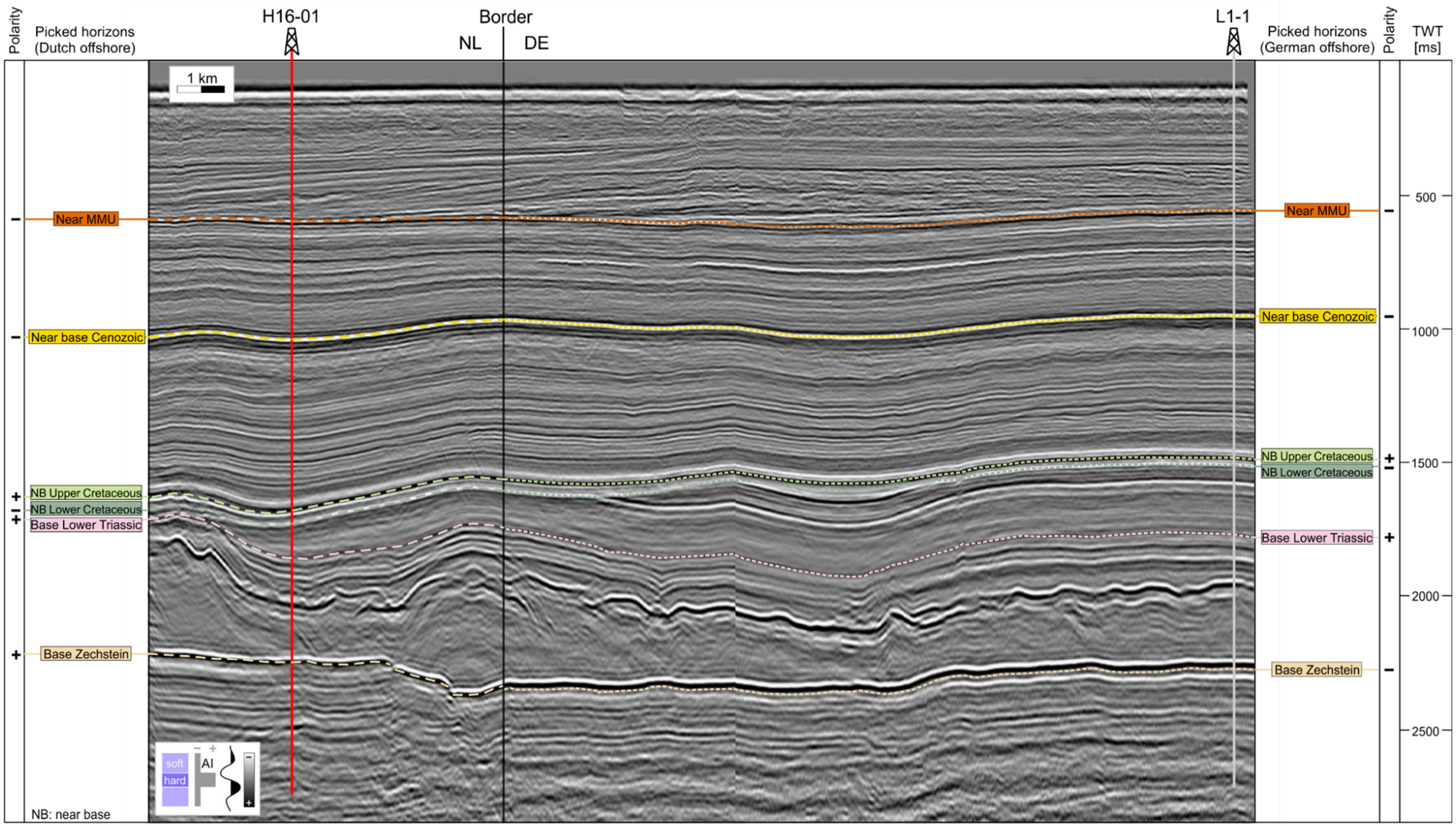

Figure 7: SW-NE oriented seismic section across the southern Dutch Schillgrund Platform and the German G- and L-Platform areas (see Figure 3 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. A well-to-seismic tie is provided for the Dutch well H16-01 (red vertical line) (see Figure 8). Except for the Base Zechstein, the same reflectors were chosen in this area for the mapping of the key horizons. The seismic section presented belongs to the "GR-86" 2D survey, which was acquired by NOPEC A.S. in 1986. Abbreviation: NB = Near base.

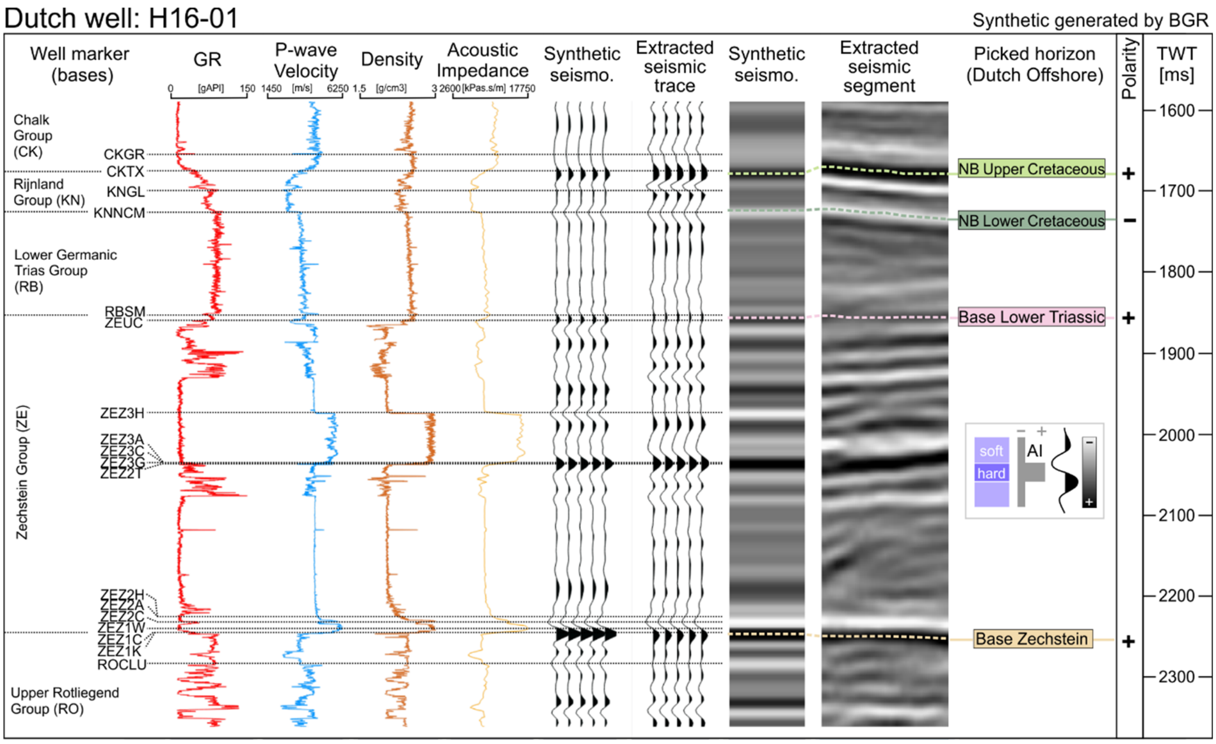

Figure 8: Synthetic seismogram for the Dutch well H16-01 showing the (litho-)stratigraphic position and polarity of horizons mapped in the Dutch North Sea. The well lies on the cross-border seismic section shown in Figure 7. The well-to-seismic tie was established by BGR. Marker abbreviations are according to the Stratigraphic Nomenclature of the Netherlands (TNO-GSN, 2020). Note that instead of a DT log, p-wave velocities are presented in the figure.

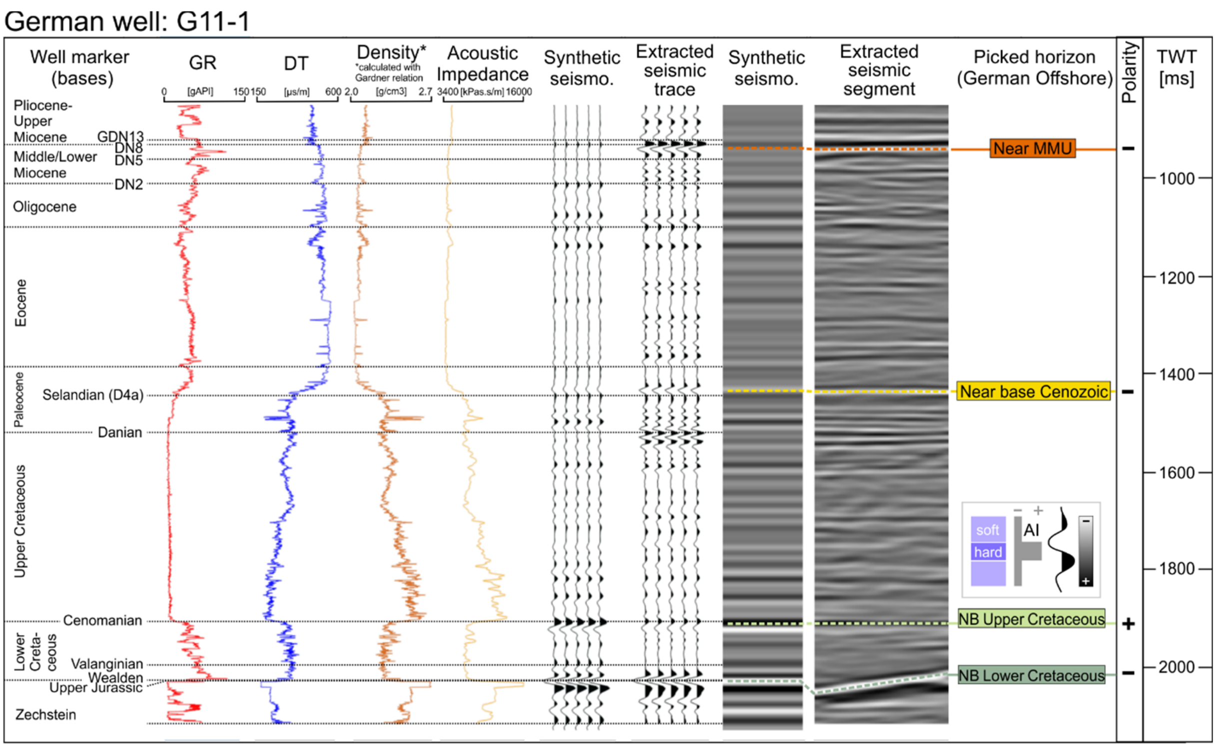

Figure 9: Synthetic seismogram for the German well G11-1 showing the (litho-)stratigraphic position and polarity of horizons mapped in the German North Sea. The well is located close to the cross-border seismic section shown in Figure 10 and was drilled on behalf of BEB Erdgas and Erdöl GmbH in 1988. The well-to-seismic tie was established by BGR. Dinocyst biostratigraphy shown for the Cenozoic interval is from Köthe (2011).

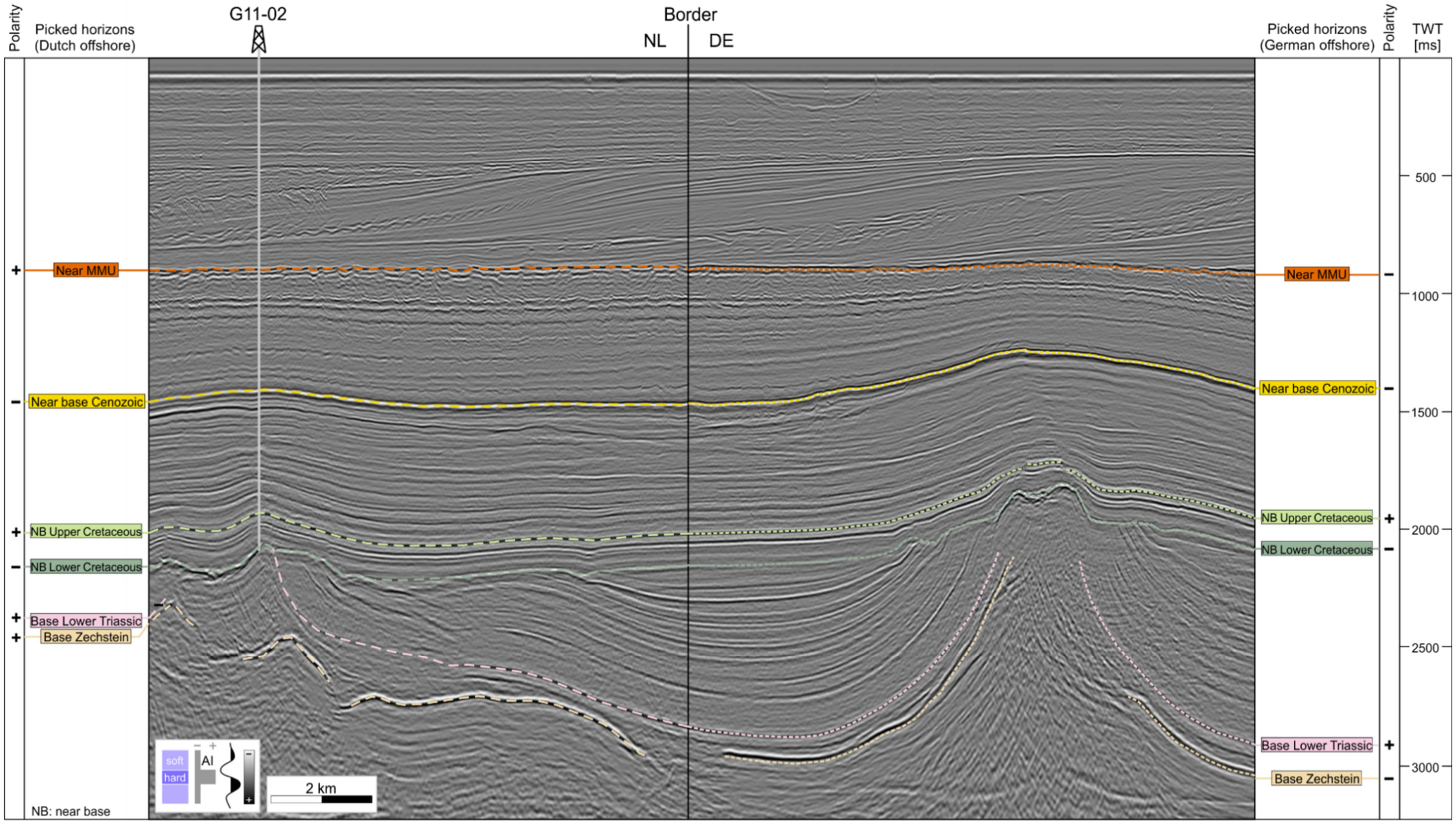

Figure 10: SW-NE oriented seismic section across the Dutch Schillgrund Platform and the western branch of the Horn Graben in the German North Sea (see Figure 3 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. The "Near MMU" and the "Base Zechstein" are mapped in the German North Sea in a trough, whereas in the Dutch sector these horizons were picked here directly above in a peak. The seismic section is part of the "G2002" 2D survey, which was acquired by TGS NOPEC in 2002. Abbreviation: NB = Near base.

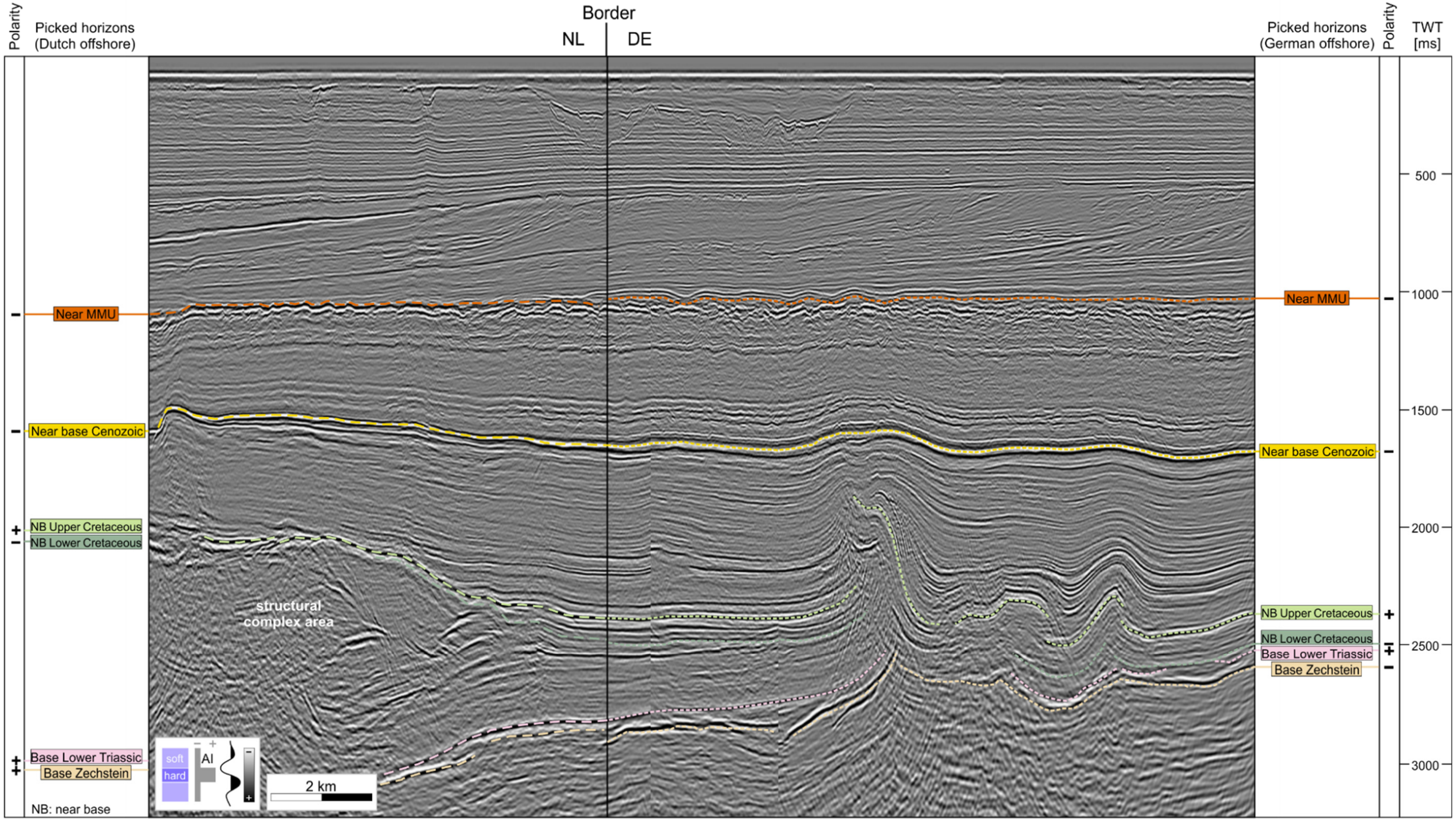

Figure 11: SW-NE oriented seismic section across the Schillgrund Platform (see Figure 3 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. The "Base Zechstein" differs by one reflector (NL: peak / GER: trough) and the "Near MMU" is mapped in the Dutch North sector in a trough and partly in a peak, whereas the German interpretation mainly follows a trough. The seismic section is part of the "G2002" 2D survey, which was acquired by TGS NOPEC in 2002. Abbreviation: NB = Near base.

Dutch well: G10-2

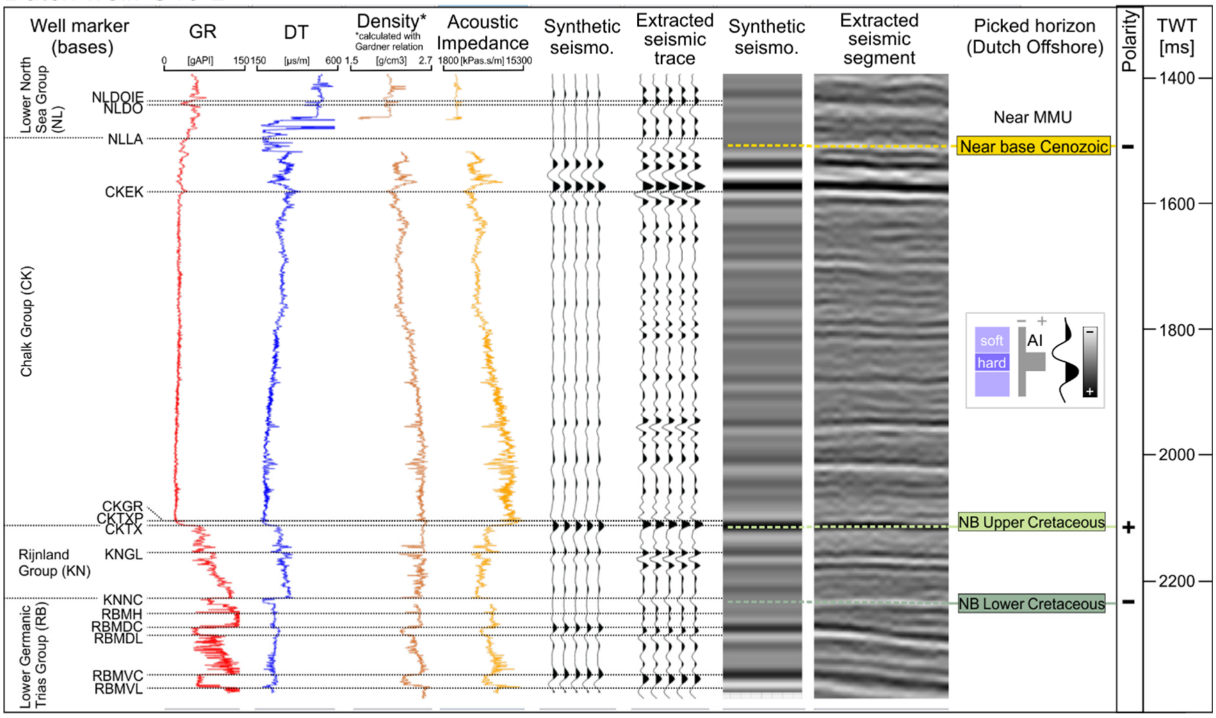

Figure 12: Synthetic seismogram for the Dutch well G10-02 showing the (litho-)stratigraphic position and polarity of horizons mapped in the Dutch North Sea. The well is located close to the cross-border seismic section shown in Figure 11. The well-to-seismic tie was provided by TNO. Marker abbreviations are according to the Stratigraphic Nomenclature of the Netherlands (TNO-GSN, 2020).

2.2 Entenschnabel region

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 13). 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, 4 seismic sections crossing the NL-GER border and 7 sections crossing the DK-GER border were compiled (Figure 13). All key horizons selected by the project partners for harmonization purposes are present in this working area:

- Near Mid Miocene Unconformity (MMU)
- Near base Cenozoic
- Base Upper Cretaceous
- Near base Lower Cretaceous
- Nea base Upper Jurassic
- Near base Lower Triassic
- Near base Lower Triassic
- Base Zechstein

For the Dutch North Sea, the seismic interpretation indicated here comply with the seismic reflectors mapped for the DGM-deep model (Duin et al., 2006; Kombrink et al., 2012). In the German offshore sector, the interpretation presented here is related to seismic mapping activities of BGR in the framework of the GPDN project. The seismic reflector interpreted as

“Near MMU” is indicated as mapped by Thöle et al. (2014) and all other horizons are drawn according to Arfai et al. (2014). As GEUS is continuously carrying out interpretation of available seismic and well data over the Danish North Sea, for example within the framework of major multi-client projects (e.g. PETSYS, CRETSYS and CENSYS), the interpretation presented here for the Danish side corresponds to GEUS current work status in this area.

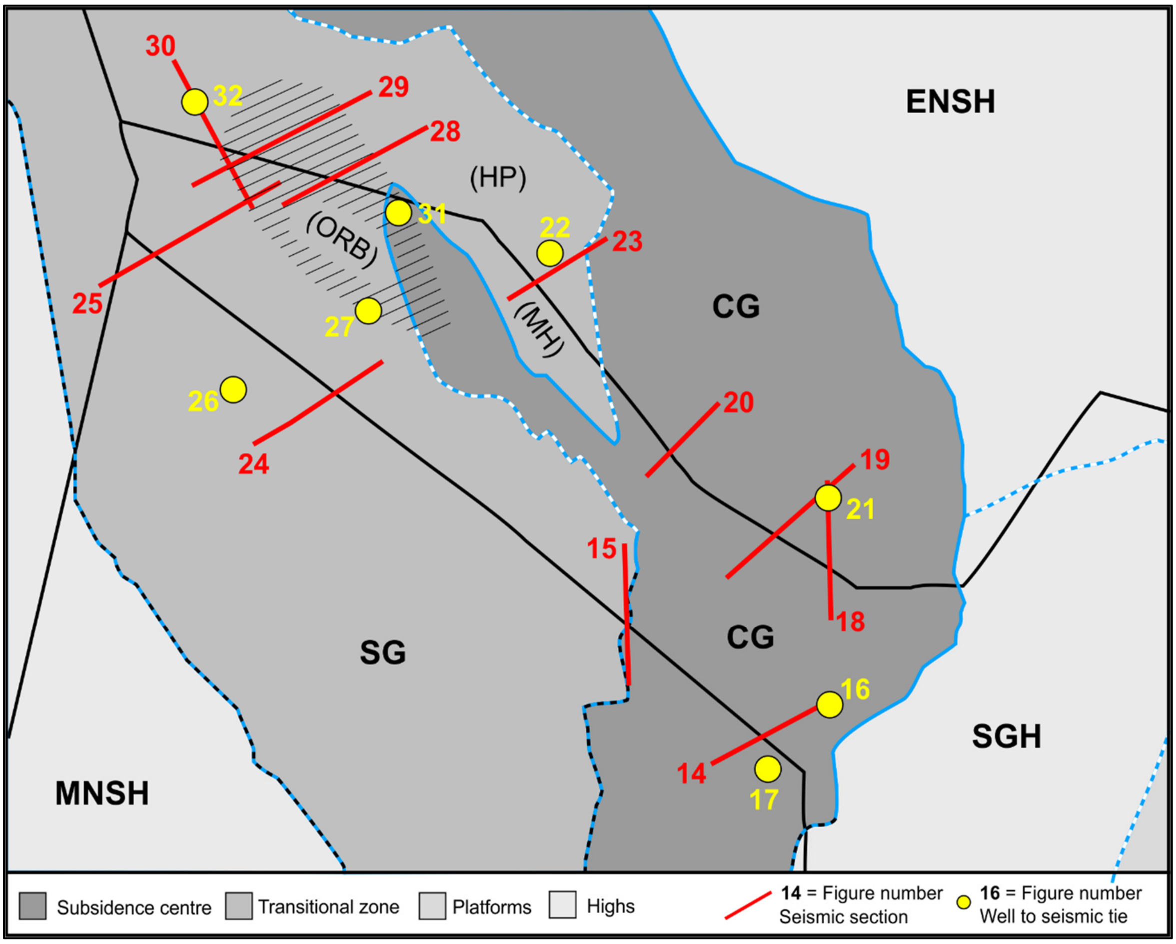

Figure 13: Preliminary map of main structural elements in the Entenschnabel region showing the location of the cross-border seismic sections and wells used for generation of seismic synthetics. Uncertain limits of structural elements which are currently under review in the project (see Deliverable 3.8) are indicated by dashed lines. Blue-black dashed lines: uncertain limits due to differing concepts in defining the boundaries, e.g. according to basement structures or distributional pattern. Blue-white dashed lines: boundaries difficult to define due to e.g. diffuse trends in distributional pattern or no clear basement structures. Abbreviations of main structural elements: SG = Step Graben / CG = Central Graben / ENSH = East North Sea High / MNSH = Mid North Sea High / SGH = Schillgrund High. Subordinate structural elements: ORB = Outer Rough Basin / MH = Mads High / HP = Heno Plateau.

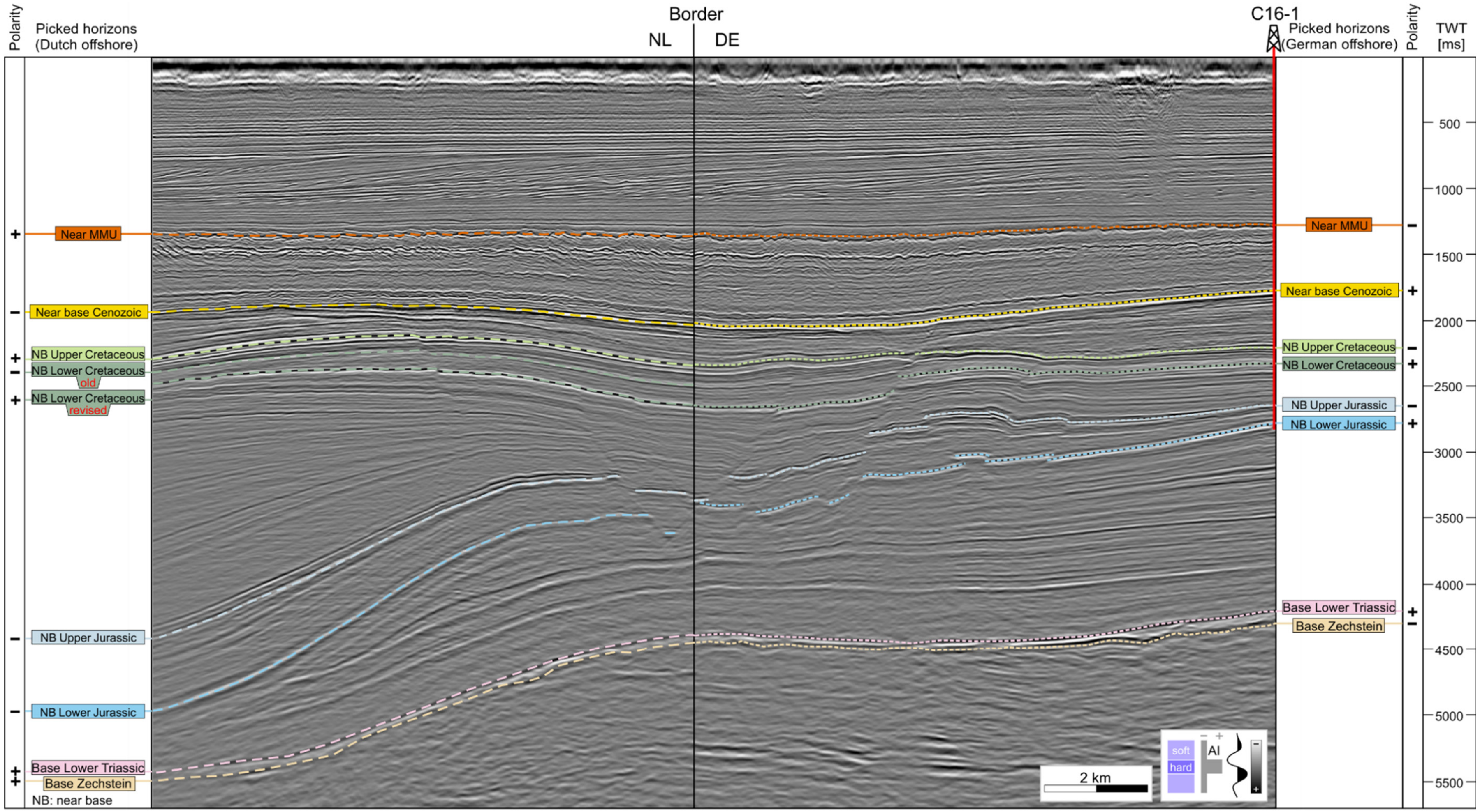

Figure 14: SW-NE oriented seismic section across the Dutch and German Central Graben in the south (see Figure 13 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. Most seismic reflectors indicated here for the Dutch and German sectors differ in their polarity, but differences of more than one reflector were only observed for the "NB Lower Cretaceous". After a re-evaluation of well and seismic data, the Dutch interpretation of this seismic horizon was revised. A well-to-seismic tie is provided for the German well C16-1 (red vertical line) (see Figure 16). The seismic section belongs to the "Entenschnabel 2002" 3D survey, which was acquired on behalf of Fugro in 2002 by PGS, with ownership passing to TGS NOPEC in 2019.

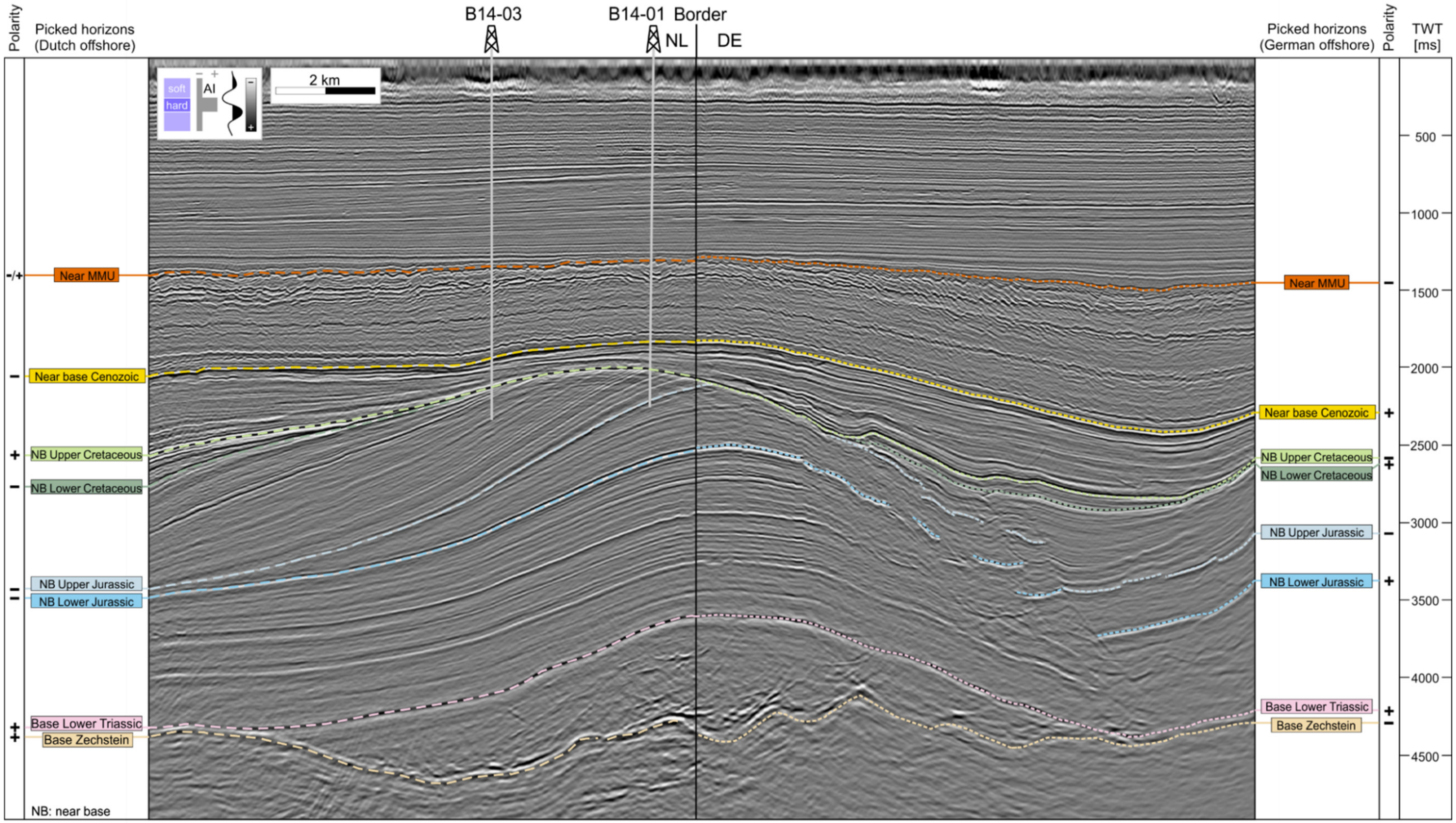

Figure 15: S-N oriented seismic section across the Dutch and German Central Graben (see Figure 13 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. Most seismic reflectors indicated here for the Dutch and German sectors differ in their polarity, but differences of more than one reflector are not observed. The seismic section belongs to the "Entenschnabel 2002" 3D survey, which was acquired on behalf of Fugro in 2002 by PGS, with ownership passing to TGS NOPEC in 2019. Abbreviation: NB = Near base.

German well: C16-1

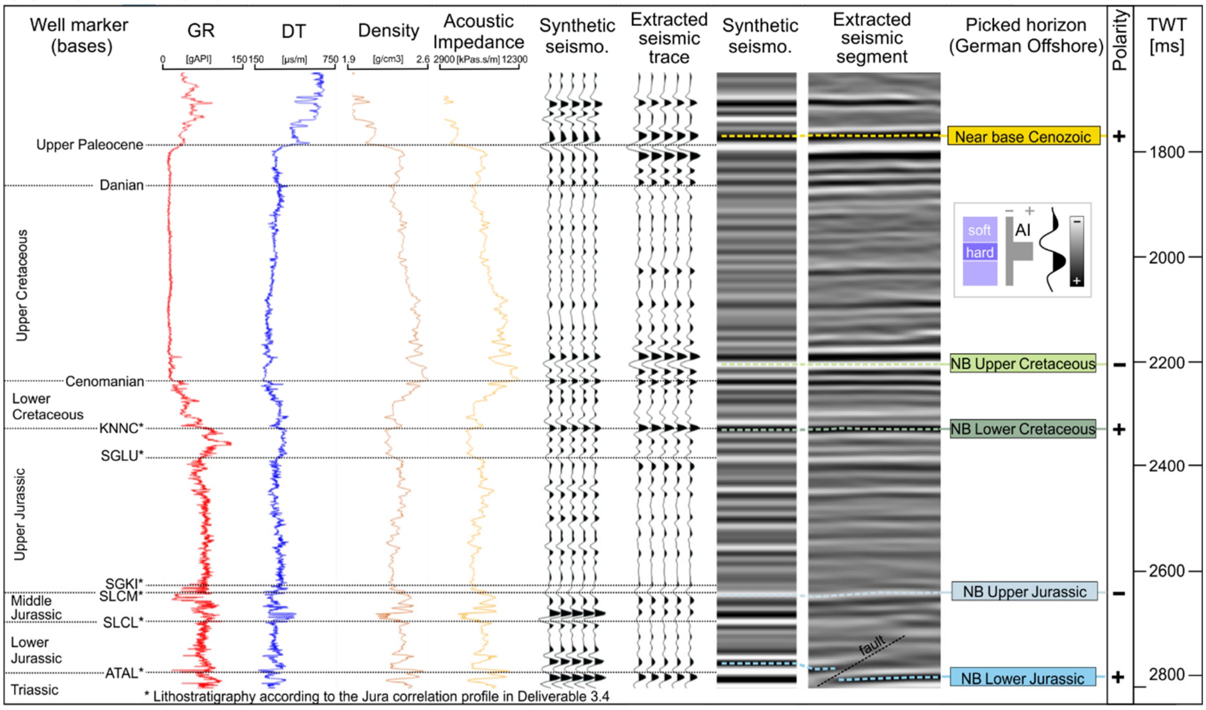

Figure 16: Synthetic seismogram for the German well C16-1 showing the (litho-)stratigraphic position and polarity of horizons mapped in the German North Sea. The well lies on the cross-border seismic section shown in Figure 14 and was drilled on behalf of British Petrol Hamburg in 1975. The well-to-seismic tie was established by BGR. Marker abbreviations for the Lower Cretaceous and older strata are according to the Stratigraphic Nomenclature of the Netherlands (TNO-GSN, 2020).

Dutch well: B18-03

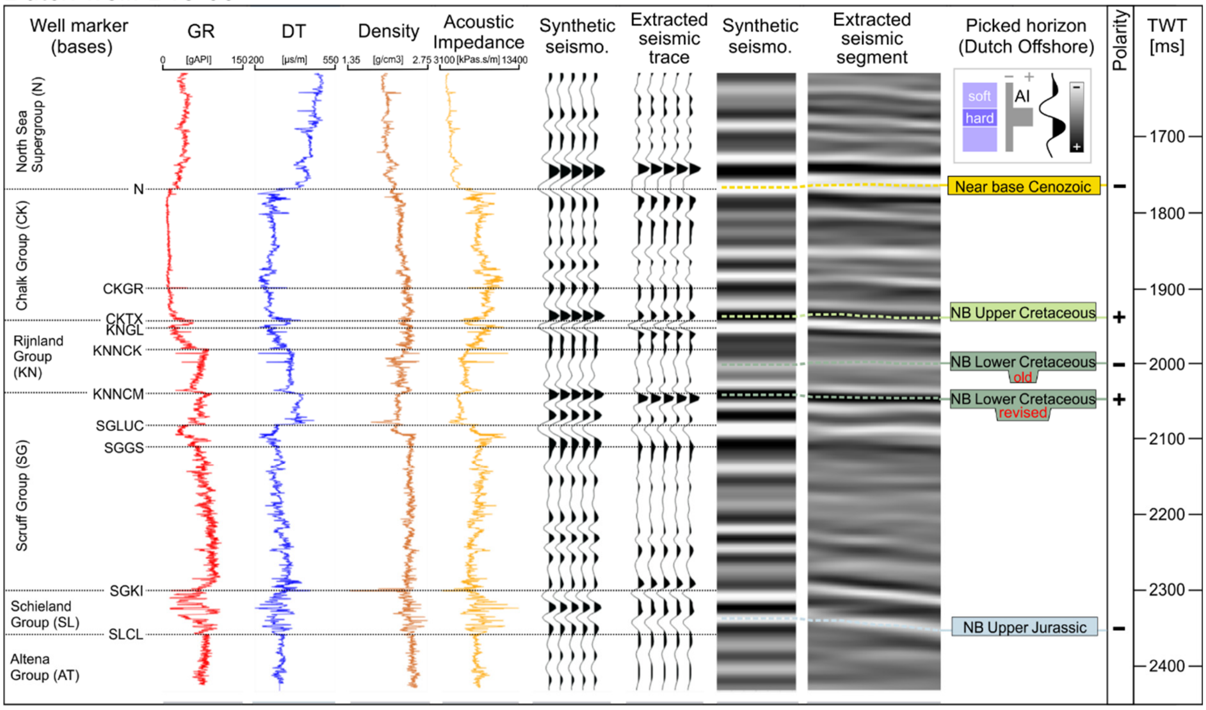

Figure 17: Synthetic seismogram for the Dutch well B18-03 showing the (litho-)stratigraphic position and polarity of horizons mapped in the Dutch North Sea. The well is located close to the cross-border seismic section shown in Figure 14. The well-to-seismic tie was established by TNO. Marker abbreviations for the Lower Cretaceous and older strata are according to the Stratigraphic Nomenclature of the Netherlands (TNO-GSN, 2020). The base marker of the Rijnland Group (KN) is indicated as shown in the Jura correlation profile in Deliverable 3.4.

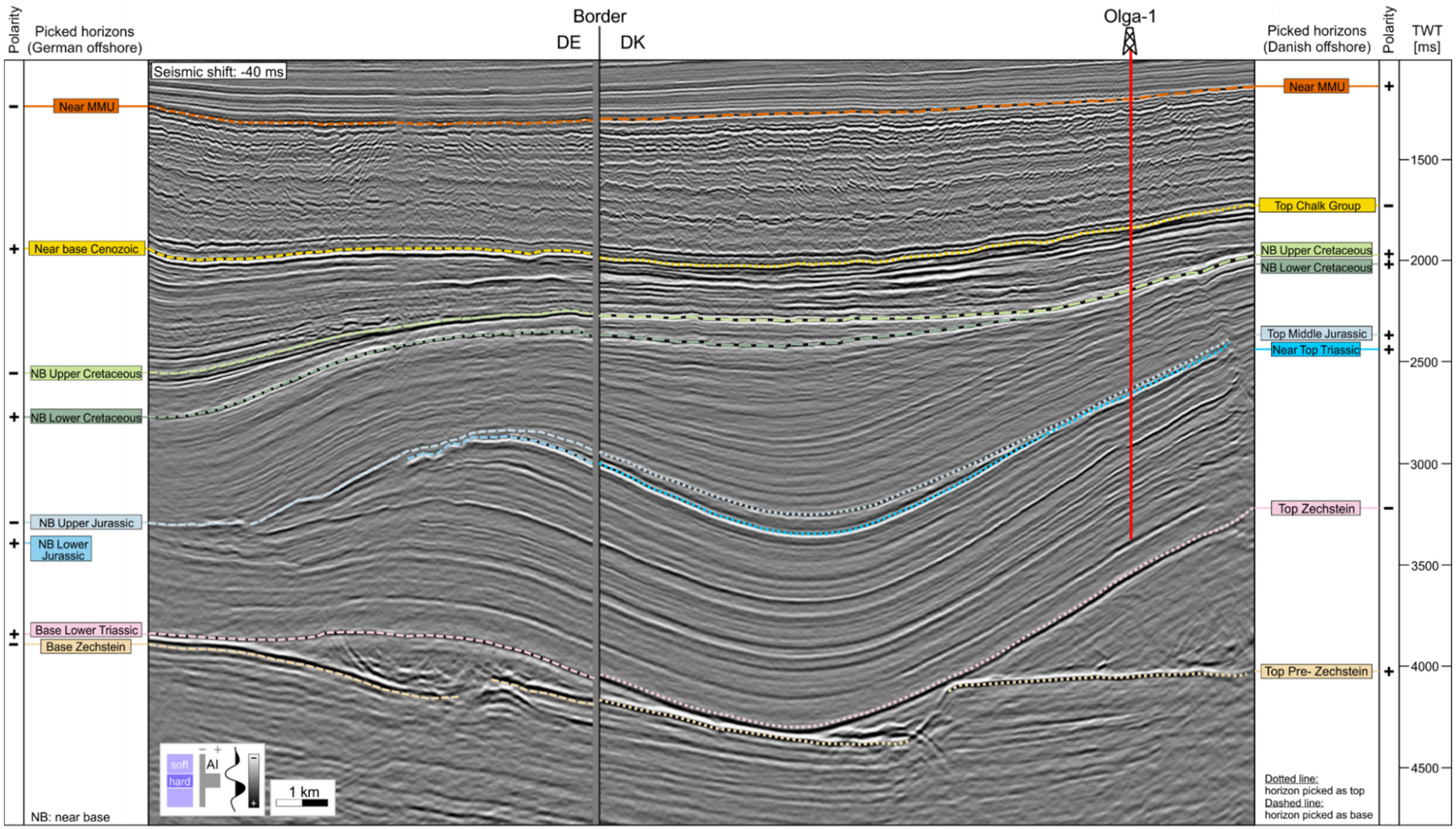

Figure 18: S-N oriented seismic section across the German and Danish part of the Central Graben (see Figure 13 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. Some seismic reflectors indicated here for the Danish and German sectors differ in their polarity, but differences of more than one reflector are not observed. Note that some of the Danish horizons are mapped as top surfaces (dotted lines). A well-to-seismic tie is provided for the Danish well Olga-1 (red vertical line) (see Figure 21). The seismic section belongs to the "Entenschnabel 2002" 3D survey, which was acquired on behalf of Fugro in 2002 by PGS, with ownership passing to TGS NOPEC in 2019. Abbreviation: NB = Near base.

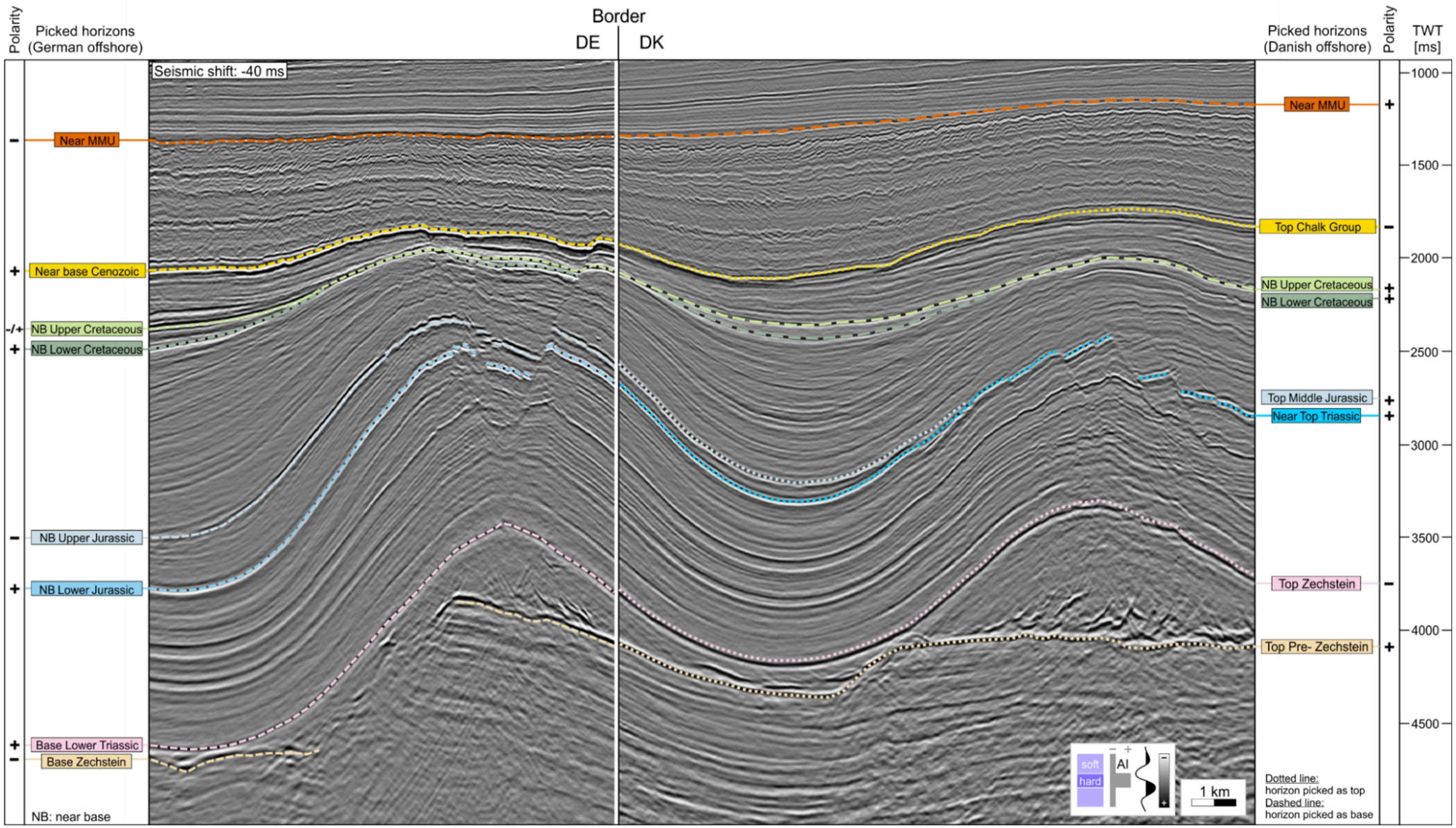

Figure 19: SW-NE oriented seismic section across the German and Danish part of the Central Graben (see Figure 13 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. Some seismic reflectors indicated here for the Danish and German sectors differ in their polarity, but differences of more than one reflector are not observed. Note that some of the Danish horizons are mapped as top surfaces (dotted lines). The seismic section belongs to the "Entenschnabel 2002" 3D survey, which was acquired on behalf of Fugro in 2002 by PGS, with ownership passing to TGS NOPEC in 2019. Abbreviation: NB = Near base.

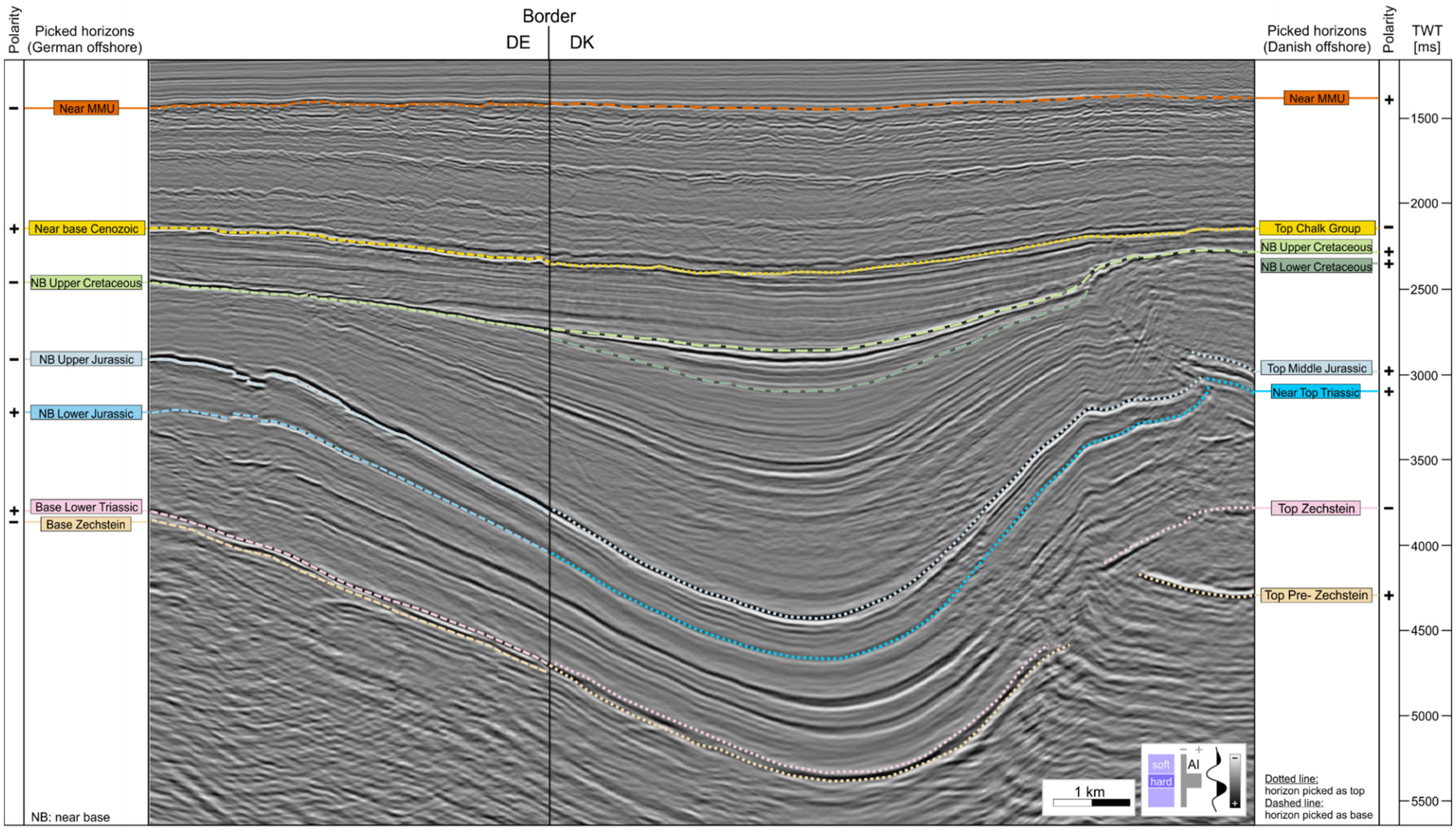

Figure 20: SW-NE oriented seismic section across the German and Danish part of the Central Graben (see Figure 13 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. Some seismic reflectors indicated here for the Danish and German sectors differ in their polarity, but differences of more than one reflector are not observed. Note that some of the Danish horizons are mapped as top surfaces (dotted lines) with the consequence that e.g. their Top Triassic reflector in some regions corresponds to the Near base Lower Jurassic and in others to the Near base Upper Jurassic. The seismic section belongs to the “GNSC 2001“ 3D survey, which was acquired on behalf of the Wintershall Noordzee B.V. in 2001 by PGS.

Danish well: Olga-1

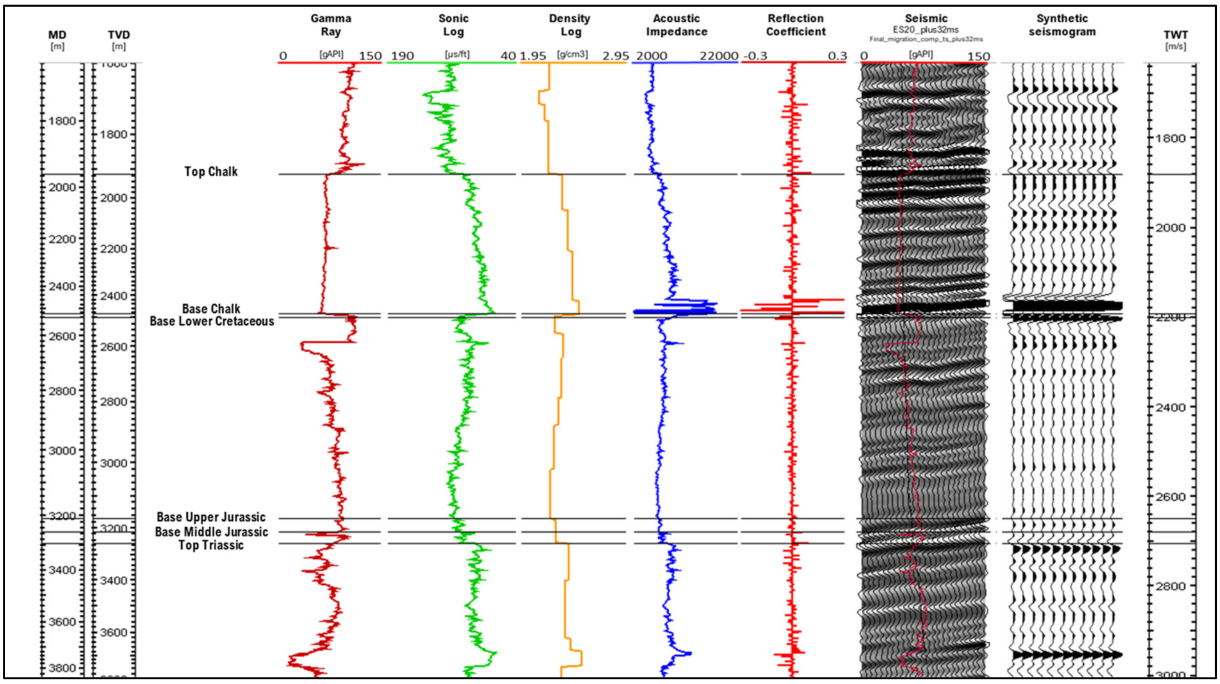

Figure 21: Synthetic seismogram for the Danish well Olga-1 showing the (litho-)stratigraphic position and polarity of horizons mapped in the Danish North Sea. The well lies on the cross-border seismic section shown in Figure 18. The well-to-seismic tie was established by GEUS.

Danish well: Skarv-1

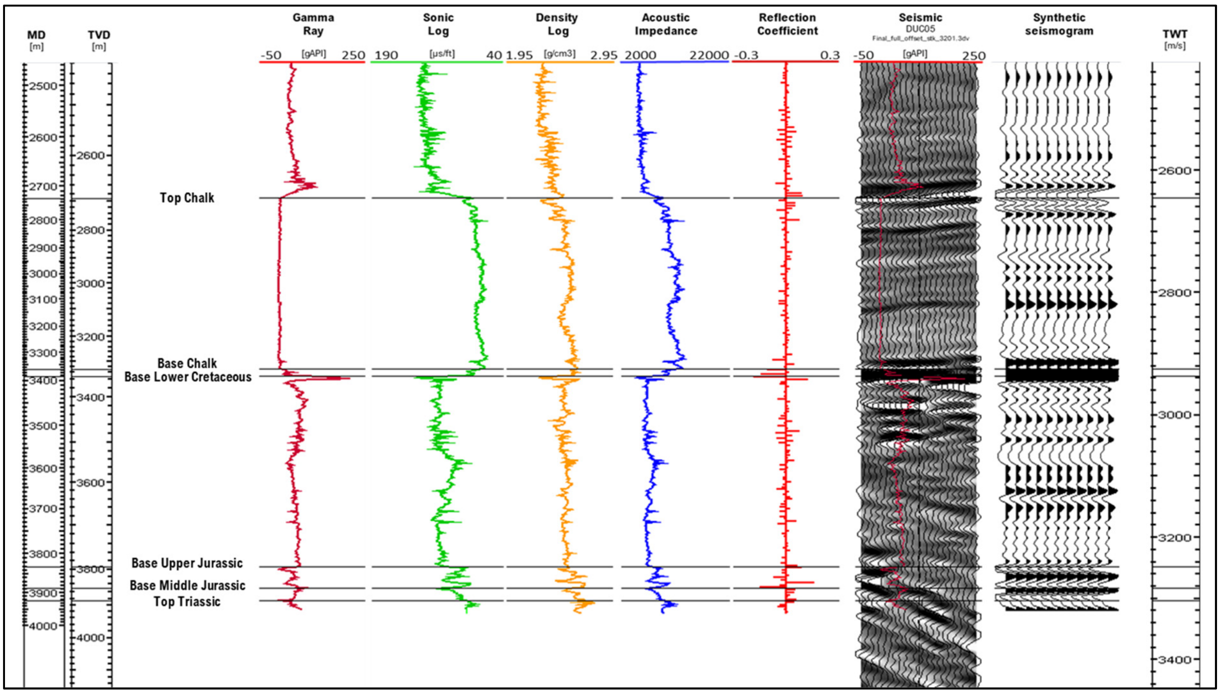

Figure 22: Synthetic seismogram for the Danish well Skarv-1 showing the (litho-)stratigraphic position and polarity of horizons mapped in the Danish North Sea. The well is located close to the cross-border seismic section shown in Figure 23. The well-to-seismic tie was established by GEUS.

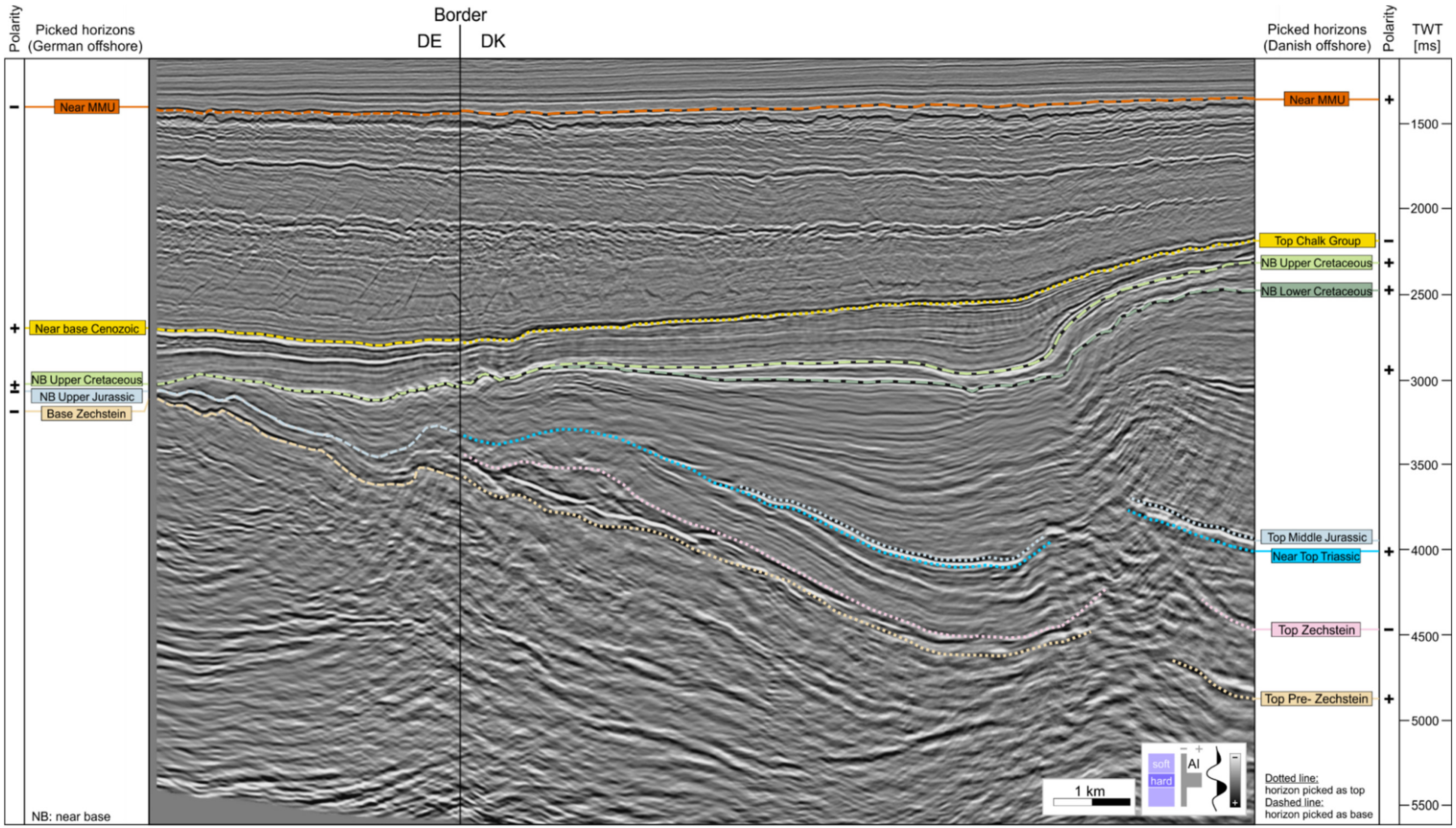

Figure 23: Seismic section across the Mads High in the SE and the Heno Plateau in the NW (see Figure 13 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. Some seismic reflectors indicated here for the Danish and German sectors differ in their polarity, but differences of more than one reflector are not observed. Note that some of the Danish horizons are mapped as top surfaces (dotted lines) with the consequence that e.g. their Top Triassic reflector in some regions corresponds to the Near base Lower Jurassic and in others to the Near base Upper Jurassic. It is also important to note that the Triassic and Lower Cretaceous are eroded along unconformities in the vicinity of the offshore-border. The seismic section belongs to the “GNSC 2001“ 3D survey, which was acquired on behalf of the Wintershall Noordzee B.V. in 2001 by PGS. Abbreviation: NB = Near base.

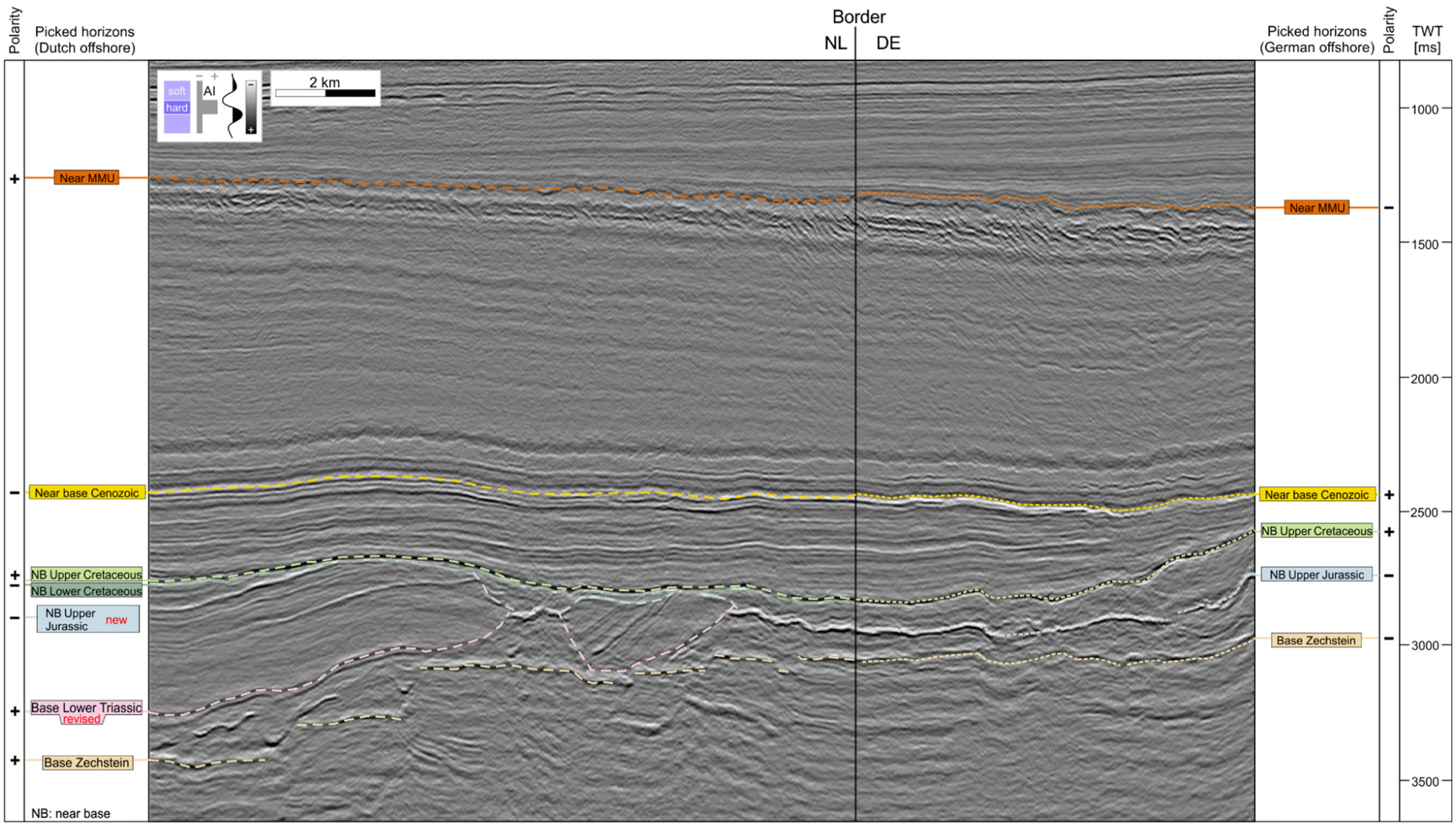

Figure 24: SW-NE oriented seismic section across the Dutch and German Step Graben system (see Figure 13 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. No Upper Jurassic horizon was initially mapped on the Dutch side in the northwestern part of the Entenschnabel region. After a cross-border re-evaluation of well and seismic data, the Dutch interpretation of the Near base Upper Jurassic and Base Lower Triassic was revised. Abbreviation: NB = Near base.

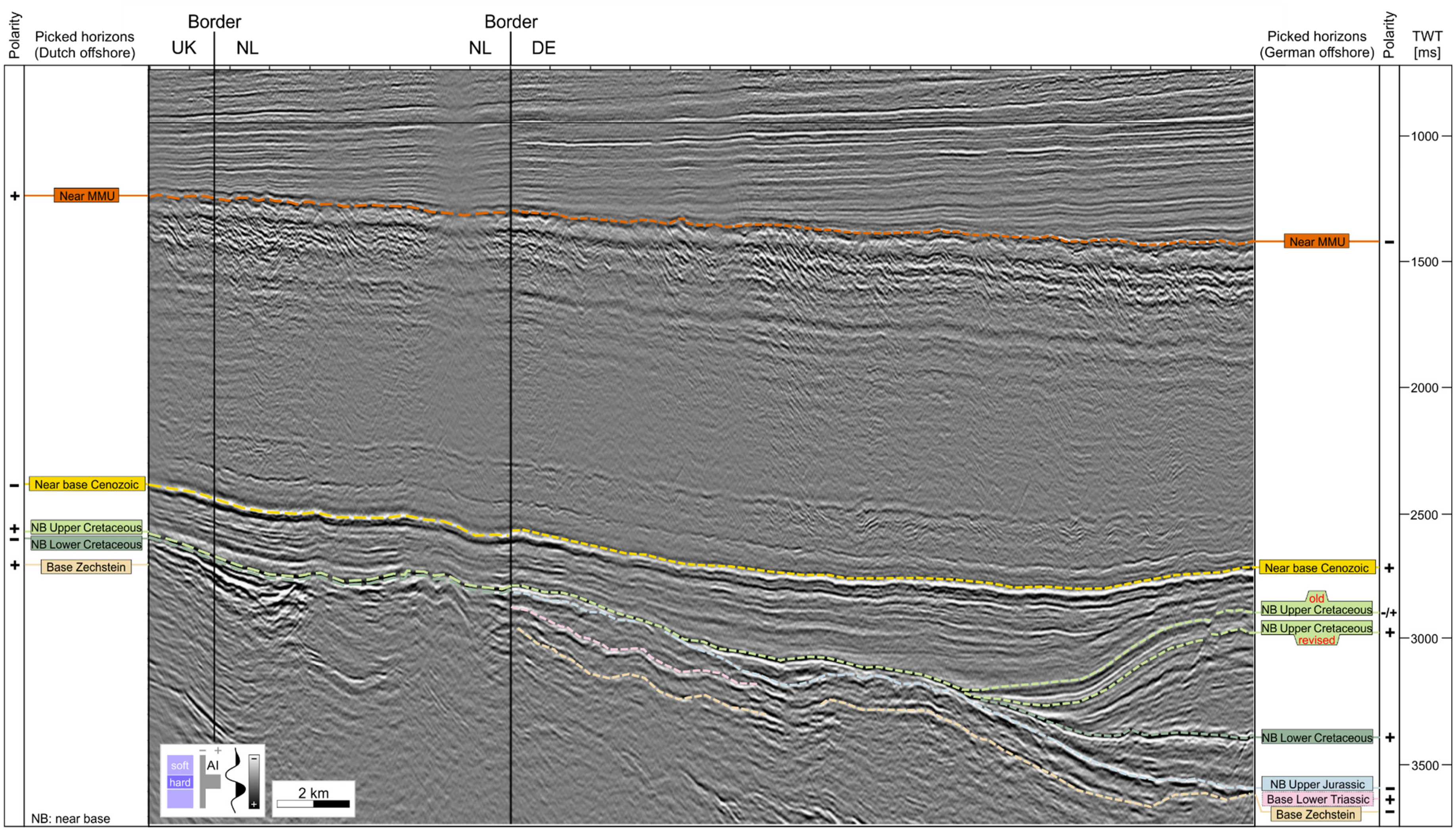

Figure 25: Seismic section across the Dutch Elbow Split High in the SW and the German Outer Rough Basin in the NE (see Figure 13 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. The seismic section is part of the „pog97“ 2D survey, which was acquired on behalf of Amerada Hess Limited in 1997. Abbreviation: NB = Near base.

Dutch well: A08-01

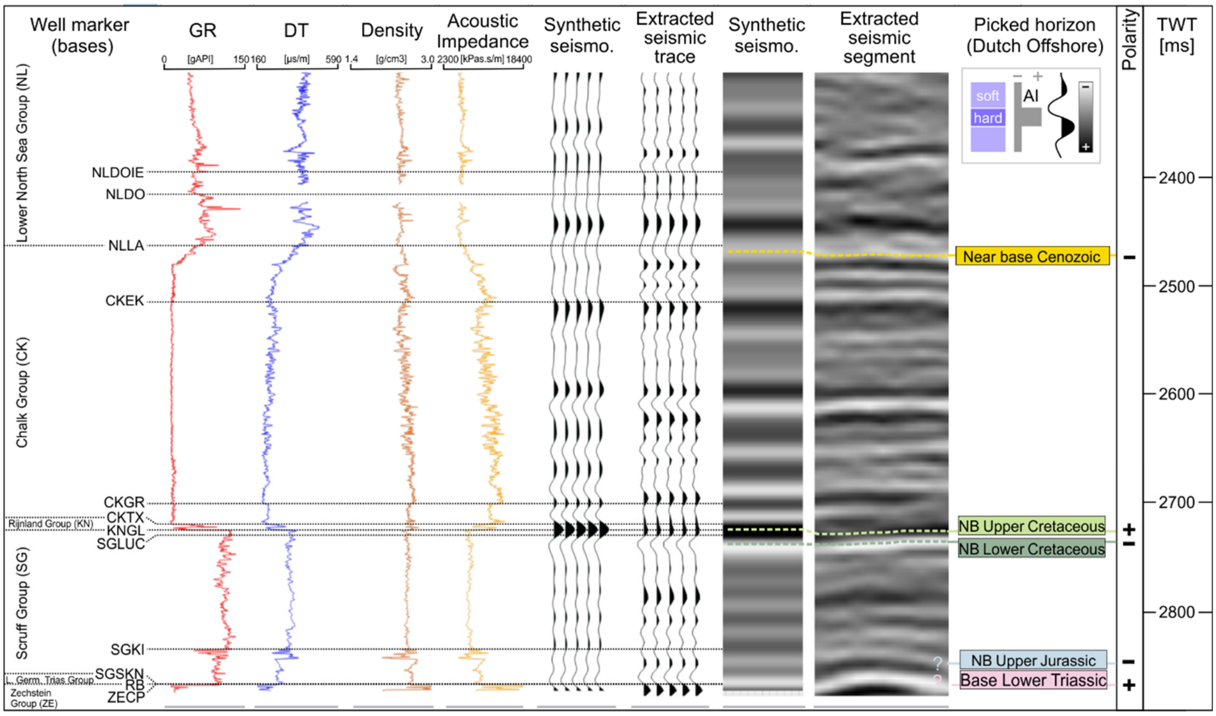

Figure 26: Synthetic seismogram for the Dutch well A08-01 showing the (litho-)stratigraphic position and polarity of horizons mapped in the Dutch North Sea. The well is located southwest to the cross-border seismic section shown in Figure 24. The well-to-seismic tie was established by TNO. Marker abbreviations for the Lower Cretaceous and older strata are according to the Stratigraphic Nomenclature of the Netherlands (TNO-GSN, 2020).

German well: A9-1

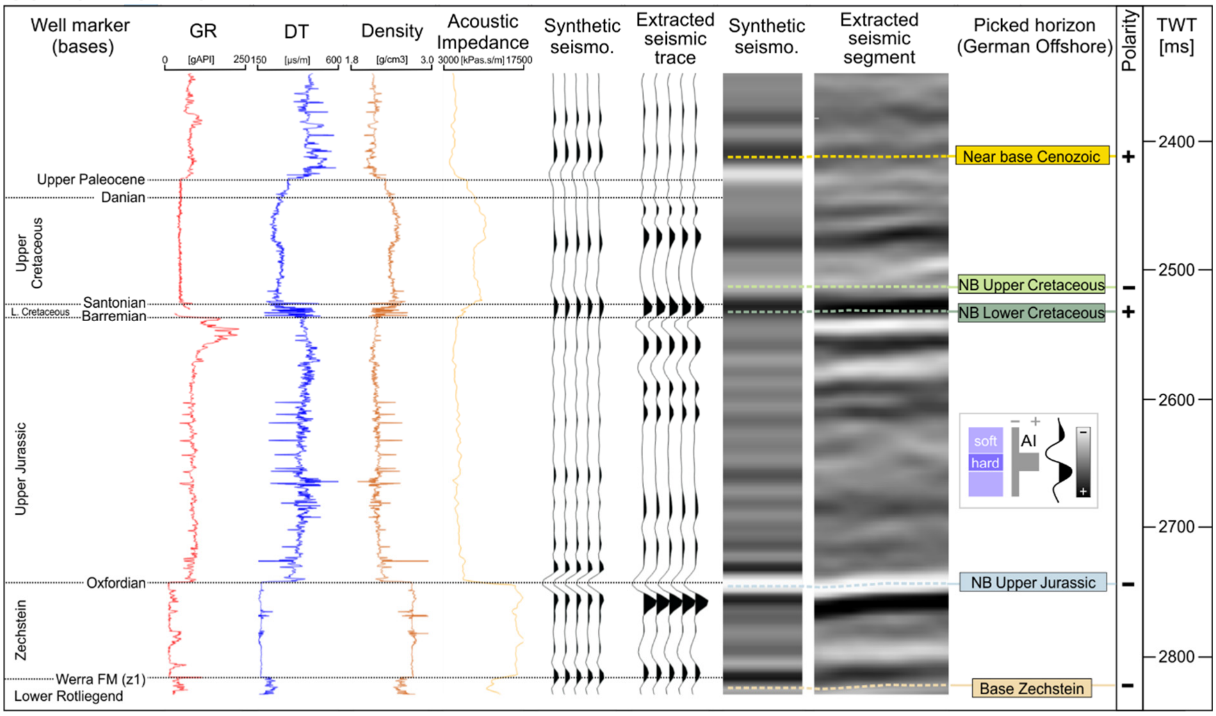

Figure 27: Synthetic seismogram for the German well A9-1 showing the (litho-)stratigraphic position and polarity of horizons mapped in the German North Sea. The well is located north to the cross-border seismic section shown in Figure 24 and was drilled on behalf of BEB Erdgas und Erdöl GmbH in 1975. The well-to-seismic tie was established by BGR.

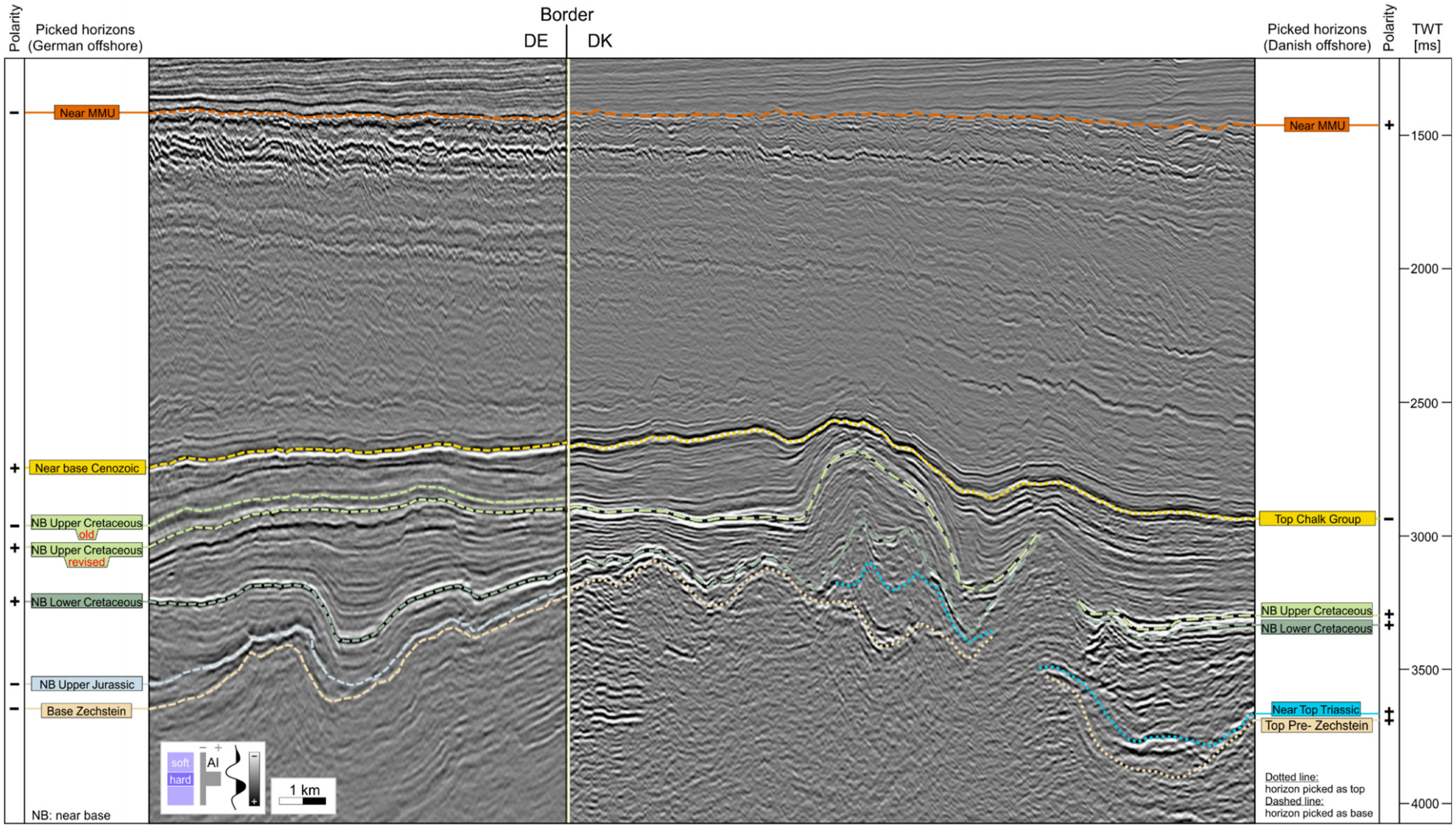

Figure 28: SW-NE orientated seismic section across the Outer Rough Basin, the Mads High and the Heno Plateau (see Figure 13 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. Some seismic reflectors indicated here for the Danish and German sectors differ in their polarity, but differences of more than one reflector were only observed for the "Near base Upper Cretaceous". After a re-evaluation of well and seismic data, the German interpretation was revised. Note that some of the Danish horizons are mapped as top surfaces (dotted lines). The seismic section belongs to the "Angelina MC3D " survey, which was acquired on behalf of Wintershall Noordzee B.V. in 2007 by PGS.

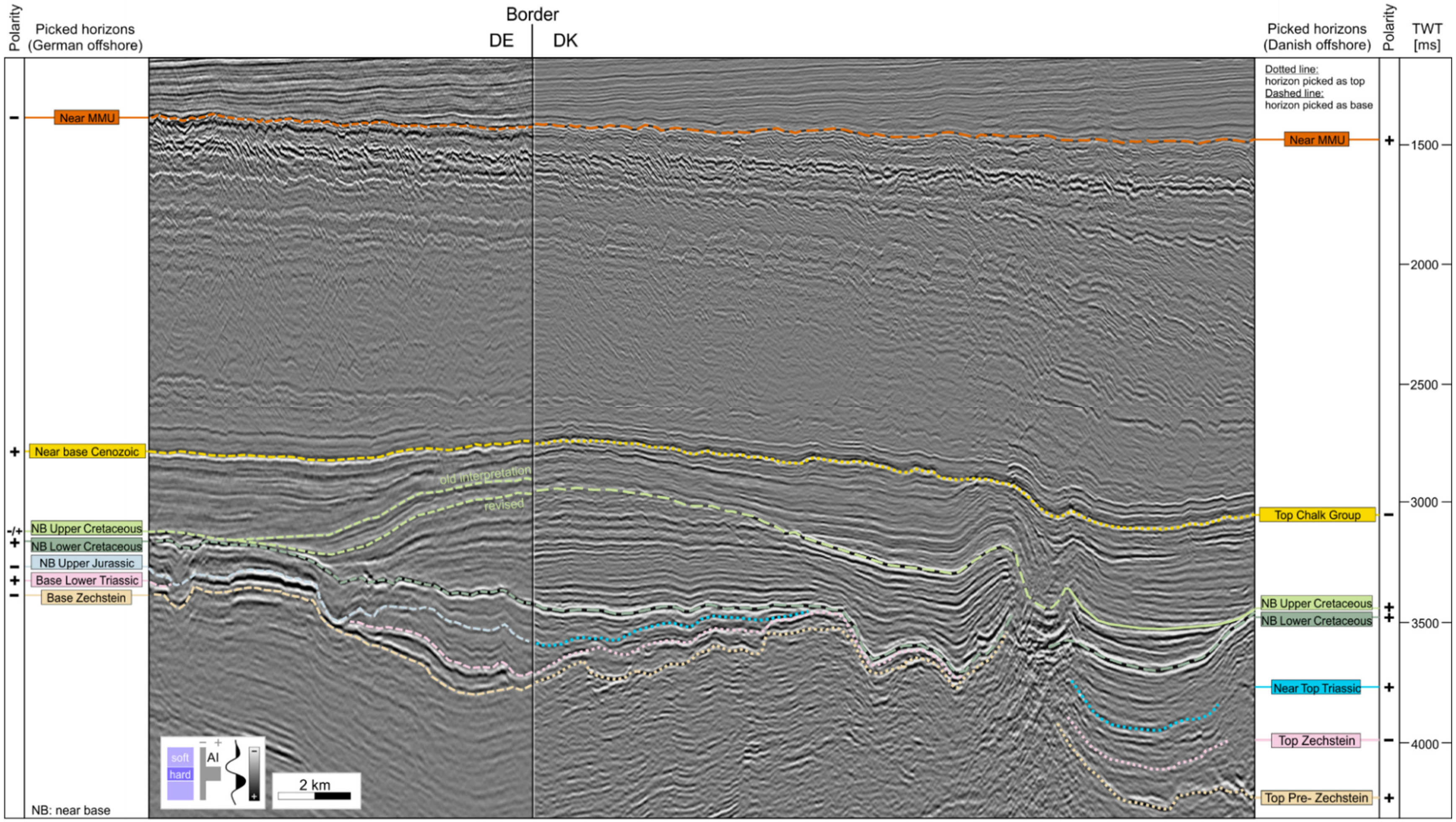

Figure 29: SW-NE orientated seismic section across the Outer Rough Basin (see Figure 13 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. Some seismic reflectors indicated here for the Danish and German sectors differ in their polarity, but differences of more than one reflector were only observed for the "Near base Upper Cretaceous". After a re-evaluation of well and seismic data, the German interpretation was revised. Note that some of the Danish horizons are mapped as top surfaces (dotted lines). The seismic section belongs to the "Angelina MC3D " survey, which was acquired on behalf of Wintershall Noordzee B.V. in 2007 by PGS.

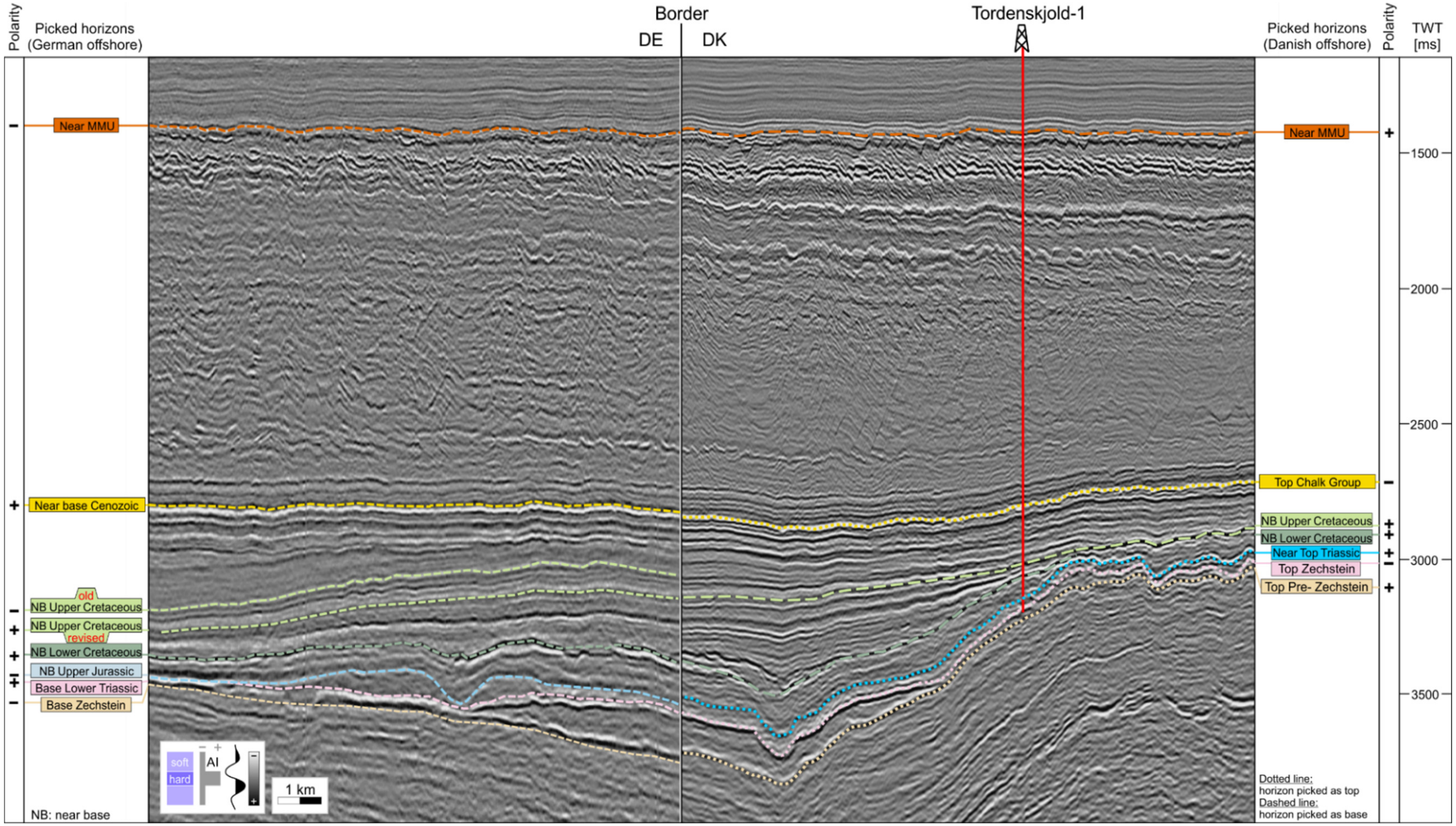

Figure 30: SSE-NNW orientated seismic section across the Outer Rough Basin (see Figure 13 for location). The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are listed at the beginning of this subchapter. Some seismic reflectors indicated here for the Danish and German sectors differ in their polarity, but differences of more than one reflector were only observed for the "Near base Upper Cretaceous". After a re-evaluation of well and seismic data, the German interpretation was revised. Note that some of the Danish horizons are mapped as top surfaces (dotted lines). A well-to-seismic tie is provided for the Danish well Tordenskjold-1 (red vertical line) (see Figure 32). The seismic section belongs to the "Angelina MC3D " survey, which was acquired on behalf of Wintershall Noordzee B.V. in 2007 by PGS. Abbreviation: NB = Near base.

German well: B4-4

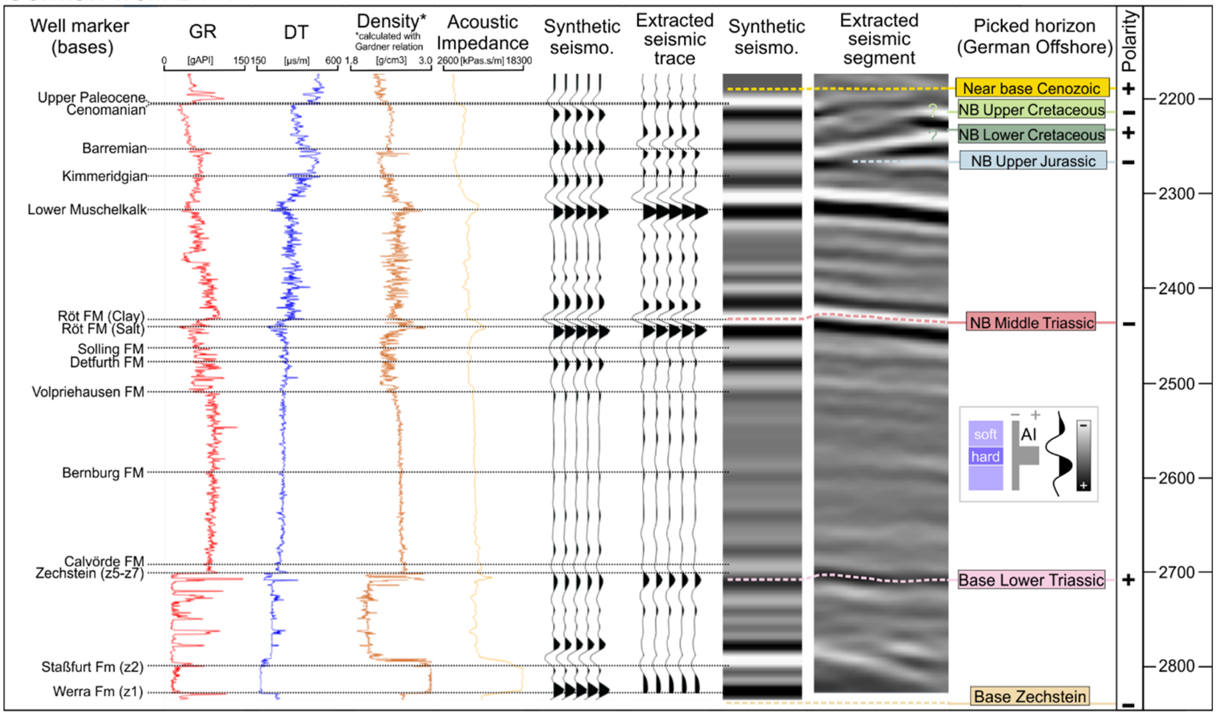

Figure 31: Synthetic seismogram for the German well B4-4 showing the (litho-)stratigraphic position and polarity of horizons mapped in the German North Sea. The well is located south of the cross-border seismic section shown in Figure 28 and was drilled on behalf of BEB Erdgas und Erdöl GmbH in 1992.. The well-to-seismic tie was established by BGR.

Danish well: Tordenskjold-1

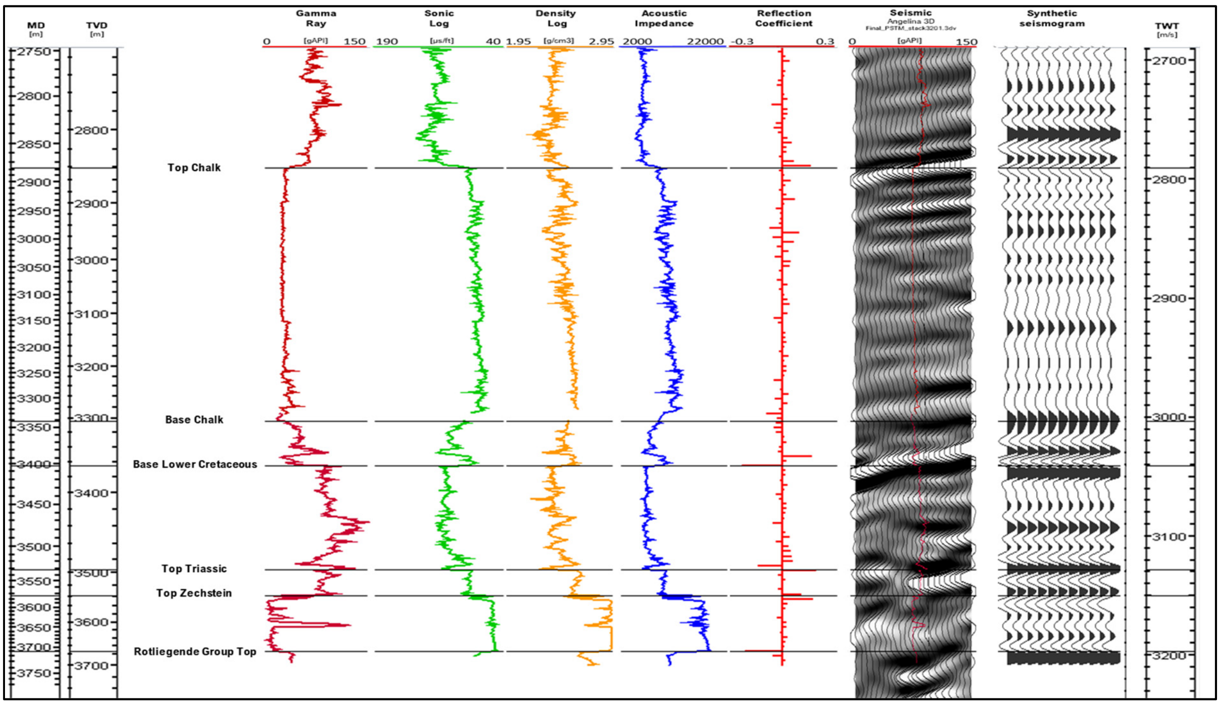

Figure 32: Synthetic seismogram for the Danish well Tordenskjold-1 showing the (litho-)stratigraphic position and polarity of horizons mapped in the Danish North Sea. The well lies on the cross-border seismic section shown in Figure 30. The well-to-seismic tie was established by GEUS.

2.3 Horn Graben region

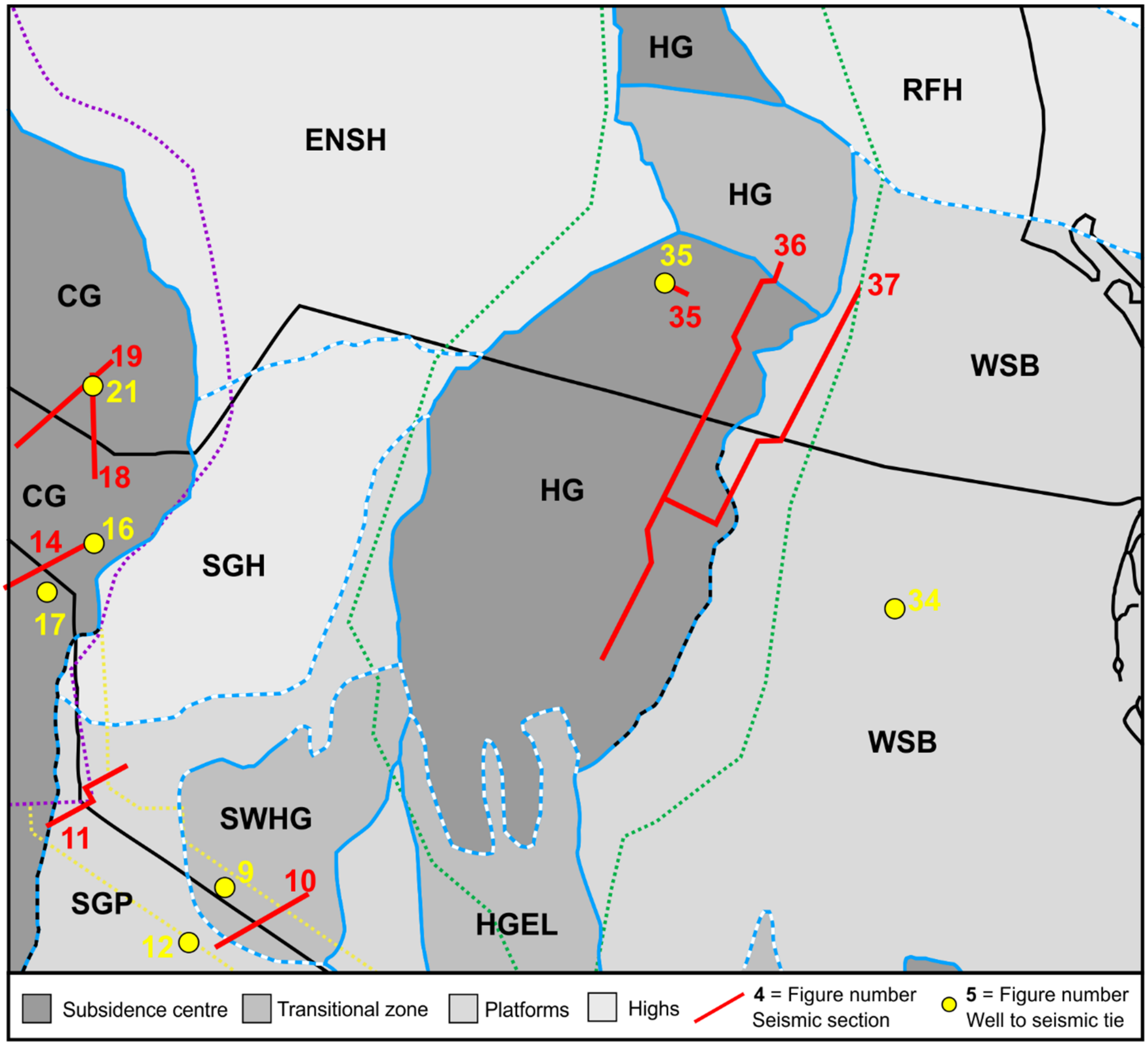

Figure 33: Preliminary map of main structural elements in the Horn Graben region showing the location of the cross-border seismic sections and wells used for generation of seismic synthetics. Uncertain limits of structural elements which are currently under review in the project (see Deliverable 3.8) are indicated by dashed lines. Blue-black dashed lines: uncertain limits due to differing concepts in defining the boundaries, e.g. according to basement structures or distributional pattern. Blue-white dashed lines: boundaries difficult to define due to e.g. diffuse trends in distributional pattern or no clear basement structures. Abbreviations of main structural elements: CG = Central Graben / HG = Horn Graben / WSB = West Schleswig Block / ENSH = East North Sea High / RFH = Ringkøbing-Fyn High / SGH = Schillgrund High / SGP = Schillgrund Platform / SWHG = southwestern branch HG / HGEL = southern branch HG – Ems lineament.

For the working area, here referred to as Horn Graben region, 2 cross-border seismic sections were constructed in order to establish a harmonized seismic stratigraphy. One section was compiled for the central part of the Horn Graben and the other section is located further SE on the West Schleswig Block (Figure 33). The German-Danish Horn Graben is a NNE-SSW-trending Mesozoic rift system cutting perpendicular to the WNW-ESE-trending Ringkøbing-Fyn High (Best et al., 1983). Within the Triassic, the Horn Graben underwent significant rifting and a thick Triassic clastic succession up to 6 km thick was deposited (Kilhams et al., 2018). In contrast, Lower/Middle Jurassic is absent and Upper Jurassic strata is only thinly developed, apart from the northern parts of the Danish Horn Graben and salt-related synclines. Because the Horn Graben is mainly dominated by Triassic deposits, GEUS and BGR have agreed to include additional Triassic horizons for harmonization purposes of structural interpretations. This includes the following horizons:

- Top Grabfeld Formation
- Near base Middle Triassic
- Near base Volpriehausen Formation

For the central German North Sea including the German part of the Horn Graben, BGR has carried out a detail seismic mapping study of the Triassic succession within the framework of the TUNB project. Outside the Horn Graben, the seismic interpretation is supported by numerous wells, whereas for the Horn Graben the interpretation is subject to uncertainties due to limited well control. Only four wells penetrate the Triassic within the Horn Graben and three of them were drilled within the Danish North Sea and detail information were not available to the BGR in the past. The German well, named R-1, furthermore reached only the Keuper, which is also poorly stratigraphically constrained here. Within the framework of the GeoERA project, GEUS started a seismic re-interpretation of the Danish part of the Horn Graben and provided to the BGR the Danish well data for cross-border harmonization. In close cooperation with GEUS, these data were used to evaluate and, if necessary, improved the former interpretations. With respect to the GeoERA horizons, the revised German interpretations largely agree with the results of the Danish re-mapping. Since the Triassic in the Danish Horn Graben has yet not been interpreted in the same detail as in the German North Sea, the revised German interpretation currently represents the best available interpretation and is therefore presented here in the compiled cross-border seismic sections.

German well: S-1

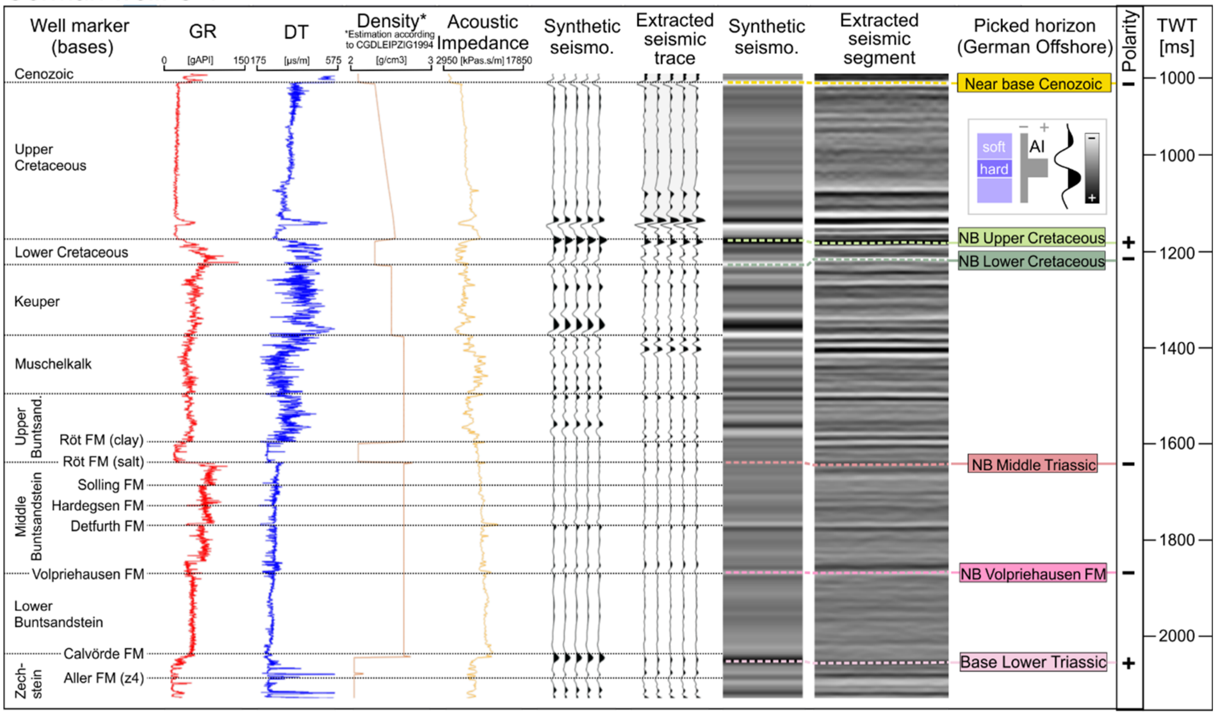

Figure 34: Synthetic seismogram for the German well S-1 showing the (litho-)stratigraphic position and polarity of horizons mapped in the German North Sea (updated interpretation). The well is located south of the cross-border seismic section shown in Figure 28 and was drilled on behalf of BEB Erdgas and Erdöl GmbH in 1967. The well-to-seismic tie was established by BGR.

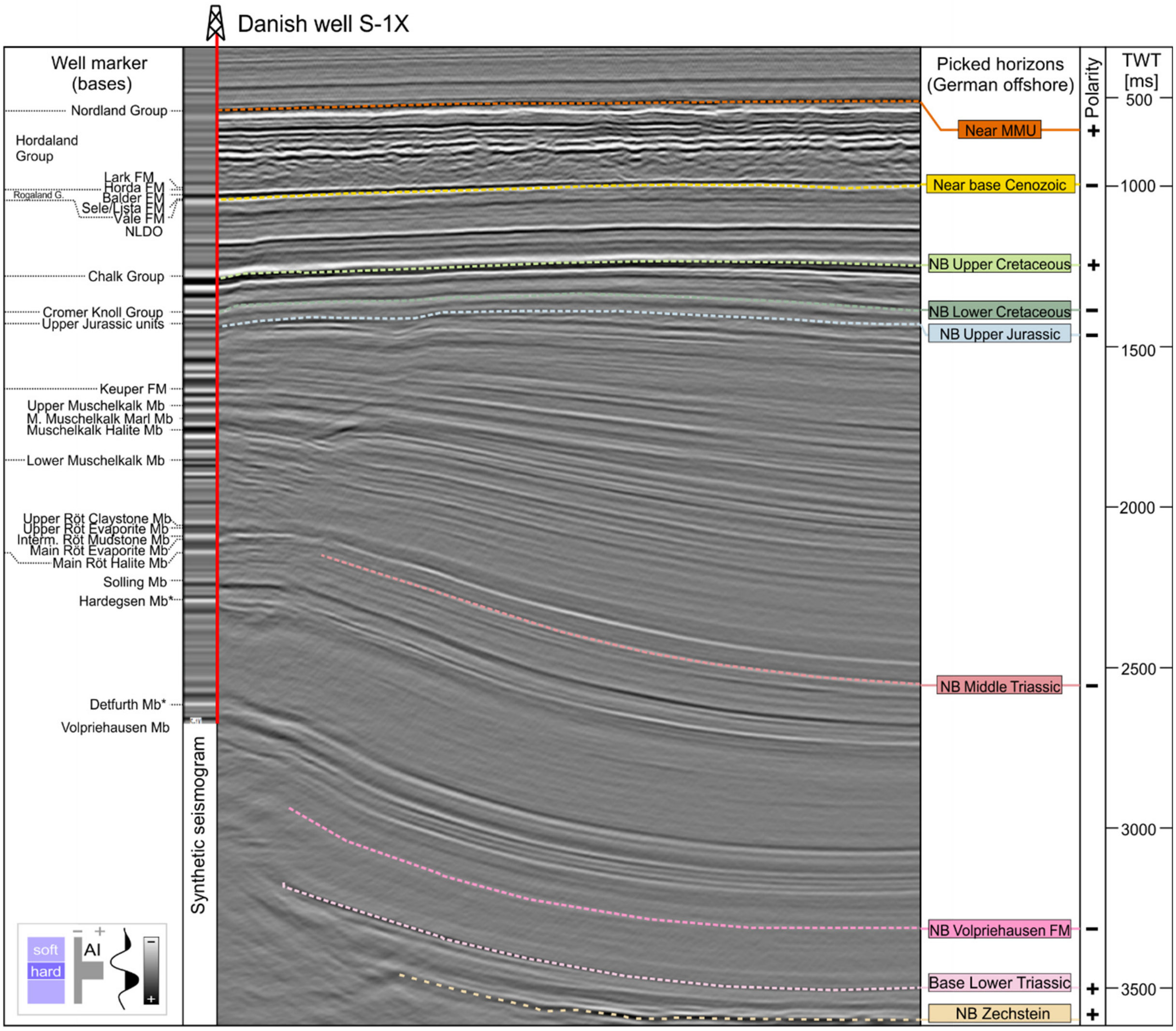

Figure 35: Well to seismic correlation of the Danish well S-1X showing the revised German interpretation. The well is located north of the cross-border seismic section shown in Figure 36. The well-to-seismic tie was established by BGR. Abbreviation: NB = Near base.

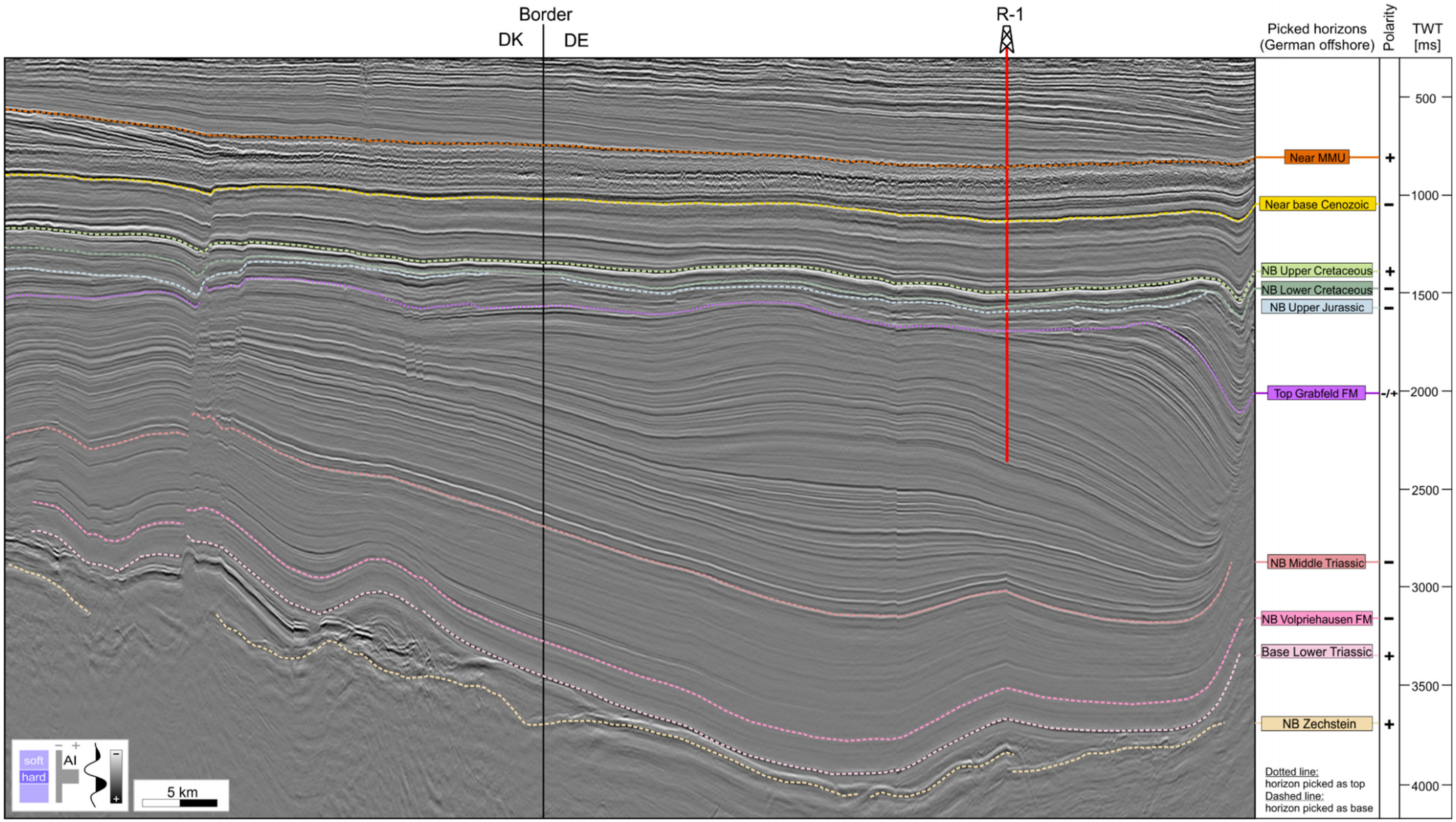

Figure 36: Cross-border seismic section across the central part of the German-Danish Horn Graben (see Figure 33 for location) showing the updated German interpretation. Since the Triassic in the Danish Horn Graben area has yet not been interpreted in the same detail as in the German North Sea, the revised German interpretation currently represents the best available interpretation and is therefore presented here in the compiled cross-border seismic section. The seismic section belongs to the "HG97" 2D survey, which was acquired on behalf of Maersk Oil and Gas A/S in 1997, with ownership passing to Total SE in 2017. Abbreviation: NB = Near base.

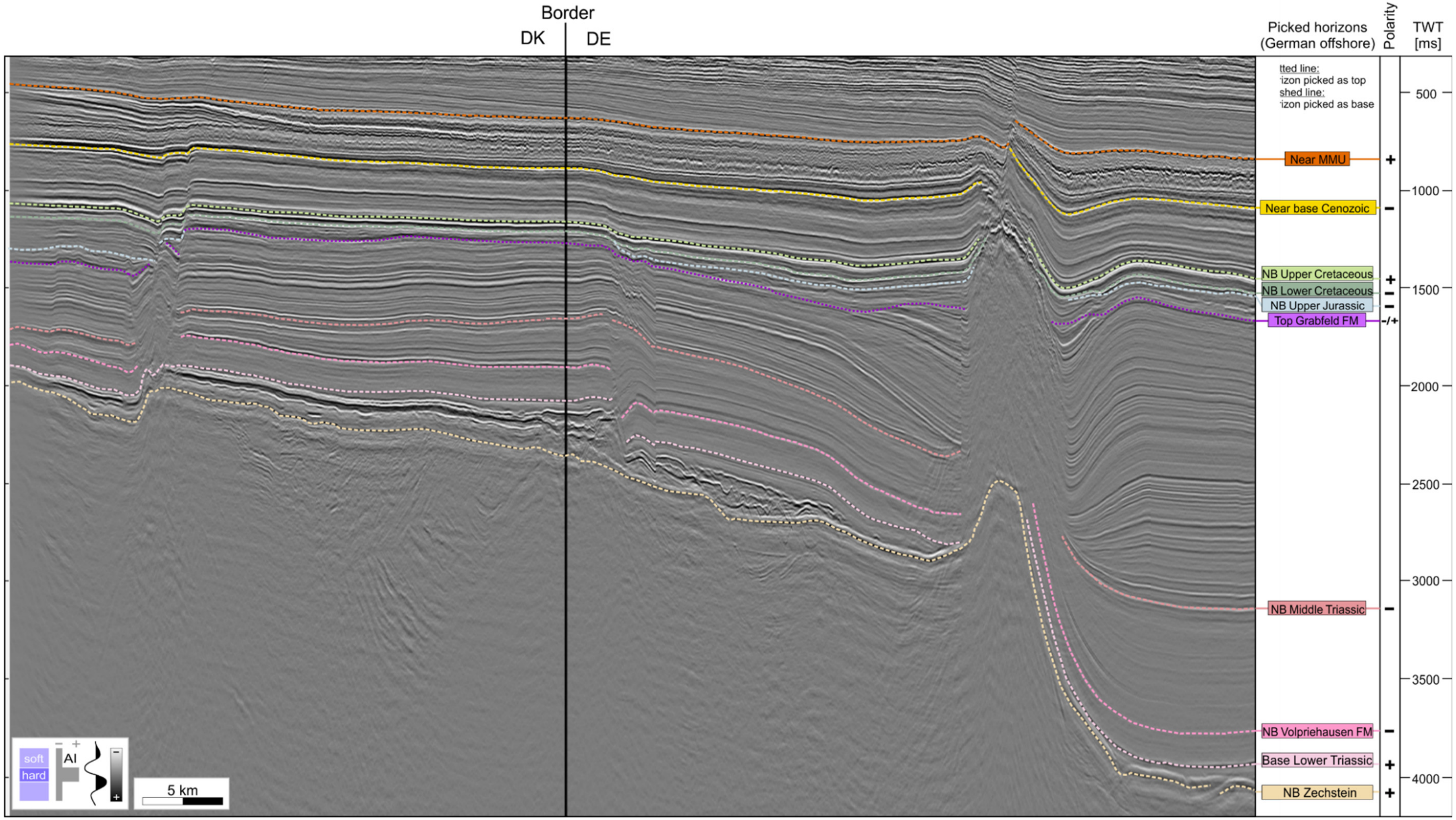

Figure 37: Cross-border seismic section across the eastern flank of the German-Danish Horn Graben (see Figure 33 for location) showing the updated German interpretation. Since the Triassic in the Danish Horn Graben area has yet not been interpreted in the same detail as in the German North Sea, the revised German interpretation currently represents the best available interpretation and is therefore presented here in the compiled cross-border seismic section. The seismic section belongs to the "HG97" 2D survey, which was acquired on behalf of Maersk Oil and Gas A/S in 1997, with ownership passing to Total SE in 2017. Abbreviation: NB = Near base.

3 HORIZON COMPARISON / HARMONIZATION

3.1 (Near) Mid Miocene Unconformity

3.1.1 (Litho-)stratigraphic definition and their differences

The youngest seismic horizon selected for harmonization is the Mid Miocene Unconformity (MMU) which is one of the most prominent seismic features in the Cenozoic sequences of the North Sea Basin. In the German North Sea, it forms the lower (seismic) stratigraphic boundary of the Eridanos delta (Thöle et al., 2014) and in the Dutch offshore sector, it was seismically equated with the base of the Upper North Sea Group (Kombrink et al., 2012). Recent studies, however, have shown that this seismic definition contradicts generally the lithostratigraphic definition and age of the Upper North Sea Group, and the MMU actually does not represent the base of this group (see for details e.g. de Bruin et al., 2015 & Munsterman et al. 2019). According to the Danish lithostratigraphy, the MMU refers to the top of the Hordaland Group (the base of the Nordland Group) sensu Eidvin & Rundberg (2007) and to the base of the fully marine Hodde Formation (Rasmussen et al. 2008, 2010), and is associated with a distinct shift from prograding delta/slope systems to deposition of deeper marine hemipelagic mud.

3.1.2 Comparison of mapped horizon

In the Danish North Sea, the horizon mapped as MMU corresponds to a distinct moderate to high amplitude positive reflection (e.g. Figures 18 and 29). The seismic signature below and above the MMU differs thereby slightly throughout the Danish sector and reveals both conformal, onlapping and downlapping features. Contrary to the Danish interpretation, a negative reflection (trough) which lies directly below the Danish base reflector was mainly mapped and interpreted in the German North Sea as MMU (Table 3). In large parts of the German North Sea, the MMU appears on seismic profiles generally as a prominent downlap surface (Figures 10 and 36), separating largely concordant sediments underneath, from units of the prograding Eridanos delta above. Progradation is evidenced by a series of large-scale, westward dipping clinoforms with amplitudes of up to 400 m (Thöle et al., 2014; 2016). The interpretation of the MMU in the Dutch North Sea is not all consistent in selecting trough or peak (Table 2), but mostly a positive reflection was mapped throughout the Dutch offshore sector. The Dutch MMU agrees thereby partly with the German interpretation, but along several seismic profiles the national interpretations differ and the Dutch MMU lies either above (Figure 10) or below the German reflector (Figures 14 and 24).

Table 2: Summary of differences and similarities for the Mid Miocene Unconformity along the Dutch-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

<table>
<tr><th colspan="9">Near MMU | Comparison of Dutch and German interpretation</th></tr>
<tr><th colspan="2" rowspan="2">Covered region/ structural elements</th><th rowspan="2">Figs.</th><th colspan="2">Mapped reflection type</th><th colspan="2">Picking concept</th><th rowspan="2">Mapped reflector</th><th rowspan="2">Comments</th></tr>
<tr><th>GER</th><th>NL</th><th>GER</th><th>NL</th></tr>
<tr><td rowspan="4">NL-GER offshore border area</td><td>GLP</td><td>4</td><td colspan="2">Trough</td><td colspan="2">Base</td><td>☑</td><td rowspan="8">NL interpretation not all consistent in selecting trough or peak (mostly a peak was mapped)</td></tr>
<tr><td>SGP/ GLP</td><td>7</td><td colspan="2">Trough</td><td colspan="2">Base</td><td>☑</td></tr>
<tr><td>SGP/ SWHG</td><td>10</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇧</td></tr>
<tr><td>SGP</td><td>11</td><td colspan="2">Trough</td><td colspan="2">Base</td><td>☑</td></tr>
<tr><td rowspan="4">Entenschnabel region</td><td rowspan="2">CG</td><td>14</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇩</td></tr>
<tr><td>15</td><td colspan="2">Trough</td><td colspan="2">Base</td><td>☒ ⇩</td></tr>
<tr><td>SG</td><td>24</td><td>Trough</td><td>Peak/ Trough</td><td colspan="2">Base</td><td>☒ ⇩</td></tr>
<tr><td>SG/ ORB</td><td>25</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇩</td></tr>
<tr><td colspan="9">☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◈ = unclear relation | ☐ = non-distribution
⇧ or ⇩ = reflector above or below the German horizon</td></tr>
</table>

Table 3: Summary of differences and similarities for the Mid Miocene Unconformity along the Danish-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

<table>
<tr><th colspan="9">Near MMU | Comparison of Danish and German interpretation</th></tr>
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<tr><th>GER</th><th>DK</th><th>GER</th><th>DK</th></tr>
<tr><td rowspan="7">Entenschnabel region</td><td rowspan="3">CG</td><td>18</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇧</td><td></td></tr>
<tr><td>19</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇧</td><td></td></tr>
<tr><td>20</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇧</td><td></td></tr>
<tr><td>MH/ HP</td><td>23</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇧</td><td></td></tr>
<tr><td>ORB/ HP</td><td>28</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇧</td><td></td></tr>
<tr><td rowspan="2">ORB</td><td>29</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇧</td><td></td></tr>
<tr><td>30</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇧</td><td></td></tr>
<tr><td rowspan="2">Horn Graben region</td><td>HG</td><td>36</td><td colspan="2">Peak</td><td colspan="2">Base</td><td>☑</td><td rowspan="2">For the Horn Graben region, a harmonized DK/GER interpretation is presented in the cross-border sections (see chapter 2.3)</td></tr>
<tr><td>WSB/ HG</td><td>37</td><td colspan="2">Peak</td><td colspan="2">Base</td><td>☑</td></tr>
<tr><td colspan="9">☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◇ = unclear relation | ☐ = non-distribution
⇧ or ⇩ = reflector above or below the German horizon</td></tr>
</table>

3.1.3 Evaluation of differences and intended harmonization

All project partners concur that the MMU generally forms in the study area the lower seismic stratigraphic boundary of a westward prograding depositional system, often referred to as the 'Eridanos delta' (Overeem et al., 2001). Progradation of the 'Eridanos delta' 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 (Michelsen et al., 1998; Thöle et al., 2014). The differences observed between the German and Danish interpretations are generally negligible (differ only by one reflector / TWT ~10 ms) and rely mainly on different decision regarding the most suitable reflector to map. A positive reflection was generally preferred in the Danish offshore sector, since the MMU coincides in the area of the Central Graben with a transition from overpressured Lower Cenozoic deposits to overlying normal pressure Upper Cenozoic deposits (Japsen, 1999). The transition from normally compacted to overpressured deposits is thereby generally associated with a downward decrease in acoustic impedance, and should therefore correspond according to the European polarity convention to a positive reflection (peak).

In the Dutch North Sea, the base of the 'Eridanos delta' is a complex boundary that is a culmination of up-to four unconformities (de Bruin et al., 2015). These are the Savian Unconformity, the early Miocene Unconformity (EMU), the MMU and the Late Miocene Unconformity (LMU), which merge westwards in the Dutch offshore sector into one single reflector (Figure 38). Consequently, the reflector mapped here as MMU should be actually regarded as a Near MMU horizon.

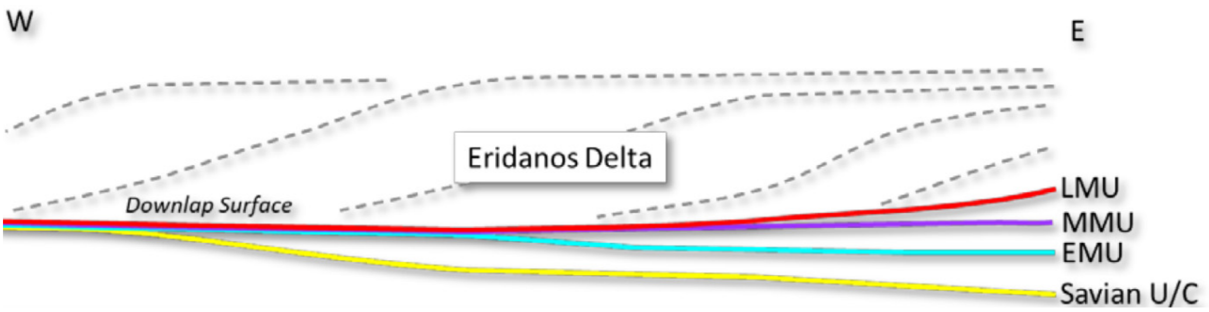

Figure 38: The base of the 'Eridanos delta' comprises of up-to four unconformities. These are the Savian Unconformity, the early Miocene Unconformity (EMU), the Mid Miocene unconformity (MMU) and the Late Miocene Unconformity (LMU) (adapted from Wilpshaar et al., 2020).

Due to the laterally changing sediments above and below these unconformities the seismic response at the base of the 'Eridanos delta' may vary laterally. Furthermore in some areas the MMU and reflectors below are heavily broken due to strong polygonal faulting. This variable character and the converging reflectors makes it difficult to continuously trace the same reflector throughout the Dutch sector and therefore both negative and positive reflections were mapped here as MMU. Although the Dutch interpretation is not all consistent in selecting trough or peak, they differ only negligible from the German MMU, with differences of ±15 ms TWT and an adaption of the Near MMU horizon is therefore generally not required for the planned regional scale harmonization.

Concerning the seismic polarity of the MMU, the Dutch horizon was intended to follow, like in Denmark, mainly a positive reflection, but with a different assumption regarding the cause of the acoustic impedance decrease. Here, it was assumed that the base of the 'Eridanos delta' represents a discordant contact between shallow marine sands/clays above and shallow marine clays below. In general this more sandy to clay transition should correspond to a decrease in acoustic impedance, with European polarity convention corresponding to a peak. A negative reflector (trough) was instead picked in the German sector as MMU, as this reflector can be easily followed over large areas. Furthermore, in certain wells the trough coincides with a prominent peak in the gamma ray which is generally characteristic for the MMU. A reliable conclusion regarding the general seismic polarity of the Near MMU horizon is currently not possible due its complex nature and requires generally a more detailed consideration.

3.2 (Near) base Cenozoic

3.2.1 (Litho-)stratigraphic definition and their differences

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 may therefore be referred to as a Near base Cenozoic reflector.

3.2.2 Comparison of mapped horizon

In the Dutch-German offshore border region, the seismic reflector mapped in the central German North Sea as Near base Cenozoic generally coincides with the interpretation in the Dutch offshore sector. In both countries, the base of the Cenozoic corresponds here to the same negative reflection (e.g. Figures 4 and 10). In the Entenschnabel region, however, the national interpretations differ slightly. Contrary to the interpretation in the central German North Sea, a positive reflection (peak) was interpreted in the German Entenschnabel by Arfai et al. (2014) as Near base Cenozoic, while in the neighboring countries a negative reflection (trough) was picked (Tables 4 and 5). The positive reflector mapped in the German Entenschnabel directly overlies a high amplitude, laterally continuous negative reflection which generally coincides with the base reflector mapped in the neighboring countries (e.g. Figures 14 and 18).

Table 4: Summary of differences and similarities for the Near base Cenozoic along the Dutch-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

<table>
<tr><th colspan="9">Near base Cenozoic | Comparison of Dutch and German interpretation</th></tr>
<tr><th colspan="2" rowspan="2">Covered region/ structural elements</th><th rowspan="2">Figs.</th><th colspan="2">Mapped reflection type</th><th colspan="2">Picking concept</th><th rowspan="2">Mapped reflector</th><th rowspan="2">Comments</th></tr>
<tr><th>GER</th><th>NL</th><th>GER</th><th>NL</th></tr>
<tr><td rowspan="4">NL-GER offshore border area</td><td>GLP</td><td>4</td><td colspan="2">Trough</td><td colspan="2">Base</td><td>☑</td><td></td></tr>
<tr><td>SGP/ GLP</td><td>7</td><td colspan="2">Trough</td><td colspan="2">Base</td><td>☑</td><td></td></tr>
<tr><td>SGP/ SWHG</td><td>10</td><td colspan="2">Trough</td><td colspan="2">Base</td><td>☑</td><td></td></tr>
<tr><td>SGP</td><td>11</td><td colspan="2">Trough</td><td colspan="2">Base</td><td>☑</td><td></td></tr>
<tr><td rowspan="4">Entenschnabel region</td><td rowspan="2">CG</td><td>14</td><td>Peak</td><td>Trough</td><td colspan="2">Base</td><td>☒ ⇩</td><td rowspan="4">During the seismic mapping carried out in the northwestern part of the German North Sea sector (Arfai et al., 2014), it was erroneously assumed that the analyzed seismic were in the American polarity. According this convention an increase in acoustic impedance corresponds to a positive amplitude (peak).</td></tr>
<tr><td>15</td><td>Peak</td><td>Trough</td><td colspan="2">Base</td><td>☒ ⇩</td></tr>
<tr><td>SG</td><td>24</td><td>Peak</td><td>Trough</td><td colspan="2">Base</td><td>☒ ⇩</td></tr>
<tr><td>SG/ ORB</td><td>25</td><td>Peak</td><td>Trough</td><td colspan="2">Base</td><td>☒ ⇩</td></tr>
<tr><td colspan="9">☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◇ = unclear relation | ☐ = non-distribution
⇧ or ⇩ = reflector above or below the German horizon</td></tr>
</table>

Table 5: Summary of differences and similarities for the Near base Cenozoic along the Danish-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

Near base Cenozoic | Comparison of Danish and German interpretation								
Covered region/ structural elements		**Figs.**	**Mapped reflection type**		**Picking concept**		**Mapped reflector**	Comments
			GER	DK	GER	DK		
Entenschnabel region	CG	18	Peak	Trough	Base	Top	☒ ⇩	During the seismic mapping carried out in the northwestern part of the German North Sea sector (Arfai et al., 2014), it was erroneously assumed that the analyzed seismic were in the American polarity. According this convention an increase in acoustic impedance corresponds to a positive amplitude (peak). Near base Cenozoic = Top Chalk in DK
		19	Peak	Trough	Base	Top	☒ ⇩	
		20	Peak	Trough	Base	Top	☒ ⇩	
	MH/ HP	23	Peak	Trough	Base	Top	☒ ⇩	
	ORB/ HP	28	Peak	Trough	Base	Top	☒ ⇩	
	ORB	29	Peak	Trough	Base	Top	☒ ⇩	
		30	Peak	Trough	Base	Top	☒ ⇩	
Horn Graben region	HG	36	Trough		Base		☑	For the Horn Graben region, a harmonized DK/GER interpretation is presented in the cross-border sections (see chapter 2.3).
	WSB/ HG	37	Trough		Base		☑	
☑ = same reflector | ☒ = minor differences | ☒ = considerable differences ◈ = unclear relation | ☐ = non-distribution ⇧ or ⇩ = reflector above or below the German horizon								

3.2.3 *Evaluation of differences and intended harmonization*

All project partners concur that the Near base Cenozoic is generally co-incident with a marked increase in acoustic impedance, reflecting the transition from the low-impedance Cenozoic shales to the high impedance chalk deposits (e.g. Figures 16, 17 and 21), and should therefore correspond according to the European polarity convention to a negative reflection (trough). In the Dutch and Danish North Sea, the Near base Cenozoic horizon was accordingly interpreted in a trough, and with exception of the Entenschnabel also in the remaining German North Sea (Tables 4 and 5). In the northwestern part of the German North Sea, referred to as Entenschnabel, however, it was erroneously assumed during the seismic mapping (Arfai et al., 2014) that the analyzed seismic were in the American polarity. According to this convention an increase in acoustic impedance corresponds to a positive amplitude, and therefore the Near base Cenozoic was interpreted here erroneously in a peak and not a trough. Since observed discrepancies in the nationally mapped reflectors are generally negligible (differ only by one reflector / TWT ~ 20 ms) and rely solely on an incorrect polarity assumption of interpreted seismic data in the German Entenschnabel (Tables 4 and 5), an adaption of the Near base Cenozoic horizon is generally not required for the planned regional-scale harmonization.

3.3 Base Upper Cretaceous

3.3.1 (Litho-)stratigraphic definitions and their differences

The Base Upper Cretaceous is associated in many parts of the study area with a major unconformity (e.g. Figures 15 and 20) and equals in all three countries the base of the Upper Cretaceous/Danian Chalk Group. In the Dutch offshore sector, the base of this group is formed by the Cenomanian Texel Formation (TNO-GSN, 2020), which is stratigraphic equivalent to the Hidra Formation in the Danish sector (Van Buchem et al., 2017). For the area of the German North Sea, a formal lithostratigraphic subdivision of the Upper Cretaceous on formation level, similar to those in the neighboring countries, has not yet been established.

3.3.2 Comparison of mapped horizons

The base of the Chalk Group usually coincides in the study area with a distinct decrease in acoustic impedance, marking the break from high impedance chalk to lower velocity Lower Cretaceous and older formations (e.g. Figures 8, 9 and 12), and should therefore correspond according to the European polarity convention to a positive reflection (peak). In the Dutch and Danish North Sea, the Base Upper Cretaceous horizon was accordingly interpreted in a peak, and with exception of the Entenschnabel also in the remaining German North Sea (Tables 6 and 7). In the so-called German Entenschnabel, however, it was erroneously assumed during the seismic mapping (Arfai et al., 2014) that the analyzed seismic were in the American polarity. According to this convention a decrease in acoustic impedance corresponds to a negative amplitude, and therefore the Base Upper Cretaceous was interpreted here mainly in a trough.
Despite the different polarity of the mapped reflectors, the national interpretations of the Base Upper Cretaceous differ only slightly in the area of the Central Graben (Figures 14 and 18). Along the cross-border seismic sections through the Outer Rough Basin (Figures 28, 29 and 30), however, marked discrepancies between the national interpretations became apparent. Here, the Base Upper Cretaceous mapped so far by Arfai et al. (2014) in the German sector lies up to 100 ms (TWT) above the Danish interpretation (Figure 30). In a locally restricted area of the Step Graben, close to the cross-border seismic section shown in Figure 24, the German base reflector also differs up to 120 ms from the Dutch interpretation. After a re-evaluation of well and seismic data, however, the German interpretation was revised in this areas following the Danish and Dutch interpretations (Tables 6 and 7; see for details Deliverable 3.6).

Table 6: Summary of differences and similarities for the Base Upper Cretaceous along the Dutch-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

Base Upper Cretaceous | Comparison of Dutch and German interpretation								
Covered region/ structural elements		**Figs.**	**Mapped reflection type**		**Picking concept**		**Mapped reflector**	Comments
			GER	NL	GER	NL		
NL-GER offshore border area	GLP	4	Peak		Base		☑	
	SGP/ GLP	7	Peak		Base		☑	
	SGP/ SWHG	10	Peak		Base		☑	
	SGP	11	Peak		Base		☑	
Entenschnabel region	CG	14	Trough	Peak	Base		☒ ⇩	During the seismic mapping carried out in the northwestern part of the German North Sea sector (Arfai et al., 2014), it was erroneously assumed that the analyzed seismic were in the American polarity. According this convention a decrease in acoustic impedance corresponds to a negative amplitude (trough).
		15	Trough	Peak	Base		☒ ⇧	
	SG	24	Trough	Peak	Base		☒ ⇩ (old)	Initially considerable differences between NL and GER interpretation (close to the seismic section)
			Peak		Base		☑ (revised)	After a re-evaluation of well and seismic data, the German interpretation was revised (see for detail D3.6)
	SG/ ORB	25	Trough/ Peak	Peak	Base		(☑)	No differences at the NL/GER border, but between DK and GER interpretation in the ORB.
			Peak		Base		☑ (revised)	After a re-evaluation of well and seismic data, the German interpretation was revised in the ORB (see for details D3.6).

☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◇ = unclear relation | ☐ = non-distribution
⇧ or ⇩ = reflector above or below the German horizon

Table 7: Summary of differences and similarities for the Base Upper Cretaceous along the Danish-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

<table>
<tr><th colspan="9">Base Upper Cretaceous | Comparison of Danish and German interpretation</th></tr>
<tr><th colspan="2" rowspan="2">Covered region/ structural elements</th><th rowspan="2">Figs.</th><th colspan="2">Mapped reflection type</th><th colspan="2">Picking concept</th><th rowspan="2">Mapped reflector</th><th rowspan="2">Comments</th></tr>
<tr><th>GER</th><th>DK</th><th>GER</th><th>DK</th></tr>
<tr><td rowspan="10">Entenschnabel region</td><td rowspan="3">CG</td><td>18</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇩</td><td rowspan="4">During the seismic mapping carried out in the northwestern part of the German North Sea sector (Arfai et al., 2014), it was erroneously assumed that the analyzed seismic were in the American polarity. According this convention an increase in acoustic impedance corresponds to a positive amplitude (peak).

GER interpretation not all consistent in selecting trough or peak (mostly a trough was mapped)</td></tr>
<tr><td>19</td><td>Peak/ Trough</td><td>Peak</td><td colspan="2">Base</td><td>☑/☒</td></tr>
<tr><td>20</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇧</td></tr>
<tr><td>MH/ HP</td><td>23</td><td colspan="2">Peak</td><td colspan="2">Base</td><td>☑</td></tr>
<tr><td rowspan="2">ORB/HP</td><td rowspan="2">28</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇩
(old)</td><td rowspan="6">Initially considerable differences between DK and GER interpretation
in the area of the ORB

After a re-evaluation of well and seismic data, the German interpretation was revised
(see for details D3.6)</td></tr>
<tr><td colspan="2">Peak</td><td colspan="2">Base</td><td>☑
(revised)</td></tr>
<tr><td rowspan="4">ORB</td><td rowspan="2">29</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇩
(old)</td></tr>
<tr><td colspan="2">Peak</td><td colspan="2">Base</td><td>☑
(revised)</td></tr>
<tr><td rowspan="2">30</td><td>Trough</td><td>Peak</td><td colspan="2">Base</td><td>☒ ⇩
(old)</td></tr>
<tr><td colspan="2">Peak</td><td colspan="2">Base</td><td>☑
(revised)</td></tr>
<tr><td rowspan="2">Horn Graben region</td><td>HG</td><td>36</td><td colspan="2">Peak</td><td colspan="2">Base</td><td>☑</td><td rowspan="2">For the Horn Graben region, a harmonized DK/GER interpretation is presented in the cross-border sections
(see chapter 2.3).</td></tr>
<tr><td>WSB/ HG</td><td>37</td><td colspan="2">Peak</td><td colspan="2">Base</td><td>☑</td></tr>
<tr><td colspan="9">☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◇ = unclear relation | ☐ = non-distribution
⇧ or ⇩ = reflector above or below the German horizon</td></tr>
</table>

3.3.3 *Evaluation of differences and intended harmonization*

An adaptation of the national seismic stratigraphic concepts for the Base Upper Cretaceous is generally not required, since all project partners concur that the base of the Upper Cretaceous generally coincides in the study area with a marked decrease in acoustic impedance, and should therefore correspond according to the European polarity convention to a positive reflection (peak). Furthermore, except for the Outer Rough Basin and a limited area along the Step Graben, the discrepancies observed in the nationally mapped reflectors are usually negligible (differ only by one reflector) and rely solely on an incorrect polarity assumption of interpreted seismic data in the German Entenschnabel rather than on a disparate seismic stratigraphic concept. The marked differences identified in the northern part of the Entenschnabel are further mainly related to interpretation uncertainties in the German sector and also not to general differences in the seismic mapping concept. In the German part of the Outer Rough Basin, for example, the transition from the Upper Cretaceous to Lower Cretaceous is generally difficult to discern in the seismic due to a fairly similar reflector characteristic close to the Upper Cretaceous/Lower Cretaceous boundary (Figure 30) and since the stratigraphic control is limited in this part of the German sector as well, the Base Upper Cretaceous could only be mapped here until now with uncertainties. The necessary alignment of the German Base Upper Cretaceous to the interpretations in the neighboring countries was, however, achieved in the course of the current project (see for details Deliverable 3.6).

3.4 (Near) base Lower Cretaceous

3.4.1 *(Litho-)stratigraphic definitions and their differences*

In the Danish sector of the North Sea, the lithostratigraphic subdivision of the Lower Cretaceous follows the lithostratigraphy of Jensen et al. (1986), Van Buchem et al. (2017) and GEUS (2017; the CRETSYS project). The base of the Lower Cretaceous is taken here as the interface between the Cromer Knoll Group and the Farsund Formation, and corresponds in the Danish Central Graben to the Base Cretaceous Unconformity (BCU). In the Dutch offshore sector, the horizon mapped as Base Lower Cretaceous is equated with the base of the Rijnland Group (Kombrink et al., 2012), which comprises the Holland Formation and the Vlieland subgroup (TNO-GSN, 2020). 'Wealden' type rocks of earliest Lower Cretaceous (Ryazanian) age are generally not included in the Dutch Rijnland Group and the Danish Cromer Knoll Group, and therefore their bases are not the actual base of the Cretaceous and should be regarded as Near base Lower Cretaceous horizons. In the central German North Sea (outside the German Entenschnabel), the horizon mapped as Base Lower Cretaceous generally follows the stratigraphic definition of the Geotectonic atlas (Baldschuhn et al., 2001), according to which Wealden deposits are also assign to the Upper Jurassic units. In the northwestern part of the German North Sea sector, referred to as Entenschnabel, the horizon mapped by Arfai et al. (2014) as Base Lower Cretaceous, however, was intended to follow the base of the Wealden when present. Due to insufficient biostratigraphic information in the German sector, however, the assigned stratigraphic position can be regarded as uncertain.

3.4.2 Comparison of mapped horizon

In the Dutch-German offshore border region, the seismic reflector mapped in the Dutch sector as Near base Lower Cretaceous generally coincides with the German interpretation (Table 8). In both countries, the Base Lower Cretaceous corresponds here to the same negative reflection (trough), often recognized as a distinct angular unconformity (Figures 7 and 10). According to the compiled synthetics shown in Figures 6, 8 and 9, the negative reflection results from a marked increase in acoustic impedance, reflecting the transition from low-impedance Lower Cretaceous sediments to truncated higher impedance Triassic deposits. In the Entenschnabel region, however, there are considerable differences between the two national interpretations. In the Central Graben, for example, the base reflector mapped so far in the Dutch sector lies about 150 ms (TWT) above the German interpretation (Figure 14). Furthermore, the polarity of the mapped reflectors differs. As in the German-Dutch offshore border region, the Dutch Base Lower Cretaceous corresponds here to a negative reflection, whereas a positive reflector (peak) was mapped in the German Entenschnabel region (Arfai et al., 2014). This positive reflection generally equals the Danish Base Lower Cretaceous (Table 9), and according to compiled synthetics (Figures 16 and 17) the Lower Cretaceous rests here upon Upper Jurassic deposits which are commonly characterized by a lower acoustic impedance than the overlying strata. Consequently, the base of the Lower Cretaceous should generally correspond according to the European polarity convention to a peak when low-impedance Jurassic deposits are present, and after a re-evaluation of well and seismic data, the Dutch interpretation was therefore in the area of the Central Graben accordingly revised (Figure 14; see for details Deliverable 3.6).

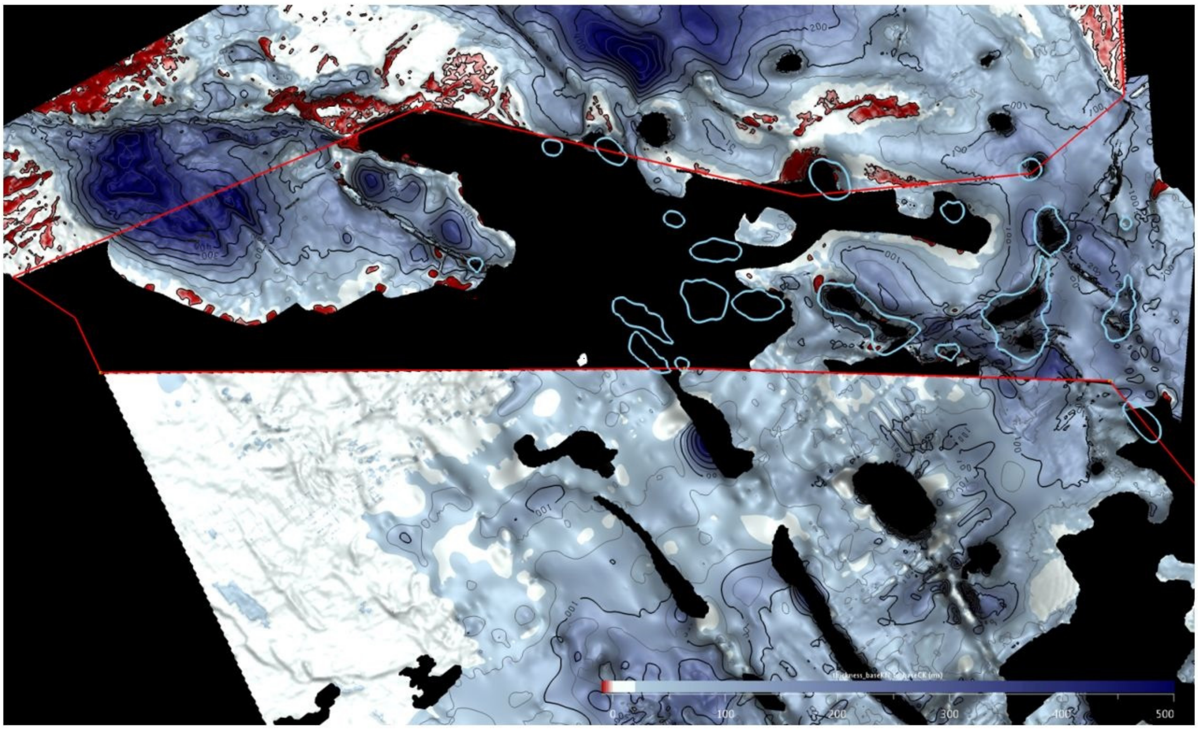

Figure 39: Thickness map of the Lower Cretaceous in the Entenschnabel region. Note the discrepancies between the distributional pattern of the Lower Cretaceous in the German offshore and neighboring countries. Color code: white = thickness between 0-25 m, light blue (> 25 m) to dark blue (500 m), red = negative thickness due to overlapping grids.

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 based on existing horizon grids of the Lower Cretaceous in the German sector with those in the Dutch North Sea (Figure 39). Except for the Outer Rough Basin, no Lower Cretaceous is generally present in the northern part of the German Entenschnabel, whereas in the Dutch sector 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 absent or below seismic resolution (e.g. Figure 25). 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. In the northern Dutch offshore, however, 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.

Table 8: Summary of differences and similarities for the Near base Lower Cretaceous along the Dutch-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

Near base Lower Cretaceous | Comparison of Dutch and German interpretation								
Covered region/ structural elements		**Figs.**	**Mapped reflection type**		**Picking concept**		**Mapped reflector**	Comments
			GER	NL	GER	NL		
NL-GER offshore border area	GLP	4	Trough		Base		☑	
	SGP/ GLP	7	Trough		Base		☑	
	SGP/ SWHG	10	Trough		Base		☑	
	SGP	11	Trough		Base		☒ ⇧	Minor differences due to structural complexity along the flank of the Central Graben
Entenschnabel region	CG	14	Peak	Trough	Base		☒ ⇧ (old)	Initially considerable differences between NL and GER interpretation
			Peak		Base		☑ (revised)	After a re-evaluation of well and seismic data, the Dutch interpretation was revised (see for details D3.6).
		15	Peak	Trough	Base		◇?	No Lower Cretaceous strata in the vicinity of the NL-GER border
	SG	24		Trough	Base		☐ (DE)	Different picking concepts: NL: thin lower Cretaceous below Base Upper Cretaceous (locally confirmed by wells) GER: no Lower Cretaceous below Base Upper Cretaceous in the vicinity of the NL/GER border (seismically not discernible)
	SG/ ORB	25	Peak	Trough	Base		☒	

☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◇? = unclear relation | ☐ = non-distribution
⇧ or ⇩ = reflector above or below the German horizon

Table 9: Summary of differences and similarities for the Near base Lower Cretaceous along the Danish-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

<table>
<tr><th colspan="9">Near base Lower Cretaceous | Comparison of Danish and German interpretation</th></tr>
<tr><th colspan="2" rowspan="2">Covered region/ structural elements</th><th rowspan="2">Figs.</th><th colspan="2">Mapped reflection type</th><th colspan="2">Picking concept</th><th rowspan="2">Mapped reflector</th><th rowspan="2">Comments</th></tr>
<tr><th>GER</th><th>DK</th><th>GER</th><th>DK</th></tr>
<tr><td rowspan="7">Entenschnabel region</td><td rowspan="3">CG</td><td>18</td><td colspan="2">Peak</td><td colspan="2">Base</td><td>☑</td><td></td></tr>
<tr><td>19</td><td colspan="2">Peak</td><td colspan="2">Base</td><td>☑</td><td></td></tr>
<tr><td>20</td><td></td><td>Peak</td><td colspan="2">Base</td><td>☐ (GER)</td><td rowspan="2">Lower Cretaceous absent on the German side / truncated by the Base Upper Cretaceous close to the DK-GER border</td></tr>
<tr><td>MH/ HP</td><td>23</td><td></td><td>Peak</td><td colspan="2">Base</td><td>☐ (GER)</td></tr>
<tr><td>ORB/ HP</td><td>28</td><td colspan="2">Peak</td><td colspan="2">Base</td><td>☑</td><td></td></tr>
<tr><td rowspan="2">ORB</td><td>29</td><td colspan="2">Peak</td><td colspan="2">Base</td><td>☑</td><td></td></tr>
<tr><td>30</td><td colspan="2">Peak</td><td colspan="2">Base</td><td>☑</td><td></td></tr>
<tr><td rowspan="2">Horn Graben region</td><td>HG</td><td>36</td><td colspan="2">Trough</td><td colspan="2">Base</td><td>☑</td><td rowspan="2">For the Horn Graben region, a harmonized DK/GER interpretation is presented in the cross-border sections.</td></tr>
<tr><td>WSB/ HG</td><td>37</td><td colspan="2">Trough</td><td colspan="2">Base</td><td>☑</td></tr>
<tr><td colspan="9">☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◇ = unclear relation | ☐ = non-distribution
⇧ or ⇩ = reflector above or below the German horizon</td></tr>
</table>

3.4.3 Evaluation of differences and intended harmonization

When harmonizing the seismic stratigraphic concept for the Near base Lower Cretaceous several aspects have to be considered, including lateral changes in depositional facies and subcropping formations that may lead to changing acoustic characteristics in neighboring countries. The base of the Lower Cretaceous may vary in lithology throughout the entire study area from marine sandstones, claystone to more marly composition (see for details Deliverable D3.3 "Harmonized stratigraphic chart for the NL-GER-DK North Sea area"). Furthermore, in many areas the Near base Lower Cretaceous corresponds to a distinct unconformity with variable lithological units below and as such a variable reflection can be expected.

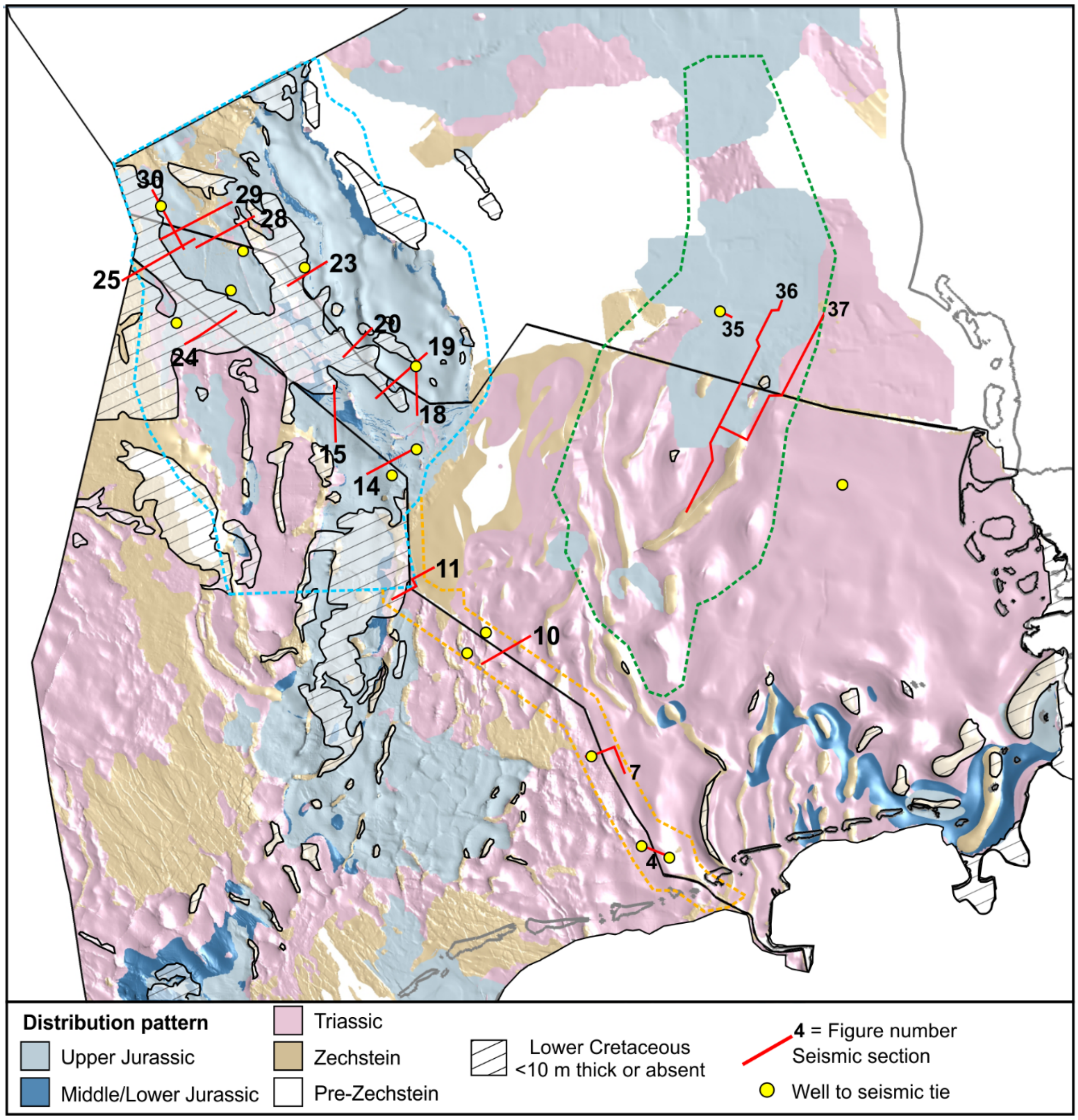

Figure 40: Subcrop map of the Near base Lower Cretaceous in the Dutch, German and Danish North Sea sectors. Distribution patterns of the subcropping units have been compiled from numerous geological models, mainly provided by the participating GSOs. Note that the distribution of the Upper Jurassic in the Horn Graben is only a rough estimation. Dashed lines indicate the working areas defined in the North Sea for the 3DGEO-EU WP3 (orange: Dutch-German offshore border area / blue: Entenschnabel region / green: Horn Graben region).

Figure 40 shows a subcrop map for the Near base Lower Cretaceous. If Triassic (or older) formations are subcropping, such as in the Dutch-German offshore border region, the Near base Lower Cretaceous coincides according to the compiled synthetics (Figures 6, 8 and 9) with an increase in acoustic impedance. Accordingly, the Base Lower Cretaceous should be generally picked in these areas in a trough (negative reflection). In contrast, in areas where Lower Cretaceous rest upon Upper Jurassic deposits, such as in large parts of the Entenschnabel region (Figure 40), a decrease in acoustic impedance can be expected (see synthetics in Figures 16 and 17). Therefore, a positive reflection (peak) should be mapped in this regions as Near base Lower Cretaceous. If Lower Jurassic is subcropping, the acoustic impedance contrast may vary, depending on Lower Cretaceous lithology and porosity and Lower Jurassic lithology and depth of burial.
A cross-border harmonized seismic stratigraphic concept for the Near base Lower Cretaceous should take into account such lateral changes in acoustic impedance. Except for the Dutch part of the Entenschnabel region, the seismic polarity of the currently mapped seismic reflectors generally coincides with the impedance contrast expected for the different subcropping units and an adaption of the Base Lower Cretaceous is generally not required here. For example, in the Dutch-German offshore border region where Jurassic sediments are absent and Triassic (or older) formations are subcropping, the Base Lower Cretaceous was accordingly to the expected acoustic impedance increase mapped here in both offshore sectors in a trough (Table 8). A decrease in acoustic impedance can be expected for large parts of the Danish and German Central Graben region as Lower Cretaceous overlies here mainly Upper Jurassic deposits (Figure 40), and in both countries the Near base Lower Cretaceous was accordingly mapped in a peak (Table 9). In the area of the Dutch Central Graben, the base reflector mapped so far, however, corresponded to a negative reflection (trough), although Lower Cretaceous deposits largely rests here on low-impedance Upper Jurassic as well. For harmonization purposes and due to the impedance contrast expected, the Near base Lower Cretaceous should be revised in these areas of the Dutch sector. The necessary alignment was already achieved for certain parts of the Dutch Central Graben in the course of the current project (see for details Deliverable 3.6).

3.5 (Near) base Upper Jurassic

3.5.1 (Litho-)stratigraphic definitions and their differences

In the Danish North Sea sector, the Upper Jurassic is associated with a transgressive period submerging structural elements bounding the half graben developed along the Coffee Soil Fault. In the basin center, the Base Upper Jurassic represents the transition from clastic dominated shallow marine deposits (Lulu Formation / Middle Graben Formation) to the clay-rich Lola Formation of Oxfordian age (Figure 41). On the Heno Plateau/Gertrud Plateau, the Base Upper Jurassic represents the base of the transgressive Lower Kimmeridgian Heno Formation overlying Triassic/Permian successions. In the Outer Rough Basin, the base Upper Jurassic represents the base of the Lower to Middle Volgian “Outer Rough Sand” overlying Triassic to Permian successions. On the Ringkøbing Fyn High, Upper Jurassic is absent and in the Horn Graben where only a thin Jurassic package is found the Base Upper Jurassic resembles the Top Triassic.

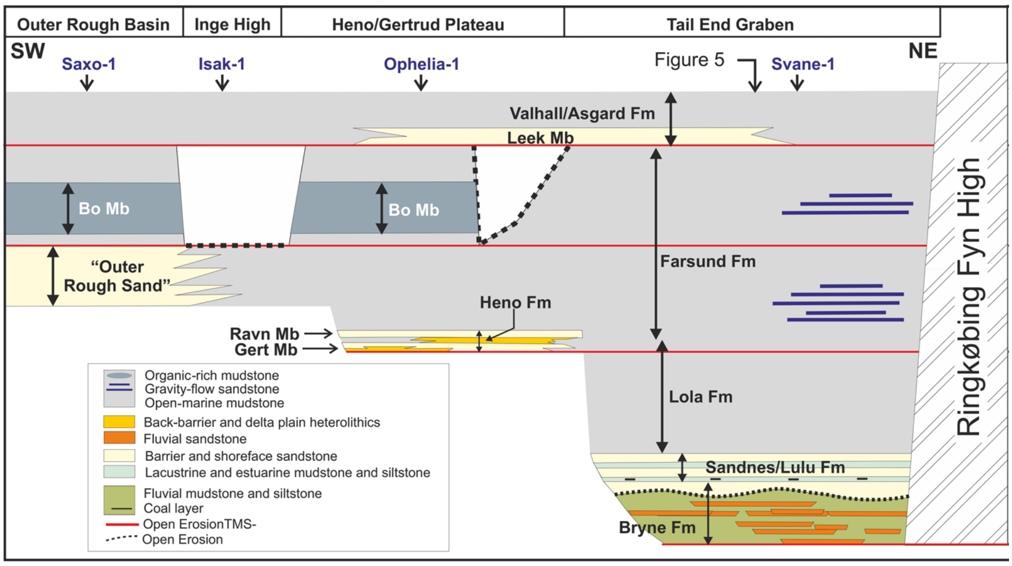

Figure 41: Lithostratigraphy of the Upper Jurassic and Lower Cretaceous in the area of the Danish Central Graben. (Verreussel et al., 2018).

In the northern Dutch offshore, the Upper Jurassic succession is subdivided into the mostly continental Schieland Group (middle Callovian to Barremian) and the predominantly marine Scruff Group (Late Oxfordian - Late Ryazanian). The combined base of these two groups form together the (Near) base Upper Jurassic in the Dutch offshore sector. For a comprehensive description of the depositional environments and the stratigraphy of the Upper Jurassic strata in the Dutch North Sea the publication of Munsterman et al. (2012) is recommended. For the area of the German North Sea, a formal lithostratigraphic subdivision of the Upper Jurassic on formation level, similar those in the neighboring countries, has not yet been established. The horizon mapped by Arfai et al. (2014) as Base Upper Jurassic in the German Entenschnabel, however, was intended to follow the base of the Oxfordian when present.

3.5.2 Comparison of mapped horizons

In the area of the Central Graben, the seismic reflector mapped in the German North Sea as Near base Upper Jurassic generally coincides with the Dutch interpretation (Table 10). In both countries, the Base Upper Jurassic corresponds here to the same negative reflection (trough), often recognized as a distinct angular unconformity (Figure 14). Considerable differences between the two national interpretations, however, became apparent in the northwestern part of the Entenschnabel region. In the area of the Step Graben, no Upper Jurassic was initially mapped on the Dutch side, whereas in the German sector Upper Jurassic strata is widely distributed. After a re-evaluation of well and seismic data, the Dutch interpretation was revised and the Base Upper Jurassic was re-mapped in the vicinity of the NL-GER offshore border (Figure 24; see for details Deliverable 3.6).
Contrary to the Dutch and German interpretations, a positive reflector (peak) forms the Near base Upper Jurassic in the Danish offshore sector (Table 11). Furthermore, a notable difference to the interpretations in the neighboring countries is that the Danish horizon actually represents a combined top surface. In areas where Lower and Middle Jurassic is preserved the base of the Upper Jurassic corresponds to a reflector mapped as Top Middle Jurassic (e.g. Figure 20), whereas in areas without these strata the Base Upper Jurassic equates the Top Triassic horizon (e.g. Figures 19 and 28).

Table 10: Summary of differences and similarities for the Near base Upper Jurassic along the Dutch-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

Near base Upper Jurassic | Comparison of Dutch and German interpretation								
Covered region/ structural elements		**Figs.**	**Mapped reflection type**		**Picking concept**		**Mapped reflector**	Comments
			GER	NL	GER	NL		
NL-GER offshore border area	GLP	4					☐	No Jurassic strata in the direct vicinity of the GER-NL offshore border
	SGP/ GLP	7					☐	
	SGP/ SWHG	10					☐	
	SGP	11					☐	
Entenschnabel region	CG	14	Trough		Base		☑	
		15	Trough		Base		☑	
	SG	24	Trough		Base		X (NL) (old)	No Upper Jurassic were initially mapped on the Dutch side in the northwestern part of the Entenschnabel region.
			Trough		Base		☑ (revised)	After a re-evaluation of well and seismic data, the Dutch interpretation was revised and the Base Upper Jurassic in the vicinity of the NL-GER offshore border re-mapped. (see for details D3.6)
	SG/ ORB	25	Trough		Base		☐ (NL)	No Upper Jurassic on the Dutch side

☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◈ = unclear relation | ☐ = non-distribution | X = not mapped
⇧ or ⇩ = reflector above or below the German horizon

Table 11: Summary of differences and similarities for the Near base Upper Jurassic along the Danish-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

Near base Upper Jurassic | Comparison of Danish and German interpretation								
Covered region/ structural elements		**Figs.**	**Mapped reflection type**		**Picking concept**		**Mapped reflector**	Comments
			GER	DK	GER	DK		
Entenschnabel region	CG	18	Trough	Peak	Base	Top	☒ ⇧	Base Upper Jurassic = Top Middle Jurassic (DK)
		19	Trough	Peak	Base	Top	☒ ⇧	
		20	Trough	Peak	Base	Top	☒ ⇧	
	MH/ HP	23	Trough	Peak	Base	Top	☒	Close to DK/GER border: Base Upper Jurassic = Top Triassic (DK)
	ORB/ HP	28	Trough	Peak	Base	Top	◈	Base Upper Jurassic = Top Triassic (DK)
	ORB	29	Trough	Peak	Base	Top	☒	
		30	Trough	Peak	Base	Top	☒ ⇧	
Horn Graben region	HG	36	Trough		Base		☑	For the Horn Graben region, a harmonized DK/GER interpretation is presented in the cross-border sections (see chapter 2.3).
	WSB/ HG	37	Trough		Base		☑	

☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◈ = unclear relation | ☐ = non-distribution | X = not mapped
⇧ or ⇩ = reflector above or below the German horizon

3.5.3 Evaluation of differences and intended harmonization

Differences in the selected seismic polarity of the mapped reflectors as well as disparate seismic picking concepts generally impede a comprehensive cross-border harmonization of the Near base Upper Jurassic. With regard to the observed discrepancies, however, larger adaptions of the nationally mapped horizons are only required for the northwestern part of the Entenschnabel region where no Upper Jurassic was initially mapped in the Dutch sector (see for details Deliverable 3.6). Beside the marked discrepancies observed here along the Dutch-German border, the differences in the nationally mapped reflectors are generally negligible (differ only by one reflector / TWT ~20 ms) and rely on slightly different assumptions regarding the seismic polarity of the base reflector as well as on differing seismic mapping concepts.

In general, different acoustic impedance can be expected at the base of the Upper Jurassic, since the base often forms an unconformity with variable lithological units below (Figure 42) and the lithology at the base may further vary from non-marine to marine sediments. In the southeastern part of the Danish Central Graben, the Upper Jurassic graben fill conformably overlies the Middle Jurassic. Here the Near base Upper Jurassic is picked in a peak above a strong trough and corresponds actually to the Danish Top Middle Jurassic horizon (Figures 18, 19 and 20). The trough-peak relationship along the boundary between Upper and Middle Jurassic is believed here to be enhanced by the interference of alternating sandstones, shales and coal beds in the uppermost part of the Middle Jurassic. In the Dutch and German sectors, in contrast, the negative reflector of this prominent double reflection has been chosen as it was assumed that the Base Upper Jurassic usually coincides in the study area with an increase in acoustic impedance. This assumption can locally be verified by compiled synthetics. For example, in areas where Upper Jurassic rest upon Middle and Lower Jurassic deposits, such as in large parts of the Central Graben, an increase in acoustic impedance can be expected as indicated by Danish and German wells (see synthetics in Figures 16, 21 and 22). Furthermore, if Upper Jurassic overlies a pre-Jurassic substratum the base is clearly associated with an increase in acoustic impedance (Figures 26 and 27), and should actually be picked in trough according to the European polarity convention. For regional mapping purposes, however, the Base Upper Jurassic in the Danish sector was also mapped in this areas in a high amplitude peak that can followed across large areas. With regard to a harmonized cross-border seismic stratigraphic concept, however, the base of the Upper Jurassic should generally be picked in a trough, since independently of the underlying sediments an increase in acoustic impedance can be expected at the base, as the synthetics compiled indicate.

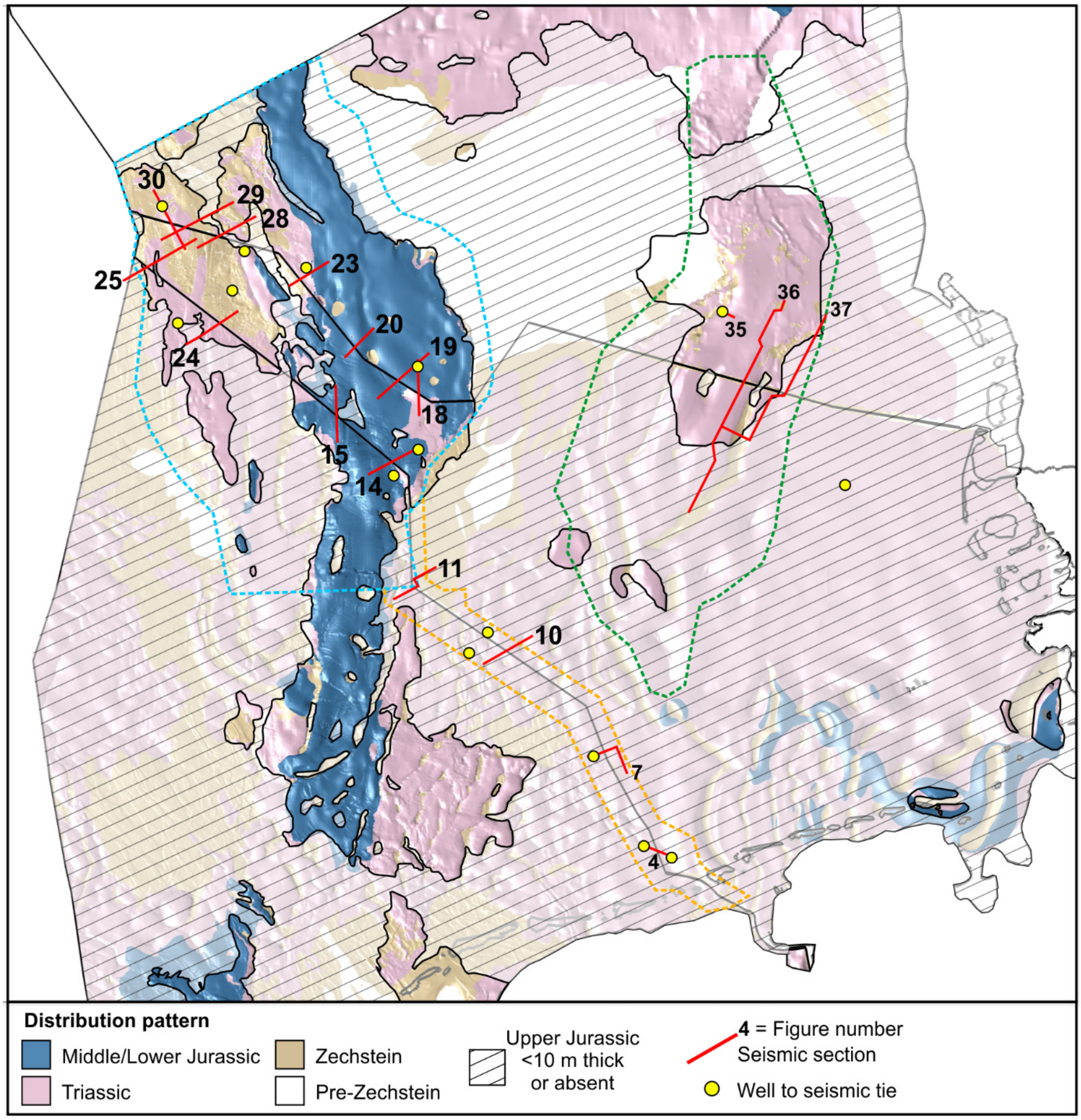

Figure 42: Subcrop map of the Near base Upper Jurassic in the Dutch, German and Danish North Sea sectors. Distribution patterns of the subcropping units have been compiled from numerous geological models, mainly provided by the participating GSOs. Note that the distribution of the Upper Jurassic in the Horn Graben is only a rough estimation. Dashed lines indicated the working areas defined in the North Sea for the 3DGEO-EU WP3 (orange: Dutch-German offshore border area / blue: Entenschnabel region / green: Horn Graben region).

3.6 (Near) base Lower Jurassic

3.6.1 *(Litho-)stratigraphic definitions and their differences*

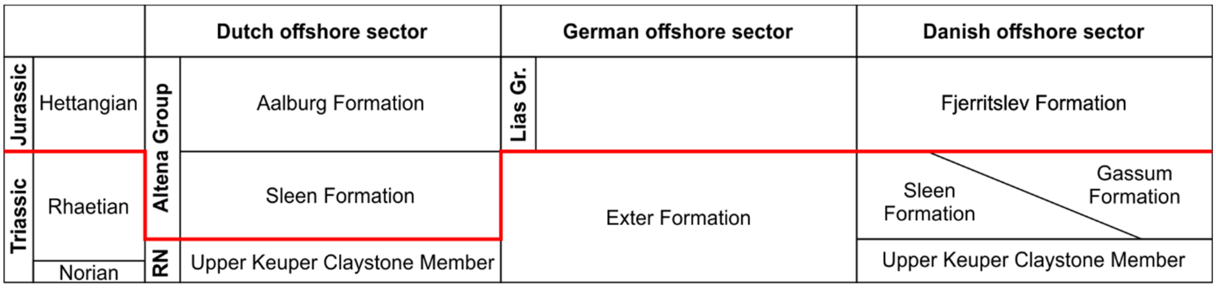

Figure 43: Lithostratigraphic correlation chart for the Netherlands, Northwest Germany and Denmark showing the differences in the stratigraphic definition of the Base Lower Jurassic (red line) (compiled from Barnasch, 2009).

Lower Jurassic deposits are in the study area restricted to the area of the Central Graben. In the Dutch offshore sector, the horizon mapped here as (Near) base Lower Jurassic is equated with the base of the Altena Group (Kombrink et al., 2012). The Altena Group comprises the Sleen, Aalburg, Posidonia Shale, Werkendam and Brabant formations. The lowermost unit of this group, the Sleen Formation, has a Rhaetian age and thus formally belongs to the Upper Triassic. The formation is treated in the Netherlands as an integral part of the Jurassic succession, since the sediments deposited here during Rhaetian bear a stronger affinity with the Jurassic succession than with Triassic sediments (Herngreen et al., 2003). This means, however, that the horizon defined here as (Near) base Lower Jurassic generally lies stratigraphically lower than in Denmark and Germany (Figure 43). In the Danish sector, the lithostratigraphic subdivision of the Jurassic succession follows generally the lithostratigraphy of Michelsen et al. (2003) for the Danish Central Graben. Here, the base of the Lower Jurassic corresponds to the base of the Fjerritslev Formation. Its equivalent in the Dutch Central Graben is the Hettangian to earliest Toarcian Aalburg Formation (Figure 43). For the Jurassic succession in the German North Sea sector, no detailed lithostratigraphic subdivision has been formally established so far. The horizon interpreted by Arfai et al. (2014) as (Near) base Lower Jurassic, however, follows Lower Jurassic well markers.

3.6.2 *Comparison of mapped horizon*

The seismic reflector mapped in the German North Sea as (Near) base Lower Jurassic generally coincides with the interpretation in the Danish sector (Table 13). In both countries, the Base Lower Jurassic is interpreted in a peak, often located above a stronger negative reflector that usually shows significant lateral continuity (Figures 18, 19 and 20). A notable difference, however, is that the Base Lower Jurassic in the Danish sector is actually interpreted as a Near Top Triassic surface. For regional mapping purposes the Base Lower Jurassic is merged here with the Base Upper Jurassic in order to represent a Base Jurassic/Top Triassic map. As a consequence, the Top Triassic surface only coincides in areas where Lower Jurassic is preserved to the Base Lower Jurassic reflector (see Figure 1 for illustration).
Contrary to the German and Danish interpretation, a negative reflector (trough) was picked in the Dutch sector as (Near) base Lower Jurassic (Table 12). The mapped reflector coincides with the negative reflection which is observed directly below the Danish/German base reflector (Figures 14 and 15).

Table 12: Summary of differences and similarities for the Near base Lower Jurassic along the Dutch-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

Near base Lower Jurassic | Comparison of Dutch and German interpretation								
Covered region/ structural elements		**Figs.**	**Mapped reflection type**		**Picking concept**		**Mapped reflector**	Comments
			GER	NL	GER	NL		
NL-GER offshore border area	GLP	4					☐	No Jurassic strata in the direct vicinity of the GER-NL offshore border
	SGP/ GLP	7					☐	
	SGP/ SWHG	10					☐	
	SGP	11					☐	
Entenschnabel region	CG	14	Peak	Trough	Base		☒ ⇩	
		15	Peak	Trough	Base		☒ ⇩	
	SG	24					☐	Middle/ Lower Jurassic absent
	SG/ ORB	25					☐	

☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◇ = unclear relation | ☐ = non-distribution | X = not mapped
⇧ or ⇩ = reflector above or below the German horizon

Table 13: Summary of differences and similarities for the Near base Lower Jurassic along the Danish-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

<table>
<tr><th colspan="9">Near base Lower Jurassic | Comparison of Danish and German interpretation</th></tr>
<tr><th colspan="2" rowspan="2">Covered region/ structural elements</th><th rowspan="2">Figs.</th><th colspan="2">Mapped reflection type</th><th colspan="2">Picking concept</th><th rowspan="2">Mapped reflector</th><th rowspan="2">Comments</th></tr>
<tr><th>GER</th><th>DK</th><th>GER</th><th>DK</th></tr>
<tr><td rowspan="7">Entenschnabel region</td><td rowspan="3">CG</td><td>18</td><td colspan="2">Peak</td><td>Base</td><td>Top</td><td>☑</td><td rowspan="3">Near base Lower Jurassic = Top Triassic (DK)</td></tr>
<tr><td>19</td><td colspan="2">Peak</td><td>Base</td><td>Top</td><td>☑</td></tr>
<tr><td>20</td><td colspan="2">Peak</td><td>Base</td><td>Top</td><td>☑</td></tr>
<tr><td>MH/ HP</td><td>23</td><td></td><td>Peak</td><td></td><td>Top</td><td>☐ (GER)</td><td>Middle/Lower Jurassic absent close to the border/ truncated by the Near base Upper Jurassic</td></tr>
<tr><td>ORB/ HP</td><td>28</td><td colspan="4" rowspan="6"></td><td>☐</td><td rowspan="6">Middle/ Lower Jurassic absent</td></tr>
<tr><td rowspan="2">ORB</td><td>29</td><td>☐</td></tr>
<tr><td>30</td><td>☐</td></tr>
<tr><td rowspan="2">Horn Graben region</td><td>HG</td><td>36</td><td>☐</td></tr>
<tr><td>WSB/ HG</td><td>37</td><td>☐</td></tr>
<tr><td colspan="9">☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◇ = unclear relation | ☐ = non-distribution | X = not mapped
⇧ or ⇩ = reflector above or below the German horizon</td></tr>
</table>

3.6.3 Evaluation of differences and intended harmonization

A comprehensive cross-border harmonization of the Near base Lower Jurassic is hampered for various reasons, including different nationally-defined lithostratigraphic boundaries and disparate seismic picking concepts. In the Dutch Central Graben, the horizon mapped as Near base Lower Jurassic corresponds to the base of the Rhaetian Sleen Formation and is interpreted here by an acoustic impedance increase (trough), as it is generally assumed that the Triassic below has a higher acoustic impedance. Since only a few wells penetrate through the Lower Jurassic and into the Triassic this assumption, however, can only verified locally (e.g. German well C-16-1; Figure 16). For the seismic mapping conducted in the German Entenschnabel (Arfai et al., 2014), it was also assumed that the Near base Lower Jurassic coincides with an increase in acoustic impedance. However, as described before, during the seismic mapping (Arfai et al., 2014) it was erroneously assumed that the analyzed seismic were in the American polarity, and consequently a peak instead of a trough was mapped here as Near base Lower Jurassic. The positive reflection, incorrectly mapped with respect to its seismic polarity in the German sector, equals the Danish Base Lower Jurassic (Table 13) which is associated according to Michelsen & Clausen (2002) with a decrease in acoustic impedance, reflecting the transition from the higher-velocity Lower Jurassic Fjerritslev Formation to the low-velocity Upper Triassic Sleen Formation. A complete succession across the Triassic/Jurassic boundary from the Upper Triassic Sleen Formation to the Lower Jurassic Fjerritslev Formation, however, is found only in the Tail End Graben and the Southern Salt Dome Province. In large parts of the Danish Central Graben the Triassic is truncated and the uppermost Late Triassic Keuper Formation is absent. As a consequence, higher velocity Triassic (or older) deposits may subcrop the Lower Jurassic and as such an acoustic impedance increase can be expected here. In the Danish sector, however, the Base Lower Jurassic is actually part of the Danish Top Triassic horizon and for regional mapping purposes the horizon is picked in a rather strong amplitude peak revealing the Near Top Triassic reflector. With regard to the impedance contrast that can be expected in areas where Triassic is truncated and the low-impedance Sleen Formation is absent, a harmonized Near base Lower Jurassic should generally coincides according to the European polarity convention with a negative reflection (trough). In areas where a thick Sleen Formation is present, however, a comprehensive harmonization of the seismic stratigraphic concept for the base of the Upper Jurassic is hampered by the different nationally-defined lithostratigraphic boundaries and the impedance contrasts associated with them. Regardless the differing national lithostratigraphic boundaries, however, differences observed in the nationally-mapped horizons are generally negligible (differ only by one reflector / TWT ~20 ms) and an adaption of the Near base Lower Jurassic is usually not required for the planned regional scale harmonization.

3.7 (Near) base Lower Triassic

3.7.1 (Litho-)stratigraphic definitions and their differences

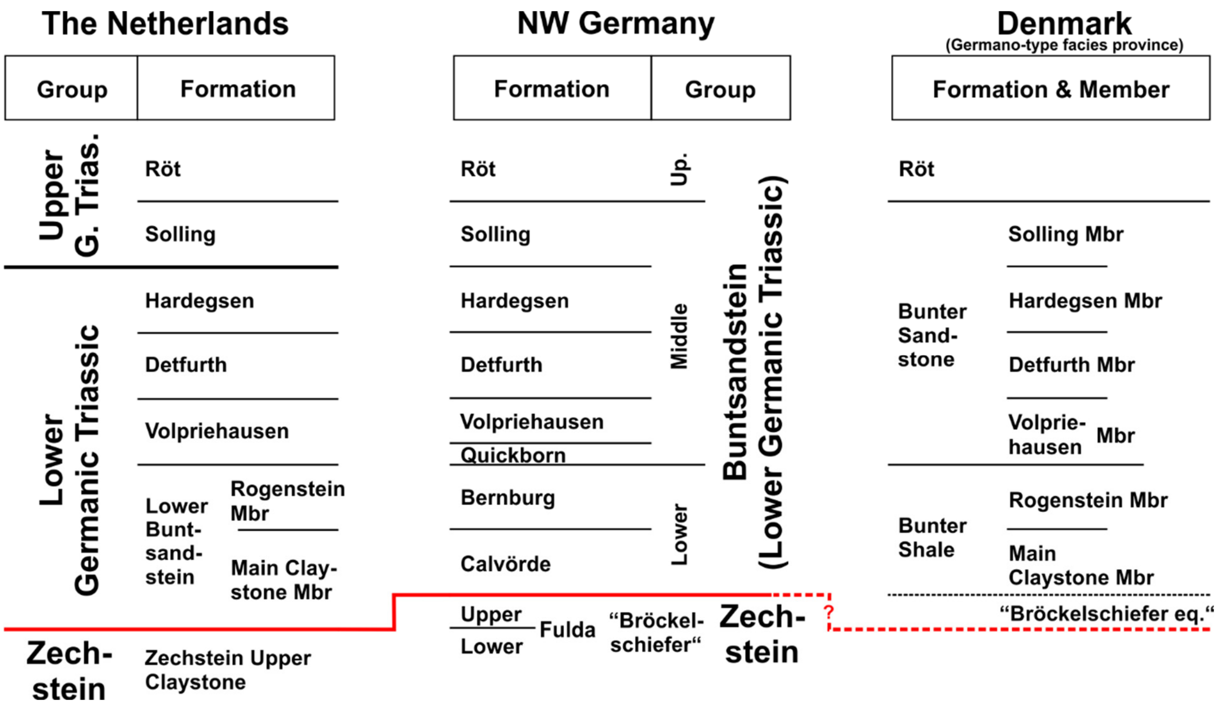

Figure 44: Lithostratigraphic correlation chart of the Triassic for the Netherlands, Northwest Germany and Denmark showing the differences in the stratigraphic definition of the Zechstein/Buntsandstein boundary (red line) (compiled from Röhling, 2013a).

In the study area, the transition from the Upper Permian Zechstein to the Lower Triassic Buntsandstein is associated with a marked change from evaporitic sabkha facies to a facies characterised by predominately playa lake and fluvial to lacustrine or alluvial sediments. In NW Germany the boundary between the Zechstein and Buntsandstein is placed at the base of the first prominent (oolitic) sandstone above the Fulda Formation, formerly known as "Bröckelschiefer" (Röhling et al., 2018 and references therein), and thus corresponds to the base of the Calvörde Formation (Figure 44). In the Netherlands, however, the Upper Fulda Formation ("Upper Bröckelschiefer") is considered to form the base of the Buntsandstein, i.e., the base of the Main Claystone Member (e.g. Geluk and Röhling, 1997). This means that the boundary between the Zechstein and Buntsandstein in the Netherlands is slightly stratigraphically lower than in Germany (Figure 44). The stratigraphic subdivision of the Triassic that is used here for the Danish North Sea follows Michelsen & Clausen (2002). They assign the clastic equivalents of the evaporite-bearing Upper Zechstein formations in NW Germany, such as the Fulda Formation, at least partially to the Triassic (see for details Röhling, 2013a).

3.7.2 Comparison of mapped horizon

The seismic reflector mapped in the German North Sea as Near base Lower Triassic generally coincides throughout the study area with the interpretation in the Dutch sector (Table 14). In both countries, the base of the Lower Triassic corresponds here to the same positive reflection (e.g. Figures 10 and 15). In contrast, a negative reflector (trough) was picked in the Danish sector as Near base Lower Triassic (Table 15). The mapped reflector coincides with a negative reflection that is directly observed above the Dutch/German base reflector (e.g. Figures 18 and 19). A further notable difference is that the Near base Lower Triassic in the Danish sector is actually interpreted as a Near Top Zechstein surface (Table 15).

Table 14: Summary of differences and similarities for the Near base Lower Triassic along the Dutch-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

Near base Lower Triassic | Comparison of Dutch and German interpretation								
Covered region/ structural elements		Figs.	Mapped reflection type		Picking concept		Mapped reflector	Comments
			GER	NL	GER	NL		
NL-GER offshore border area	GLP	4	Peak		Base		☑	
	SGP/ GLP	7	Peak		Base		☑	
	SGP/ SWHG	10	Peak		Base		☑	
	SGP	11	Peak		Base		☑	
Entenschnabel region	CG	14	Peak		Base		☑	
		15	Peak		Base		☑	
	SG	24	(Peak)	Peak	Base		☐ (GER)	Triassic strata eroded on GER side above structural highs (e.g. Outer rough High). Only residual Triassic is locally present.
	SG/ ORB	25	Peak	(Peak)	Base		☐ (NL)	Residual Triassic on GER side

☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◈ = unclear relation | ☐ = non-distribution | X = not mapped
⇧ or ⇩ = reflector above or below the German horizon

Table 15: Summary of differences and similarities for the Near base Lower Triassic along the Danish-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

Near base Lower Triassic | Comparison of Danish and German interpretation								
Covered region/ structural elements		**Figs.**	**Mapped reflection type**		**Picking concept**		**Mapped reflector**	**Comments**
			GER	DK	GER	DK		
Entenschnabel region	CG	18	Peak	Trough	Base	Top	☒ ⇧	Near base Lower Triassic = Top Zechstein (DK)
		19	Peak	Trough	Base	Top	☒ ⇧	
		20	Peak	Trough	Base	Top	☒ ⇧	
	MH/ HP	23		Trough		Top	☐ (GER)	Triassic strata eroded on GER side (Mads High) / truncated by the Near base Upper Jurassic close to the border
	ORH/ HP	28					☐	Triassic strata absent
	ORB	29	Peak	Trough	Base	Top	☒ ⇧	Near base Lower Triassic = Top Zechstein (DK)
		30	Peak	Trough	Base	Top	☒ ⇧	
Horn Graben region	HG	36	Peak		Base		☑	For the Horn Graben region, a harmonized DK/GER interpretation is presented in the cross-border sections (see chapter 2.3).
	WSB/ HG	37	Peak		Base		☑	

☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◇ = unclear relation | ☐ = non-distribution | X = not mapped
⇧ or ⇩ = reflector above or below the German horizon

3.7.3 Evaluation of differences and intended harmonization

The seismic character of the Near base Lower Triassic strongly depends on the lithology of the underlying Zechstein Group which varies laterally throughout the study area. Sabkha sediments and lagoonal evaporites dominated by limestone, dolomite and anhydrite were generally deposited along the basin margins, while in the basin centers facies dominated by rock salt prevailed. The laterally variable nature of the underlying Zechstein deposits and the changing acoustic impedance associated with them makes a comprehensive cross-border harmonization of the Near base Lower Triassic a challenging task and slightly different approaches were followed in the three countries to map the basal horizon.

In the Danish sector, the Near base Lower Triassic is interpreted and mapped actually as Top Zechstein. In basins with thick mobile salt the Top Zechstein is interpreted hereby in a trough above a distinct peak. The negative reflection is assumed to represent a dense/hard zone on top of the salt sequence, probably formed by dissolution processes that led to an accumulation of anhydrite/dolomite. In the marginal parts of the basin, the Base Triassic / Top Zechstein reflector in the Danish sector is less well defined due to regional variations in lithology above and (especially) below the boundary and should be interpreted as a +/- zero-crossing feature. For practical reasons, however, GEUS has mapped here and also in the entire Central Graben instead a moderate amplitude trough as Top Zechstein.

In the Dutch and German North Sea, the seismic reflector mapped as Near base Lower Triassic generally coincides with the distinct peak that is directly observed below the Danish base reflector (e.g. Figures 18 and 19). This positive reflection can be easily followed across large parts of the study area, even in the deeper graben systems, and was therefore chosen in the German sector as Near base Lower Triassic horizon. The distinct peak corresponds at least locally to the top of Zechstein salt, as verified by Dutch and German synthetics (Figures 8 and 31), and is probably the result of a decrease in acoustic impedance from the overlying formations into the low-density salt. The actual base of the Lower Triassic as defined in both countries, however, does not always coincide with the top salt reflector, as clearly documented e.g. for the German well B-4-4 in Figure 31. In large areas, the Zechstein salt is overlain by a fine-clastic sediment interval of varying thickness, which belongs to the youngest Zechstein. Due to small difference in petrophysical properties between these deposits and the overlying oldest Buntsandstein, a clear identification of the actual base reflector is partly hampered by the low acoustic impedance contrast that can be expected at the stratigraphic boundary. In addition, in areas with Upper Zechstein anhydrites the low-amplitude reflectors may be further obscured by strong reflections caused by anhydrites below. Generally, if anhydrite/carbonate or anhydritic caprock is present underneath an impedance increase can be expected at the base of the Lower Triassic, and consequently a negative reflector should be mapped.

Due to the existing lateral changes in depositional facies across the Zechstein/Triassic boundary and the changing acoustic characteristics associated with them, it is generally difficult to predict the seismic polarity of the base reflector throughout the study area. Consequently, it is also difficult to state whether the Danish interpretation or the reflector mapped in the Netherlands and Germany is closest to the actual base of the Lower Triassic. Regardless these uncertainties, however, it can be stated that an adaption of the Near base Lower Triassic is usually not required for this regional scale study as the differences in the nationally-mapped horizons are generally negligible (differ only by one reflector / TWT ~ 20 ms).

3.8 Base Zechstein

3.8.1 (Litho-)stratigraphic definitions and their differences

The oldest horizon selected for harmonization in the study area corresponds to the base of the Upper Permian Zechstein Group. In the Southern Permian Basin the lower boundary of this group coincides in all three countries and is marked here by the Kupferschiefer (German for Copper Shale) when present. The Kupferschiefer is a finely laminated, brownish-black bituminous shale with a thickness of up to ~2 m and can be generally recognized throughout the basin except above local highs and in marginal areas such as the northern flank of the Mid North Sea-Ringkøbing Fyn High.

3.8.2 Comparison of mapped horizons

In the German North Sea, a rather weak negative reflection below a distinct double reflection (trough-peak) was interpreted as Base Zechstein (e.g. Figures 7 and 18). Contrary to the German interpretation, a positive reflector (peak) was generally picked in the Dutch and Danish sectors as the base of the Zechstein Group (Tables 16 and 17). In both countries, the mapped reflector coincides thereby with the peak of the distinct double reflection, which is commonly observed directly above the German base reflector. A remarkable difference, however, is that the Base Zechstein horizon in the Danish sector is actually interpreted and mapped as a Top Pre-Zechstein surface, and thus is also present in areas where Zechstein is absent.

Table 16: Summary of differences and similarities for the Base Zechstein along the Dutch-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

Base Zechstein | Comparison of Dutch and German interpretation								
Covered region/ structural elements		Figs.	Mapped reflection type		Picking concept		Mapped reflector	Comments
			GER	NL	GER	NL		
NL-GER offshore border area	GLP	4	Trough	Peak	Base		☒ ⇧	
	SGP/ GLP	7	Trough	Peak	Base		☒ ⇧	
	SGP/ SWHG	10	Trough	Peak	Base		☒ ⇧	
	SGP	11	Trough	Peak	Base		☒ ⇧	
Entenschnabel region	CG	14	Trough	Peak	Base		☒ ⇧	
		15	Trough	Peak	Base		☒ ⇧	
	SG	24	Trough	Peak	Base		☒ ⇧	
	SG/ ORB	25	Trough	Peak	Base		☒ ⇧	

☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◇ = unclear relation | ☐ = non-distribution
⇧ or ⇩ = reflector above or below the German horizon

Table 17: Summary of differences and similarities for the Base Zechstein along the Danish-German offshore border. The seismic interpretation compared here comply with seismic reflectors mapped by the participating GSOs in former studies. The corresponding studies are summarized thereby in chapter 2. Abbreviations of structural elements: see Figure 3.

Base Zechstein | Comparison of Danish and German interpretation								
Covered region/ structural elements		**Figs.**	**Mapped reflection type**		**Picking concept**		**Mapped reflector**	**Comments**
			GER	DK	GER	DK		
Entenschnabel region	CG	18	Trough	Peak	Base	Top	☒ ⇧	Base Zechstein = Top Pre-Zechstein (DK)
		19	Trough	Peak	Base	Top	☒ ⇧	
		20	Trough	Peak	Base	Top	☒ ⇧	
	MH/ HP	23	Trough	Peak	Base	Top	☒ ⇧	
	ORB/ HP	28	Trough	Peak	Base	Top	☒ ⇧	
	ORB	29	Trough	Peak	Base	Top	☒ ⇧	
		30	Trough	Peak	Base	Top	☒ ⇧	
Horn Graben region	HG	36	Peak		Base		☑	For the Horn Graben region, a harmonized DK/GER interpretation is presented in the cross-border sections (see chapter 2.3).
	WSB/ HG	37	Peak		Base		☑	

☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◇ = unclear relation | ☐ = non-distribution
⇧ or ⇩ = reflector above or below the German horizon

3.8.3 *Evaluation of differences and intended harmonization*

With the use of the generated synthetics it is possible to determine the general seismic character of the Base Zechstein and thus to evaluate the seismic stratigraphic concepts currently applied in the three countries. According to the synthetics, the Base Zechstein is generally defined by a high amplitude negative reflection followed by a high amplitude positive reflector (Figures 5, 6 and 8). This double reflection can usually be attributed to an interval of basal Zechstein units comprising mainly anhydrites and carbonates. The whole basal Zechstein interval can be seen thereby as one unit with a relative high acoustic impedance with respect to the overlying Zechstein salt and the subcropping Rotliegend/Carboniferous formations. The top of this interval, which is commonly defined by an impedance increase, coincides with the distinct trough of the double reflection, whereas its base corresponds to the high amplitude positive reflection below. The Kupferschiefer, which marks the lower boundary of the Upper Permian Zechstein Group in the Southern Permian Basin, generally coincides with the distinct lower peak (Figure 6 and 8). As its thickness (~2 m), however, falls below seismic resolution the Kupferschiefer is not visible as an independent reflector.

The distinct peak of the double reflection was commonly mapped in the Dutch and Danish North Sea as Base Zechstein horizon and can be considered as the actual base of the Zechstein Group since its equates the Kupferschiefer when present. In contrast, the seismic reflector mapped in the German North Sea is stratigraphically slightly too low and should generally be revised in the future following the Dutch and Danish interpretations. With regard to the ongoing harmonization, however, an adaption of the nationally-mapped horizons is not necessary as the differences in the Base Zechstein reflector are generally negligible (differ only by one reflector / TWT ~ 25 ms).

3.9 Additional Triassic horizon – Horn Graben region

For the Horn Graben region, which is mainly dominated by thick Triassic clastic strata, GEUS and BGR agreed to include three additional Triassic horizons. The (litho-)stratigraphic definitions of these horizons as well as their general seismic character are briefly described below.

3.9.1 Top Grabfeld Formation

The Grabfeld Formation (formerly known as "Unterer Gipskeuper") is a lithostratigraphic unit of the Middle Keuper in the German Triassic and is dated within the Ladinian and Carnian (Menning & Hendrich, 2016). The formation is characterized by a widespread evaporite deposition, comprising mainly shaly-evaporitic lithologies and halite layers occur at up to five distinct levels.
At the end of the Grabfeld Formation a general change in structural pattern can be observed for the area of the Horn Graben, evident by several local to far-reaching unconformities in the overlying Middle Keuper. The top of the Grabfeld Formation is thereby partly characterized by an amalgamation of different unconformities. The most widespread discordances at the top are associated with the Schilfsandstein Unconformity (Base Stuttgart Formation) and an outstanding Early Cimmerian Unconformity at the base of the Arnstadt Formation. Local stratigraphic discordances resulting from salt mobilisation further complicate the stratigraphic pattern in the Keuper succession and makes it difficult to continuously trace the top of the Grabfeld Formation throughout the study area. In general, due to regional variation in overlying and subcropping strata, different acoustic impedance can further be expected at the top of the Grabfeld Formation. For mapping purposes, the top horizon was therefore interpreted in a trough representing the best traceable reflection in the area of the Horn Graben (Figures 36 and 37; Table 18).

Table 18: Summary on the harmonized Top Grabfeld Formation in the Danish und German sectors. Abbreviations of structural elements: see Figure 3.

<table>
<tr><th colspan="10">Top Grabfeld Formation | Harmonized Danish and German interpretation</th></tr>
<tr><th colspan="2" rowspan="2">Covered region/ structural elements</th><th rowspan="2">Figs.</th><th colspan="2">Mapped reflection type</th><th colspan="2">Picking concept</th><th rowspan="2">Mapped reflector</th><th rowspan="2">Comments</th></tr>
<tr><th>GER</th><th>DK</th><th>GER</th><th>DK</th></tr>
<tr><td rowspan="2">Horn Graben region</td><td>HG</td><td>36</td><td colspan="2">Trough</td><td colspan="2">Top</td><td>☑</td><td rowspan="2">For the Horn Graben region, a harmonized DK/GER interpretation is presented in the cross-border sections. (see chapter 2.3)</td></tr>
<tr><td>WSB/ HG</td><td>37</td><td colspan="2">Trough</td><td colspan="2">Top</td><td>☑</td></tr>
<tr><td colspan="9">☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◈ = unclear relation | ☐ = non-distribution | X = not mapped
⇧ or ⇩ = reflector above or below the German horizon</td></tr>
</table>

3.9.2 (Near) base Middle Triassic

The seismic horizon, which was mapped in the German North Sea as Near base Middle Triassic (Arfai et al., 2014; Wolf et al., 2015) and extended for harmonization purposes into the Danish Horn Graben, equates to the base of the German Upper Buntsandstein and thus to the base of the Röt Formation. According to Röhling (2013a), the definition of the Base Röt Formation is thereby the same in Germany (Menning & Hendrich, 2016) and in Denmark (Michelsen & Clausen, 2002). Although the Dutch Near base Middle Triassic is not considered here more closely, a notable difference to the German definition has to be mentioned in this context. In the Netherlands, the Near base Middle Triassic was seismically equated with the base of the Upper Germanic Trias Group, i.e., the base of the Solling Formation (Kombrink et al., 2012). This means that the Dutch Near base Middle Triassic is defined stratigraphically lower than in Germany.

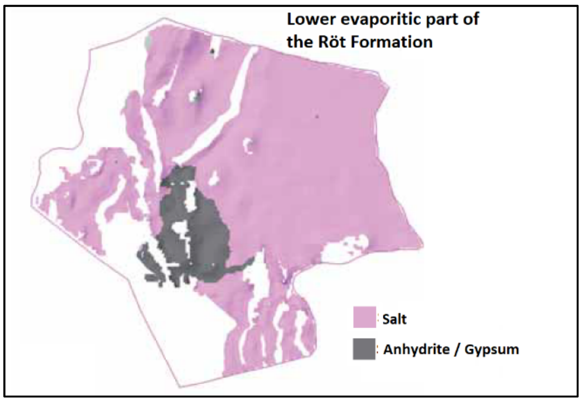

Figure 45: Slice from lithological model of the lower evaporitic part of the Röt Formation in the central German North Sea showing widespread salt with anhydrite in the southeast of the Horn Graben (Wolf et al., 2015).

In Northern Germany, the lower part of the Röt Formation is dominated by evaporitic sediments with thick halite deposits present in the German Vitzenburg Subformation and in the Glockenseck Subformation (Röhling, 2013b). The acoustic impedance contrast with the underlying claystones of the Solling Formation depends thereby strongly on the nature of the evaporitic deposits. If halite is mostly present at the base of the Röt Formation an acoustic impedance increase can be expected caused by the lower density of the salt compared to the underlying clastic interval. In areas where the lower evaporitic interval, however, is not dominated by halite and other evaporites such as anhydrite are present, the acoustic impedance may decrease downwards. In the Danish well S-1X, the lower part of the Röt Formation coincides with an interval dominated mainly by low-density halite (Main Röt Halite Member) and a distinct negative reflection (trough) is associated here with base of the Middle Triassic (Figure 35). This negative reflection can be easily followed across large parts of the Horn Graben (Figure 36) and was therefore chosen as Near base Middle Triassic horizon in the German and Danish sectors (Table 19). Outside the Horn Graben area, the negative reflection is less distinct (Figure 37) and the polarity of the base reflector may change due to varying lithologies of the lower Röt Formation (Figure 45). For seismic mapping purposes, however, a negative reflection was also mapped in the remaining German North Sea sector.

Table 19: Summary on the harmonized Near base Middle Triassic in the Danish und German sectors. Abbreviations of structural elements: see Figure 3.

Near base Middle Triassic | Harmonized Danish and German interpretation								
Covered region/ structural elements		**Figs.**	**Mapped reflection type**		**Picking concept**		**Mapped reflector**	**Comments**
			GER	DK	GER	DK		
Horn Graben region	HG	36	Trough		Base		☑	For the Horn Graben region, a harmonized DK/GER interpretation is presented in the cross-border sections. (see Chapter 2.3)
	WSB/ HG	37	Trough		Base		☑	
☑ = same reflector | ☒ = minor differences | ☒ = considerable differences ◇ = unclear relation | ☐ = non-distribution | X = not mapped ⇧ or ⇩ = reflector above or below the German horizon								

3.9.3 Near base Volpriehausen Formation

The base of the Volpriehausen Formation coincides in large parts of Germany with the base of the Middle Buntsandstein, which is stratigraphic equivalent to the Bunter Sandstone Formation in the Danish North Sea (Röhling, 2013a). In parts of the North German Basin, however, an additional sandstone unit occurs slightly below the Volpriehausen Formation. This formerly much more widespread sandstone unit was eroded already before the deposition of the Volpriehausen Sandstone, so that it is preserved today only in remnants in the subsidence axis of the North German Basin and in parts of the Ems Low (Röhling, 1999; 2013b). In the Netherlands and in Denmark, this sandstone unit is generally incorporated into the Volpriehausen Sandstone (Geluk and Röhling, 2013; Röhling, 2013a), whereas in Germany it has been recently defined as an independent lithostratigraphic unit (see Röhling, 2013a and references therein). In the German North Sea, however, the Volpriehausen and Quickborn formations were mapped as one unit in past projects (Wolf et al., 2015), since most well descriptions do not differ the relative newly defined Quickborn Formation and a differentiation based on seismic data alone was not possible. Accordingly, the mapped seismic reflector should actually be regarded as a Near base Volpriehausen Formation horizon.

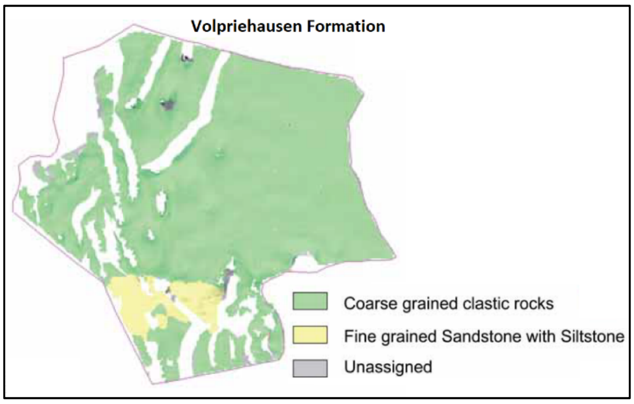

Figure 46: Slice from lithological model of the Volpriehausen Formation in the central German North Sea showing widespread coarse-grained sediments at the base of the formation (Wolf et al., 2015)

In the central German North Sea, the Volpriehausen Formation represents a large-scale fining upward sequence, with widespread coarse grained sediments at the base of the unit (Figure 46), grading into finer clastic sediments towards the top (Wolf et al., 2015). In most wells the coarse grained basal part of the Volpriehausen Formation corresponds thereby to a low-velocity interval compared to the underlying finer clastic sediments of the Lower Buntsandstein (e.g. German well S-1; Figure 34). Here, the base of the Volpriehausen Formation generally coincides with an increase in acoustic impedance and was accordingly picked in a negative reflection (trough). However, particularly in the southernmost part of the German North Sea sector, where finer clastic sediments occur more often (Figure 46), the basal part of the Volpriehausen Formation could show higher seismic velocities. Accordingly, a decrease in acoustic impedance may be present here for the base of the Volpriehausen Formation. For seismic mapping purposes, however, a negative reflection was also mapped in this parts of the German North Sea sector.

Table 20: Summary on the harmonized Near base Volpriehausen Formation in the Danish und German sectors. Abbreviations of structural elements: see Figure 3.

<table>
<tr><th colspan="9">Near base Volpriehausen FM | Harmonized Danish and German interpretation</th></tr>
<tr><th colspan="2" rowspan="2">Covered region/ structural elements</th><th rowspan="2">Figs.</th><th colspan="2">Mapped reflection type</th><th colspan="2">Picking concept</th><th rowspan="2">Mapped reflector</th><th rowspan="2">Comments</th></tr>
<tr><td>GER</td><td>DK</td><td>GER</td><td>DK</td></tr>
<tr><td rowspan="2">Horn Graben region</td><td>HG</td><td>36</td><td colspan="2">Trough</td><td colspan="2">Base</td><td>☑</td><td rowspan="2">For the Horn Graben region, a harmonized DK/GER interpretation is presented in the cross-border sections. (see Chapter 2.3)</td></tr>
<tr><td>WSB/ HG</td><td>37</td><td colspan="2">Trough</td><td colspan="2">Base</td><td>☑</td></tr>
<tr><td colspan="9">☑ = same reflector | ☒ = minor differences | ☒ = considerable differences
◇ = unclear relation | ☐ = non-distribution | X = not mapped
⇧ or ⇩ = reflector above or below the German horizon</td></tr>
</table>

4 SUMMARY ON HARMONIZED STRATIGRAPHIC HORIZONS

Except for some regions where larger discrepancies in national interpretations were observed (see for details Deliverable 3.6), the seismic reflectors mapped in the three countries generally differ only slightly from each other, and this usually only in their seismic polarity. In the preceding chapters, the seismic polarity of the different stratigraphic horizons selected for harmonization was therefore mainly discussed and evaluated. The following tables summarize the seismic polarity of the harmonized stratigraphic horizons and show for which horizons a harmonization of the polarity is generally problematic and a more detailed consideration is required.

Table 21: Overview of the seismic polarity of key stratigraphic horizons selected for harmonization. The indicated polarities follow the European polarity convention, in which a positive amplitude (peak) represents a downward decrease in impedance and a negative amplitude (trough) an impedance increase. AI = acoustic impedance

<table>
<tr><th>Seismic horizon</th><th>Seismic polarity</th><th colspan="2">General comments</th></tr>
<tr><td rowspan="3">Near MMU</td><td colspan="3">A reliable conclusion regarding its seismic polarity is currently not possible due to the complex nature of the Near MMU and requires generally a more detailed consideration.</td></tr>
<tr><td>Peak (DK/NL)</td><td colspan="2">NL: It is generally assumed that the Near MMU is associated with a transition from shallow marine sands/clays (above) to shallow marine clays (below) and therefore a decrease in AI can be expected (peak). But due to its variable character both peak and trough was mapped.
DK: For the Central Graben area, it is assumed that the MMU coincides with a transition from normally compacted (above) to overpressured deposits (below) and therefore a decrease in AI can be expected (peak)</td></tr>
<tr><td>Trough (GER)</td><td colspan="2">GER: For practical reasons a negative reflection (trough) was chosen (best traceable reflector). In certain wells, the trough coincides thereby with a distinct Gamma ray-Peak that is characteristic for the MMU</td></tr>
<tr><td>Near base Cenozoic</td><td>Trough</td><td colspan="2">The Near base Cenozoic coincides with a downward increase in AI, reflecting the transition from the low-impedance Cenozoic shales to the high impedance chalk deposits, and should therefore corresponds to a negative reflection (trough).</td></tr>
<tr><td>Base Upper Cretaceous</td><td>Peak</td><td colspan="2">The Base Upper Cretaceous coincides with a distinct decrease in AI, marking the break from high impedance chalk to lower velocity Lower Cretaceous and older formations, and should therefore corresponds to a positive reflection (peak).</td></tr>
<tr><td rowspan="3">Near base Lower Cretaceous</td><td colspan="3">In many areas an unconformity is observed with variable older lithological units below and as such a variable reflection characteristic can be expected.</td></tr>
<tr><td>Peak</td><td>(Upper) Jurassic</td><td>If Upper Jurassic is subcropping then an AI decrease can be expected, and the Near base Lower Cretaceous should be picked in a peak.
If Middle/Lower Jurassic is subcropping an increase or decrease in AI may occur.</td></tr>
<tr><td>Trough</td><td>Triassic or older subcrops</td><td>If Triassic (or older) is subcropping an AI increase is present (trough)</td></tr>
</table>

Table 22: Overview of the seismic polarity of key stratigraphic horizons selected for harmonization. The indicated polarities follow the European polarity convention, in which a positive amplitude (peak) represents a decrease in impedance and a negative amplitude (trough) an impedance increase. AI = acoustic impedance; NB = Near base.

<table>
<tr><th>Seismic horizon</th><th>Seismic polarity</th><th colspan="2">General comments</th></tr>
<tr><td rowspan="4">Near base Upper Jurassic</td><td colspan="3">In many areas an unconformity is observed with variable older lithological units below and as such a variable reflection can be expected.</td></tr>
<tr><td>Peak (DK)</td><td rowspan="2">Middle / Lower Jurassic</td><td rowspan="2">If Middle/Lower Jurassic strata is present below, a reliable conclusion regarding its seismic polarity is difficult to draw due to lateral changes in depositional facies above and below the base.
NL/GER: If Middle/Lower Jurassic is present underneath, an AI increase was expected (trough), which is locally verified by compiled synthetics.</td></tr>
<tr><td>Trough (NL/GER)</td></tr>
<tr><td>trough</td><td>Triassic or older subcrops</td><td>If Triassic or older subcrops are present underneath, the Near base Lower Jurassic coincides with an increase in AI (trough).</td></tr>
<tr><td rowspan="3">Near base Lower Jurassic</td><td colspan="3">A comprehensive harmonization of the seismic stratigraphic concept for the Near base Lower Jurassic is generally hampered by the different nationally-defined lithostratigraphic boundaries and the impedance contrasts associated with them (see chapter 3.6.3)</td></tr>
<tr><td>Peak (DK)</td><td rowspan="2">Triassic (excl. Sleen FM in NL) or older subcrops</td><td>DK: If the Lower Jurassic Fjerritslev FM rests upon the uppermost Triassic Sleen FM a decrease in AI is expected (peak).</td></tr>
<tr><td>Trough (NL/GER*)</td><td>An increase in AI was assumed for the NB Upper Jurassic both in the Dutch and German North Sea.
GER*: For the interpreted seismic data a wrong polarity was assumed, and therefore an AI decrease (peak) was mistakenly mapped.</td></tr>
<tr><td rowspan="3">Near base Lower Triassic</td><td colspan="3">A reliable conclusion regarding its seismic polarity is not possible due to numerous lateral changes in depositional facies across the Zechstein/Triassic boundary and changing AI associated with them. Moreover, it is also difficult to conclude whether the Danish interpretation or the reflector mapped in the Netherlands and Germany is closest to the actual base of the Lower Triassic.</td></tr>
<tr><td>Trough (DK)</td><td rowspan="2">Zechstein or older subcrops</td><td>DK: In basinal settings, a negative reflection (trough) was mapped which is assumed to represent a dense/hard zone on top of the salt sequence. For practical reason a trough was also picked in marginal regions.</td></tr>
<tr><td>Peak (NL/GER)</td><td>GER: For practical reason a peak was mapped (best traceable reflector, even in deeper graben systems).
NL: A peak was mapped in the border area</td></tr>
<tr><td>Base Zechstein</td><td>Peak</td><td>Rotliegend or older subcrops</td><td>The basal Zechstein consists generally of anhydrites and carbonates. On top of clastic Rotliegend / Carboniferous this will result in an acoustic impedance decrease (peak)</td></tr>
</table>

Table 23: Overview of the seismic polarity of additional Triassic horizons selected for the Horn Graben region. The indicated polarities follow the European polarity convention, in which a positive amplitude (peak) represents a decrease in impedance and a negative amplitude (trough) an impedance increase. AI = acoustic impedance;

Seismic horizon	Seismic polarity	General comments
Top Grabfeld Formation	Trough	Due to regional variation in overlying and subcropping strata, different acoustic impedance can be expected. For mapping purposes, the top horizon was interpreted in a trough representing the best traceable reflection in the area of the Horn Graben
Near base Middle Triassic	Trough	In the area of the Horn Graben, the base of the Röt Formation is dominated by salt deposits. Due to the lower density of the salt compared to the underlying clastic interval, an AI increase can be expected and accordingly a negative reflection (trough) should be mapped as basal horizon.
Near base Volpriehausen Formation	Trough	In the area of the German Horn Graben, the coarse grained basal part of the Volpriehausen Formation generally coincides with a low-velocity interval compared to underlying finer clastic units. Accordingly, a negative reflection (trough) should be mapped as basal horizon.

5 CONCLUDING REMARKS

In the present report, 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, ensuring that different interpreters within or outside the geological surveys can easily follow and reproduce the former interpretations made in the respective countries. Moreover, the cross-border comparison allowed to discern the causes of larger discrepancies in the existing national horizon models and to revise inconsistent interpretations. Details on the revisions made can be found thereby in Deliverable 3.6.

Apart from the larger discrepancies observed in some areas, the nationally mapped stratigraphic horizons generally differ only negligible, often only by a single seismic reflection. These minor differences rely in part on different assumption regarding the acoustic impedance contrast to be expected at the stratigraphic horizon, slightly different mapping concepts (top vs. base; Figure 1), but partly the interpretations differ solely for practical reasons, since the best traceable reflector was mapped. The causes for the selection of a specific reflector were discussed and evaluated and, if possible, solutions for a cross-border harmonization were proposed. The compilation of this information provides thereby an important starting point for the harmonization of existing and future interpretations.

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