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State of the Art Report

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GENERAL 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. 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) are responsible for the cross-border harmonization in this pilot area.

The following State-of-the-Art report, the first deliverable of WP3, will provide an overview of existing model and map data of the North Sea area primarily developed by the project partners in the last decades. This overview is preceded by a brief project introduction. Recent research activities of the project members are summarized in another chapter, followed by a chapter evaluating legal constraints in sharing subsurface data among the different national project partners. Furthermore, the results of an initial analysis of cross-border discrepancies between existing geomodels are presented in the annex.

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1 PROJECT BACKGROUND

1.1 Rationales and aims

Harmonization of geological data across geological, topographical, but especially across national borders is one of the most important work steps to create a base for trans-European assessments of resource potentials and possible conflicts of use of European subsurface. In the last decades a variety of different thematic maps were developed, but often not on a similar and consistent data base. Differences in the geological & geophysical interpretation (e.g. stratigraphy, velocity-model, structural interpretation, different methods of assessments) across the borders remain unchanged and were masked by generalizations in an overview scale. In the last years these “border-discontinuities” have become obvious by a variety of 3D-modeling projects. But workflows for harmonization of different geological 3D models are yet not established and proofed.

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. One of the main task of WP3 in this context will be to find and exemplarily test efficient workflows for harmonization or the consistent translation between the established national concepts. The methodologic advantages (agreements on best practices, optimized workflows, etc.) and the gain in experience on cross-border 3D harmonization work will be a keystone for further transnational harmonization projects.

1.2 Cross-border harmonization (WP3)

General aspects of the planned cross-border harmonization within WP3 were discussed during an early meeting held in Hannover (11.-13. September 2018). During this meeting, the project participants agreed on the definition of a harmonized model, working areas, the stratigraphic framework and general requirements such as formats for data exchange. The agreements reached are briefly summarized below.

1.2.1 Definition of a harmonized model

The integration of existing national (and regional) geomodels into a harmonized, consistent cross-border geomodel of the North Sea area between the Netherlands, Germany and Denmark is one of the main objectives of 3DGEO-EU WP3. A harmonized geomodel in this context means, as defined by the GSOs in charge, a consistent structural framework of horizon grids, major faults and diapirs, but without modeling a “topological clean” structural 3D model with modelled horizon – fault, horizon – diapir, fault – diapir contacts. Fault modeling and diapir modeling will be limited to the near surrounding of the offshore borders.

1.2.2 *Working areas*

For the planned cross-border harmonization, three working areas have been defined as shown in Figure 1. These areas comprise the cross-border area of the Danish, German and Dutch Central Graben in the central North Sea, a small stripe along the NL-GER border and the area of the Horn Graben. The working area defined by the Central Graben, here referred to as the Entenschnabel region, corresponds to the model area of the GARAH project.

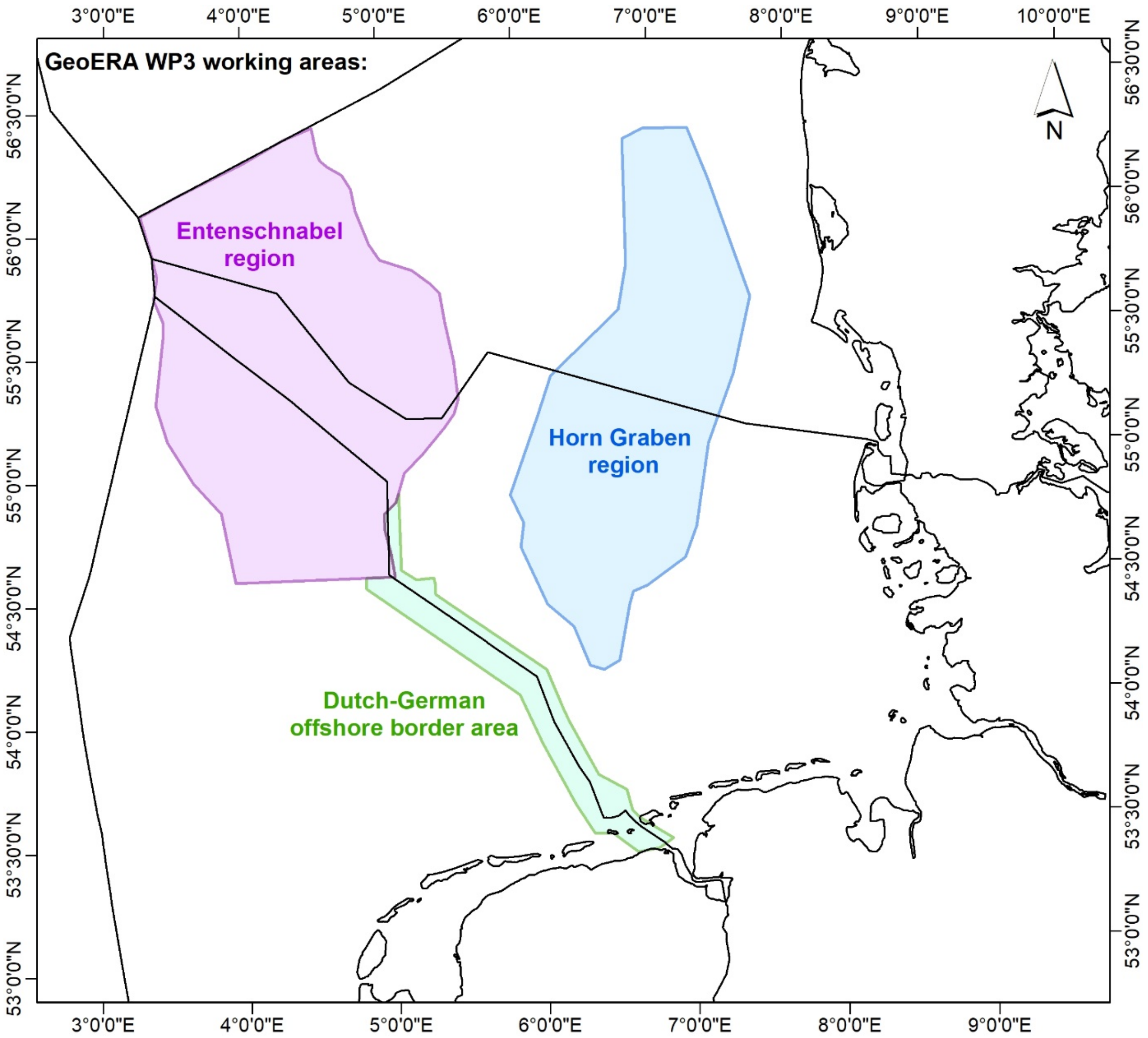

Figure 1: Working areas defined in the North Sea for the 3DGEO-EU WP3.

1.2.3 Stratigraphic framework

Nine key horizons have been selected tentatively by the project members for harmonization purposes (Figure 2). Subsequent changes of certain horizons or the inclusion of further horizons in the different working areas may occur during the course of the project.

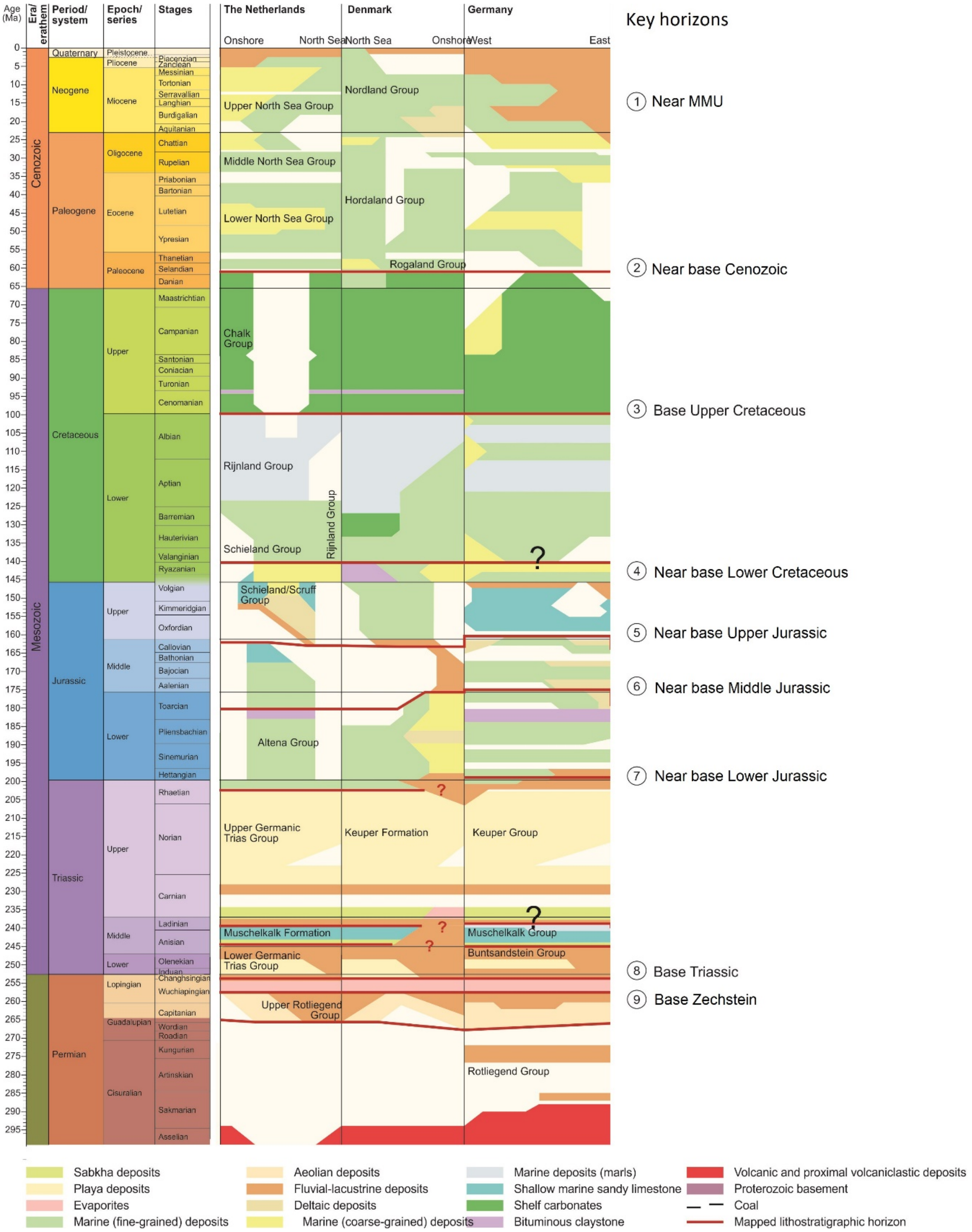

Figure 2: Stratigraphic framework modified after Doornenbal and Stevenson (2010) and key horizons defined for the 3DGEO-EU WP3.

1.2.4 General requirements

The successful resolution of cross-border issues requires a comprehensive harmonization of data, methodologies and software systems ensuring full interoperability among the project partners. The following table gives an overview of software systems used by the partners for seismic interpretation and modelling purposes. As Petrel is a common used software, the project members decided to exchange data in Petrel compatible formats and projects.

Table 1: Software systems used by the project partners and defined formats for data exchange.

	TNO	BGR	GEUS
Internal used software	Petrel©	SeisEarth Paradigm© Petrel©	Decision Space© Petrel©
Data exchange among partners	Petrel compatible formats & projects		

A further concern in multinational projects is the coexistence of different coordinate reference systems used by the partners. The GSOs in charge decided to use ED50 / UTM Zone 31N as the common coordinate system to share and provide data (Table 2).

Table 2: Coordinate systems (CS) used by the partners.

	TNO	BGR	GEUS
Internal used CS	ED50 / UTM Zone 31N (EPSG: 23031)	WGS84 / UTM Zone 31N (EPSG: 32631)	ED50 / UTM Zone 31N (EPSG: 23031)
Product & Petrel CS	ED50 / UTM Zone 31N (EPSG: 23031)		

2 EXISTING GEOMODELS – AN INVENTORY OF PUBLICLY AVAILABLE DATA

Elaboration on criteria for harmonization of geomodels requires the knowledge of differences between the datasets. The intention of the following chapter is to give an overview of the publicly available subsurface models covering the offshore border areas of the participating countries and to describe their main characteristics.

2.1 Geomodels in the area of the Dutch North Sea

2.1.1 DGM-deep

Over the last few decades, the Geological Survey of the Netherlands (TNO-GSN) has carried out several major mapping projects in order to better understand the deep subsurface of the Netherlands, both on- and offshore. The results were first published on paper (depth, isopach and subcrop maps at a scale of 1 : 250,000; compiled at 1 : 1,000,000 in TNO-NITG, 2004), and later became the constituents of a regional subsurface layer model now referred to as Digital Geological Model-deep (DGM-deep; Duin et al., 2006; Kombrink et al., 2012). The DGM-deep model is based on interpretations of publicly available 2D and 3D seismic survey data, combined with a variety of well data, supported by biostratigraphical, petrophysical and geochemical analysis. The latest version (v5.0) comprises the geometrically coherent succession of 12 seismic interpreted horizons and one thickness-based horizon (Figure 3), which were modelled at 250x250m grid resolution. The interpreted horizons, ranging from Carboniferous to Neogene in age, are the bases of lithostratigraphic units, which are defined in the Stratigraphic Nomenclature of the Netherlands.

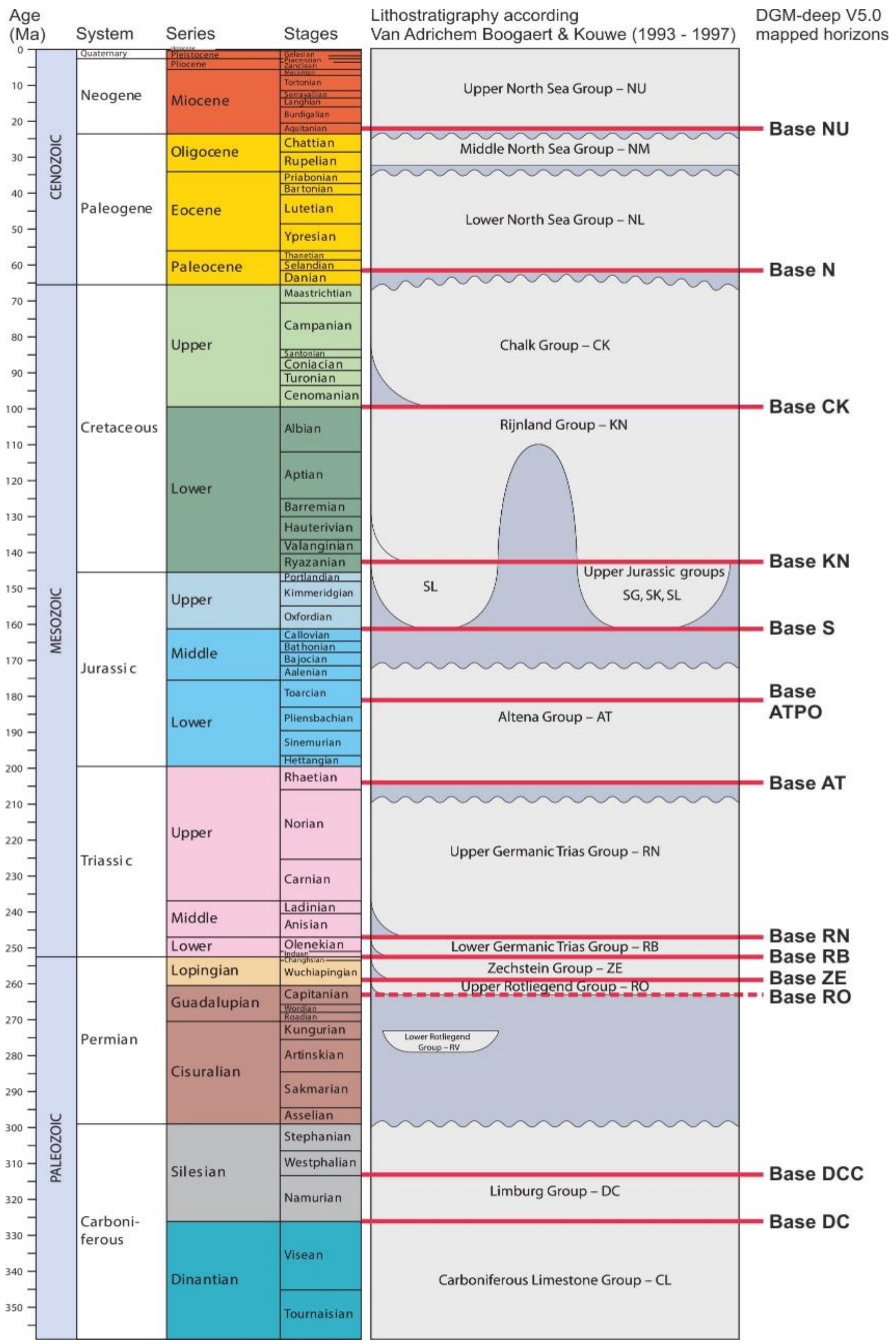

Figure 3: Simplified stratigraphic diagram of the Netherlands showing the horizons of DGM-deep v5.0.

DGM-deep v5.0 combines models of the onshore and offshore into one model in projection ED50 / UTM Zone 31N. New seismic interpretation and faults have not been included and the model has been depth converted with the VELMOD 3.1 velocity model. In this version all non-confidential wells have been consulted, of which after filtering out aberrant data a subset was finally used to well-tie the individual stratigraphic layers. The latest version of the DGM-deep models (v5.0) will be made publicly available end of Q2 2019. Previous versions of DGM-deep, including the data used, are disseminated through the Netherlands Oil and Gas Portal (NLOG). The main features of actual and previous versions of DGM-deep are summarized in Table 3.

Table 3: Actual and previous versions of the DGM-deep model and its main features

Model name	**DGM – deep**				
DGM version	V1.0	V2.0	V3.0	V4.0	V5.0
Published	2002	2006	2010	2012	2019
Regional extent	Onshore Netherlands	On- and offshore Netherlands	Offshore Netherlands	Onshore Netherlands	On- and offshore Netherlands
Project	GEO-atlas	NCP-1	NCP-2		
Projection	RD-Bessel 1841	ED50 / UTM 31N	ED50 / UTM 31N	RD-Bessel 1841	ED50 / UTM 31N
Input data	Publicly available 2D and 3D seismic survey data, combined with a variety of well data, supported by biostratigraphical, petrophysical and geochemical analysis				
Stratigraphic nomenclature	Stratigraphic Nomenclature of the Netherlands (https://www.dinoloket.nl/en/nomenclator)				
Modelled horizons	8 seismically based horizons (NU, NL+NM, CK, KN, S, AT, RB, ZE) 1 thickness-based horizon (RO+RV)	10 seismically based horizons (NU,NL+NM,CK, KN, S, AT, RNK, RN, RB, ZE) 1 thickness-based horizon (RO)	10 seismically based horizons (NU,N,CK, KN, S, ATPO, AT, RN, RB, ZE) 1 thickness-based horizon (RO)	11 seismically based horizons (NU,N,CK, KN, S, ATPO, AT, RB, ZE, DCC, DC) 1 thickness-based horizon (RO)	12 seismically based horizons (NU,N,CK, KN, S, ATPO, AT, RN, RB, ZE, DCC, DC) 1 thickness-based horizon (RO)
Faults	Yes	Yes (3D fault planes)	Yes (3D fault planes)	No	
Velocity model	Multiple	VELMOD-1	VELMOD-2	VELMOD-3	VELMOD-3.1
Output data (sort/type)	depth, isopach and subcrop maps	depth, thickness and fault maps	TWT-, time thickness-(TWT), depth-, thickness-, uncertainty-and reservoir-grids	TWT-, time thickness-(TWT), depth-, thickness-, velocity- and uncertainty-grids	TWT-, time thickness-(TWT), depth-, thickness-, - and uncertainty-grids
Data format	Atlas on paper	Pdf, arc-grid and zmap-grid			
Access via	DGM-deep, including the data used, is disseminated through the Netherlands Oil and Gas Portal (www.nlog.nl)				
References	TNO-NITG	Duin et al. (2006)	Kombrink et al. (2012)		

2.2 Geomodels in the area of the German North Sea

Between 2009 and 2013, the BGR carried out in collaboration with the Lower Saxony State Authority for Mining, Energy and Geology (LBEG) and the German Federal Maritime and Hydrographic Agency (BSH) the project GPDN (German acronym for "Geo-scientific Potentials of the German North Sea"). The main objective of the project was to compile and provide geo-scientific information about the subsurface in the German North Sea (Reinhardt et al., 2010). Within this joint project, a number of geomodels were developed by the project partners for the

German sector of the North Sea. These publicly available models are described in detail below, and their main characteristics are summarized in Tables 4 and 5

2.2.1 GTA3D – North Sea

The “Geotectonic Atlas 3D” (GTA3D) is a regional structural model covering the area of Lower Saxony and the central German North Sea (Figure 4). It was compiled by the LBEG and mainly relies on structural depth maps of the “Geotectonic Atlas of Northwest Germany and the German North Sea” (GTA; Baldschuhn et al., 2001) which were transferred into 3D (GTA3D; Bombien et al., 2012). This atlas is the fundamental work on regional geology in that area and was developed at the BGR from the 1970’s to the 1990’s based on wells and digital seismic profiles acquired mostly for hydrocarbon exploration, and for the exploration of salt and mineral resources. The implementation of the GTA as a 3D model was done for the area of Lower Saxony within the GTA3D project, and for the central German North Sea within the GPDN project (Figure 4; Bombien et al., 2012). Fourteen lithostratigraphic horizons defined in the GTA, ranging from Upper Permian to Neogene in age, are the main constituents of the GTA3D model (Figure 5). Data inconsistencies such as intersecting horizon surfaces were not revised during modelling and due to the lack of detailed information, faults were modelled separately for each horizon as vertical offsets without trans-horizontal correlation. In the area of the German North Sea, the GTA3D model is complemented by three further horizons which were constructed within the framework of the GPDN project. These are the bases of the Quaternary and Holocene (Asprion et al., 2013a; Asprion et al., 2013b) as well as the seabed surface (Asprion et al., 2013c). The GTA3D model is divided into several map tiles, derived from the 1:100.00 scale topographic map (Figure 4). For the German North Sea sector these models are disseminated through the GPDN webpage, and for the entire model area on the NIBIS® MAPSERVER.

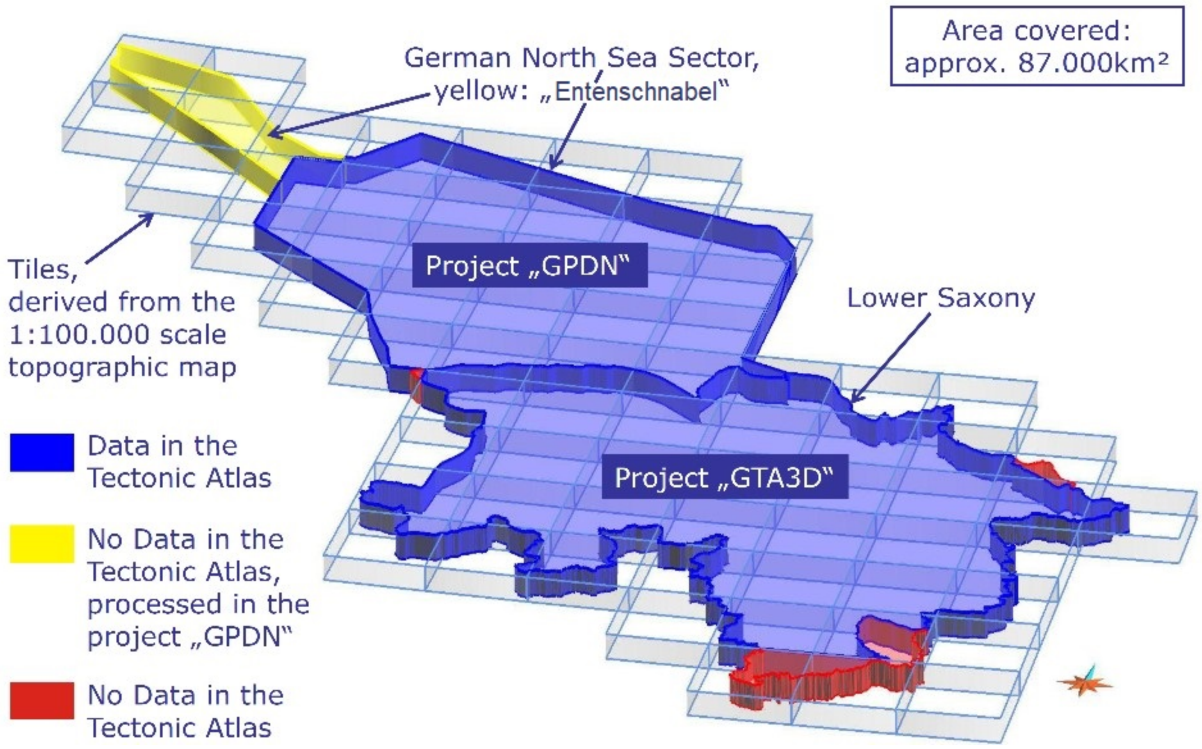

Figure 4: Regional extent of the GTA (©Marcus Helms, LBEG).

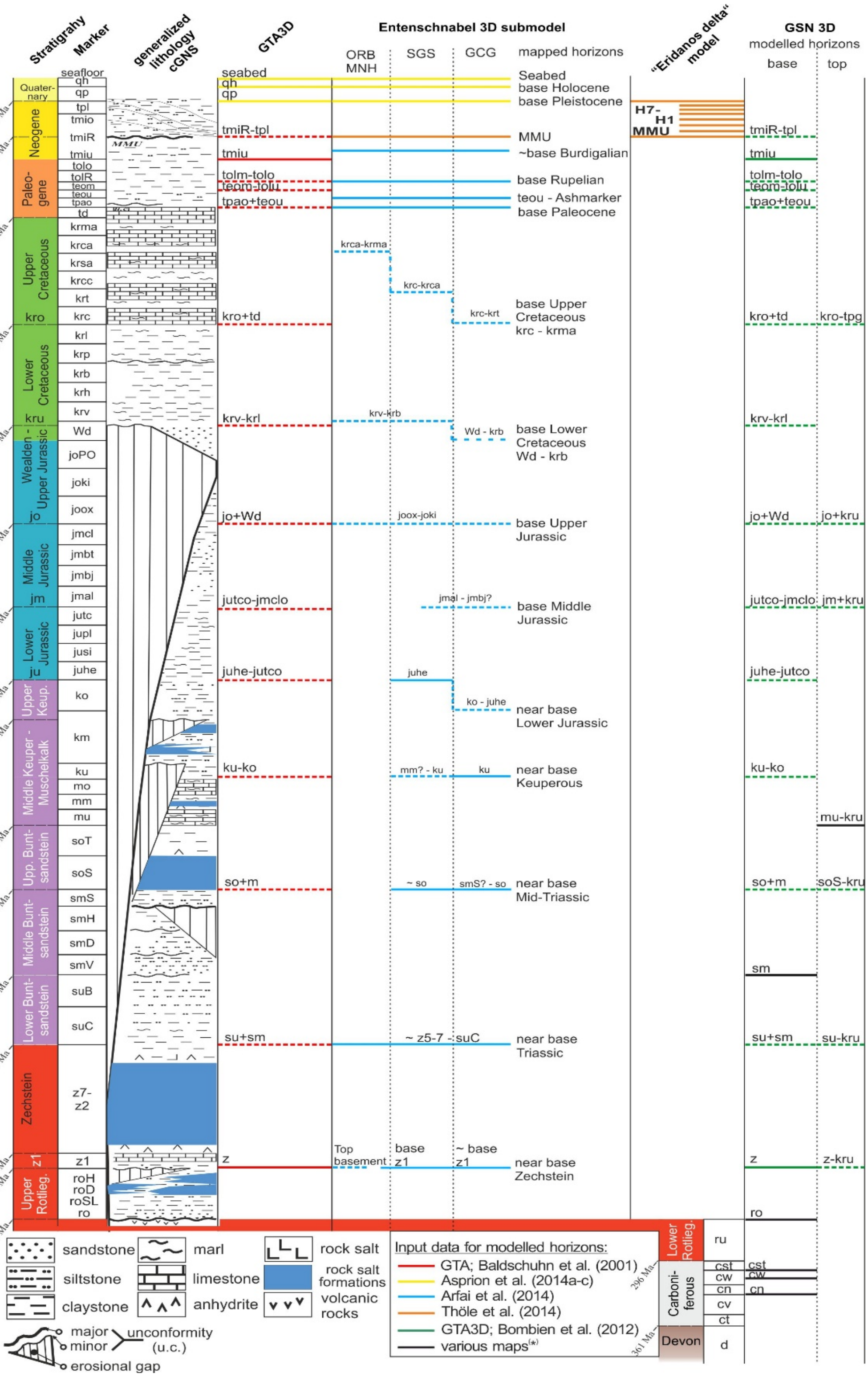

Figure 5: Overview of horizons modelled in different publicly available 3D models of the German North Sea. Due to the supra-regional character of the GTA, generalized bases of lithostratigraphic horizons were defined and mapped. These lithostratigraphic boundaries do not always represent isochronous horizons, but may vary in their chronostratigraphic position as well as in their structural characteristics (concordant layering, interlayer gap, angular unconformity). The age range of individual horizons is highlighted with stratigraphic markers (see LBEG, 2015). Horizons regarded as quasi-chronostratigraphic are indicated by bold lines, whereas as diachronous horizons are marked by dashed lines (Abbreviations: cGNS – central German North Sea; ORB – Outer Rough Basin; MNH – Mid North Sea High; SGS – Step Graben System; GCG – German Central Graben).

2.2.2 3D Entenschnabel model

Within the framework of the GPDN project a detailed seismic mapping study has been carried out by the BGR in the northwestern part of the German North Sea, also referred to as the Entenschnabel (Arfai et al., 2014). No detailed geological interpretation were previously published for this area. Former studies of the deeper underground by Baldschuhn et al. (2001) which were transferred into a 3D model (GTA3D; Bombien et al., 2012) covered only the central part of the German North Sea (Figure 4).

Fourteen seismic horizons, ranging from Upper Permian to Middle Miocene in age, were mapped for the Entenschnabel (Figure 5). These horizons are mostly in accordance with those horizons in the central German North Sea that were previously identified by Baldschuhn et al. (2001). In addition, numerous salt structures and around 800 faults were mapped. Seismic interpretation was based on 3D and 2D seismic data and information from 27 wells.

The results of the mapping campaign were then converted by the LBEG within the GPDN project into a consistent but generalized 3D structural model, referred here to as “3D Entenschnabel model“. The final model is complemented by three further horizons which were also constructed within the framework of the GPDN project. These are the Quaternary and Holocene bases (Asprion et al., 2013a; Asprion et al., 2013b) as well as the seabed surface (Asprion et al., 2013c) (Figure 5). The 3D model of the Entenschnabel region, as well as the seismic interpretation on which the model is based on, are disseminated through the GPDN webpage.

2.2.3 “Eridanos delta” model

The Late Cenozoic sedimentation in the southern North Sea Basin was dominated by a westward prograding depositional system, often referred to as the «Eridanos delta» (Overeem et al., 2001). Within the GPDN project, a detailed seismic stratigraphic subdivision of the post-Mid Miocene succession in the German North Sea was devised by the BGR (Thöle et al., 2014). This framework subdivides the post-Mid Miocene succession into seven seismic units (SU1-SU7), which are separated by distinct seismic surfaces (MMU, H1-H7) that represent major depositional or erosional boundaries. Seismic interpretation was based on more than 29.000 km of 2D seismic data and a limited number of 3D seismic surveys. The age of the seismic units were constrained by biostratigraphic studies on dinocyst assemblages. Depth and thickness maps of the interpreted horizons can be accessed through the GPDN webpage.

2.2.4 GSN 3D

A generalized structural model of the central German North Sea, referred to as GSN 3D, was compiled by the BGR within the GPDN project (Kaufmann et al., 2014). The model is based on the GTA3D (Bombien et al., 2012), the SPBA (Doornenbal and Stevenson, 2010) and further references (Brückner-Röhling, 1999; Krull, 2005; Röhling, 1988). Twenty-six horizons, ranging from Carboniferous to Neogene in age (Figure 5), and 105 fault planes were modelled. The horizons were generalized and inconsistencies (e.g. crossing horizons) were removed. Further, the flanks of salt structures were modelled as vertical walls and faults were only incorporated into the model if they matched certain criteria (fault heave > 100m; fault length > 5 km). Verification was performed using numerous 2D seismic profiles and information from 60 wells. Detailed information on model building is given by Kaufmann et al. (2014). The GSN 3D model formed the base for further modelling within the GPDN project (see sections 2.2.5 & 2.2.6) and can be accessed through the GPDN webpage.

Table 4: Publicly available geomodels in the area of the German North Sea and their main characteristics (part 1).

Model name	GTA3D – North Sea	3D Entenschnabel model	"Eridanos delta" model	GSN 3D
Published	2012	2012	2012	2013
Regional extent	central German North Sea	German Entenschnabel area	German North Sea sector	central German North Sea
Project	GPDN	GPDN	GPDN	GPDN
Projection	WGS84-UTM31N	WGS84-UTM31N	WGS84-UTM31N	WGS84-UTM31N
Input data	Structural depth maps of the GTA (Baldschuhn et al., 2001) Bases of the Quaternary and Holocene (Asprion et al., 2013a; Asprion et al., 2013b) Seabed surface (Asprion et al., 2013c)	2D / 3D seismic survey data, combined with a variety of well data	2D / 3D seismic survey data, combined with a variety of well data	GTA3D – North Sea (Bombien et al., 2012) Various maps (Baldschuhn et al., 2001; Brückner-Röhling et al., 1994; Doornenbal and Stevenson, 2010; Krull, 2005; Röhling, 1988) 2D seismic survey data, combined with a variety of well data
Modelled horizons	16 horizons, ranging from upper Permian to Holcene in age + seabed surface	14 seismically interpreted horizons, ranging from upper Permian to Neogene in age	8 seismically interpreted horizons (MMU to base Pleistocene)	26 modelled horizons, ranging from Carboniferous to Neogene in age
Faults	Vertical fault traces without trans-horizontal correlation	Yes (3D fault planes)	No	105 generalized faults
Velocity model	see Groß (1986)	see Arfai et al. (2014)	See Thöle et al. (2014)	
Output data (sort/type)	Individual 3D models as tiles, derived from the 1:100.000 scale topographic map	3D model + depth and thickness maps	Depth and thickness maps	Depth maps and fault planes
Data format	3D PDF and GOCAD TS object	GOCAD TS object, CPS3 and ESRI-shp Format	CPS3 and ESRI-shp Format	GOCAD TS object
Access via	All 3D models are disseminated through the GPDN webpage (www.gpdn.de). The GTA3D model is also available on the NIBIS MAPSERVER (https://nibis.lbeg.de/cardomap3/)			
References	Bombien et al. (2012)	Arfai et al. (2014)	Thöle et al. (2014)	Kaufmann et al. (2014)

2.2.5 3D lithofacies model – Buntsandstein

A 3D lithofacies model of the Lower Triassic Buntsandstein covering the central German North Sea was built at the BGR within the GPDN project (Wolf et al., 2015). It mainly relies on the pre-existent GSN 3D model (Kaufmann et al., 2014), a new dense 2D seismic reinterpretation of the Buntsandstein formations and 21 wells. The model is layer based and contains 5,015,660 rectangular grid cells, each measuring 1km² with a varying thickness mostly between 5 m and 80 m, reaching a maximum in the western Horn Graben with 130 m for each cell. It shows the spatial distribution of 18 lithology classes for the formations of the Buntsandstein. The lithofacial 3D model, exemplary maps of lithology distribution for different Buntsandstein formations, and a technical report in German are accessible to the public at the GPDN webpage. The model is provided both as a Petrel project file and as a RESCUE grid.

2.2.6 3D petroleum system models

For the area of the German North Sea, three petroleum system models (PSMs) were recently developed at the BGR (Figure 6) and are accessible to the public at the GPDN webpage.

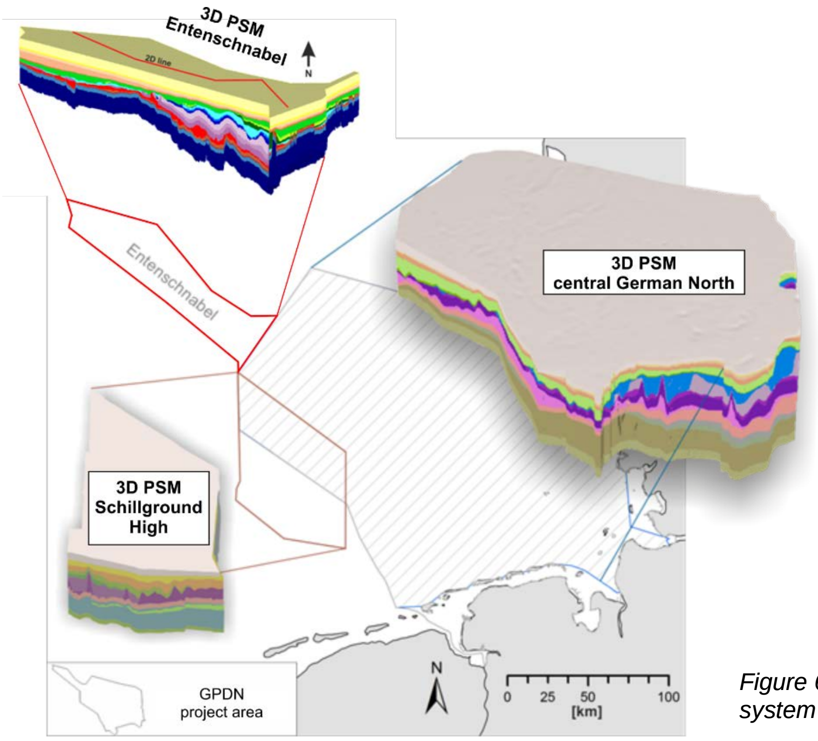

Figure 6: Regional extent of petroleum system models in the German North Sea.

PSM – southern Schillgrund High

One of these models is a cross-border study of the Schillgrund High in the Dutch-German offshore area, which was performed in order to evaluate the hydrocarbon generation and migration from Carboniferous source rocks (Heim et al., 2013). The model includes 20 different stratigraphic layers covering a time interval between Dinantian to the present. Input data for the German part of the 3D basin model were taken from the GSN 3D model of the Central German North Sea (Kaufmann et al., 2014) and from literature. For the Dutch part of the model, TNO provided expertise and data from previous studies of the Dutch North Sea sector (Duin et al., 2006; Kombrink et al., 2012). Both map sets were merged and generalized by smoothing the vertical offset at the map boundaries and by removing layer intersections. In order to reconstruct the considered geological processes during basin evolution, the consistent base model of the present-day situation was supplemented by numerous thickness and depth maps for erosion and salt tectonic processes.

PSM – central German North Sea

Another PSM was developed for the central German North Sea. It comprises 19 different stratigraphic layers covering a time interval between Namurian to the present. Input data for the 3D basin model were taken for the Zechstein to MMU layers from the GSN 3D model of the central German North Sea (Kaufmann et al., 2014) and for Pre-Zechstein formations from literature (Brückner-Röhling et al., 1994; Krull, 2005; Plein, 1995). The map of the seabed surface was taken from the GTA3D model (Asprion et al., 2013c; Bombien et al., 2012). The base model was supplemented by numerous thickness and depth maps for erosion and salt tectonic processes in order to reconstruct the geological processes during basin evolution.

PSM – Entenschnabel

For the northwestern part of the German North Sea (Entenschnabel area), a PSM has been recently developed in order to reconstruct the thermal history, maturity and petroleum generation of three potential source rocks, namely the Namurian–Visean coals, the Lower Jurassic Posidonia Shale and the Upper Jurassic Hot Shale (Arfai and Lutz, 2017). The model is built from recently compiled maps and structural information from the Entenschnabel area (Arfai et al., 2014). These include thickness and depth maps of important stratigraphic seismic horizons as well as locations of faults and salt structures. Petrophysical values and facies information from industrial wells are assigned to the different geological layers in the 3D model. The latter, is further calibrated with temperature and maturity data from wells and the literature. The time span from the Late Paleozoic to the present is represented by the model including three erosional phases related to large-scale tectonic events: the Saalian (Late Carboniferous-Early Permian), the Late Cimmerian (Late Jurassic) and the Sub-Hercynian inversion phase during the Late Cretaceous. Additionally, salt activity through time expressed as diapirs and pillows in the study area are considered within the 3D model.

Table 5: Publicly available geomodels in the area of the German North Sea and their main characteristics (part 2).

Model name	**3D lithofacies model – Buntsandstein**	**3D PSM central German North Sea**	**3D PSM southern Schillgrund High**	**3D PSM Entenschnabel**
Published	2012	2012	2012	201
Regional extent	central German North Sea	central German North Sea	Southern Schillgrund High	German Entenschnabel area
Project	GPDN	GPDN	GPDN	TUNB
Projection	WGS84-UTM31N	WGS84-UTM31N	WGS84-UTM31N	WGS84-UTM31N
Input data	GSN 3D (Kaufmann et al., 2014) Seismic and well data	GSN 3D (Kaufmann et al., 2014) Pre-Zechstein formations compiled from literature (Brückner-Röhling et al., 1994; Krull, 2005; Plein, 1995)	German North Sea: GSN 3D (Kaufmann et al., 2014) Dutch North Sea: DGM-deep (Duin et al., 2006; Kombrink et al., 2012) Various maps	Entenschnabel submodel (Arfai et al., 2014) Pre-Zechstein formations adopted from Doornenbal and Stevenson (2010); Geluk (2007); Krull (2005)
Modelled layers / units	6 Buntsandstein units 18 lithology classes	19 stratigraphic layers (Namurian to the present)	20 stratigraphic layers (Dinantian to the present)	27 modelled layers (Early Carboniferous to the present)
Output data / format	Lithofacies model as Petrel project file or RESCUE grid Lithofacies maps as PDFs	PetroMod model Depth maps, initial thickness maps, erosional maps as CPS3 and ESRI-shp Format	PetroMod model	PetroMod model
Access via	All 3D models are disseminated through the GPDN webpage (www.gpdn.de).			
References	Wolf et al. (2015)		Heim et al. (2013)	Arfai and Lutz (2017)

2.3 Geomodels in the area of the Danish North Sea

GEUS has a long tradition for generating geomodels of the deep surface in the area of the Danish North Sea. In 1995, GEUS published four digital map series of the Danish Central Graben, containing 'Top Chalk' and the Post Chalk Group (Britze et al., 1995d), 'Base Chalk' and the Chalk Group (Britze et al., 1995a), 'Base Cretaceous' and the Cromer Knoll Group (Britze et al., 1995b), and 'Base Upper Jurassic' and the Upper Jurassic (Britze et al., 1995c). The same year GEUS published a digital map of 'The Top pre-Zechstein' covering the Danish territory (Vejbaek and Britze, 1994). More recently, GEUS has generated comprehensive 3D structural models of the Jurassic, Cretaceous and the Cenozoic within the framework of three major multi-client projects:

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

These studies have been made financed by private companies and have not yet been publicly available. 3D maps evolved from the projects, however, are provided by GEUS for the use within the 3DGEO-EU project (see chapter 5.1: "Shared subsurface models").

2.4 Transnational atlases

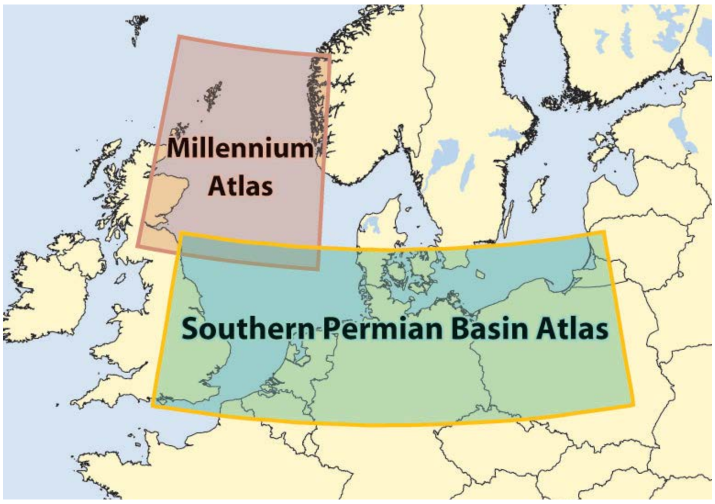

Figure 7: Areas described in the Southern Permian Basin Atlas and the Millennium Atlas (from Doornenbal and Stevenson, 2010).

2.4.1 Southern Permian Basin Atlas (SPBA)

The Petroleum Geological Atlas of the Southern Permian Basin (SPB) area, here referred to as Southern Permian Basin Atlas (SPBA), aims to present a comprehensive and systematic overview of the results of over 150 years of petroleum exploration and research in the SPB (Doornenbal and Stevenson, 2010). The SPBA was a joint project of the Geological Surveys of the United Kingdom, Belgium, Denmark, the Netherlands, Germany and Poland initiated by Ken Glennie and coordinated by the TNO. The atlas was published in both paper and digital format and reviews the entire Southern Permian Basin (SPB) area, including the United Kingdom (UK), Belgium, the Netherlands, Denmark, Germany and Poland between latitudes 50°30'N and 56°N and longitudes 1°45'W and 22°E (Figure 7). It addresses the geological evolution from the pre-Cambrian basement to the Holocene. Various structural and stratigraphic settings and developments are illustrated by a series of overview maps, diagrams and field examples. An important aspect of the atlas is the stratigraphic correlation on a European scale that includes of course the local lithostratigraphic units of Netherlands, Germany and Denmark and large-scale depth and thickness maps. GIS Maps, which are presented in the Atlas can be imported in Petrel and ArcGIS.

2.4.2 Millennium Atlas

The Millennium Atlas describes the petroleum geology of the central and northern North Sea region (Evans et al., 2003). It covers the Danish, Norwegian and UK sectors of the hydrocarbon producing regions of the North Sea from 55°20'N to 62°N (Figure 7). The atlas is organized in twenty chapters and mainly reviews the tectonic evolution and basin history from the Sub-Devonian to the Holocene times. A GIS version of the Millennium Atlas was recently produced and is marked through Beagle Geoscience.

3 RECENT STUDIES OF NL, GER AND DK IN THE NORTH SEA

The following chapter gives an overview of recent and ongoing studies carried out by the participating GSOs in the Dutch, German and Danish North Sea sectors. Findings from these studies may provide helpful information and data for the planned cross-border harmonization. For example, 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") will lead to an revised structural model of the German North Sea. Preliminary grids of this model covering the central German North Sea are already the current base for the cross-border harmonization in 3DGEO-EU WP3.

Dutch North Sea

TNO has recently carried out several multi-client sponsored research projects in cooperation with partners from the E&P industry in the area of the North Sea. These projects had different research focuses and some of their results are already publicly available or will be soon released. These studies are summarized below in Tables 6 and 7.

German North Sea

In 2014, BGR and the geological surveys of the northern German federal states started the above mentioned TUNB project with the primary intention to construct a harmonized 3D model of the North German Basin (NGB). Embedded in the TUNB project, additional research and development work is performed by BGR in the German North Sea area, continuing the systematic work of the GTA (Baldschuhn et al. 2001) and the GPDN project (Reinhardt et al., 2010). This work includes detailed seismic mapping and seismic stratigraphic analysis of Triassic, Jurassic, Cretaceous and Cenozoic sedimentary successions, seismic velocity modelling as well as petroleum system modeling. A more detailed overview of R&D activities carried out within the TUNB project is provided in the annex by two posters presented at the DGGV GeoBremen in 2017.

Danish North Sea

GEUS is continuously carrying out interpretation of available seismic and well data over the Danish North Sea. The aforementioned major multi-client projects (PETSYS, CRETSYS and CENSYS) are particularly notable in this context. A detailed description is provided on the GEUS webpage.

Table 6: Overview of recent and ongoing Joint Industry Research Projects conducted by TNO in the North Sea Basin (part 1).

Project	Title	Stratigraphic interval	Geographic context	Data used	Disciplines	Partner	Periods	Confi-dentiality
CREST	Chalk structural and depositional evolution in the vicinity of salt tectonics structures in the Dutch offshore and onshore: Geophysical and Geological characterization.	Chalk Group	Dutch offshore (Blocks A to M)	Seismic, well and core	Stratigraphy, tectonics seismic processing, seismic amplitude mapping, biostratigraphy	EBN, NAM, Wintershall, Spectrum and Dutch Ministry of Economic Affairs,	Upcoming	Until 2021
Paleo-Five	Paleozoic petroleum potential of the five countries area, Southern-Central North Sea	Lower Carboniferous	Offshore UK, Norway, Denmark, Germany and Netherlands	Outcrop, seismic, well and core data	Biostratigraphy, geochemistry, stratigraphy, sedimentology	Equinor, Total, Repsol, Dana, Edison Norge, Lundin Petroleum, Neptune Energy, ONE-DYAS, PGS, Spectrum, Spirit Energy, Wintershall, BGS	Ongoing	Until 2022
MAXIM	Basin margin-to-axis: tectonostratigraphy of the Dutch Central Graben during the late Jurassic	Middle Jurassic to Lower Cretaceous	Dutch offshore (Blocks A to M)	Seismic, well and core data	Seismic mapping, tectonostratigraphy, provenance, biostratigraphy, paleogeography	Wintershall, NAM, EBN, Neptune, Spectrum and Dutch Ministry of Economic Affairs	Ongoing	Until 2021
MMU	Unravelling the Mid-Miocene Unconformity in the Dutch offshore	Miocene and Pliocene	Dutch offshore (Blocks A to K)	Seismic, cuttings and well data	Seismic mapping, petrography, biostratigraphy, isotope analysis	Wintershall, Neptune, EBN, Rosewood, Taqa and Dutch Ministry of Economic Affairs	2016-2017	Until 2021
HYPOLIAS	Hydrocarbon potential of the Lias	Lower Jurassic	On-and offshore UK, offshore Norway and Netherlands	Outcrop, well and core data	Biostratigraphy, stratigraphy and geochemistry	NAM, Statoil, EBN, OGA and Dutch Ministry of Economic Affairs	2016-2017	End late 2019
STEM	Salt tectonics early movement in the Dutch Offshore	Permo-Triassic	Dutch Offshore (Blocks A to M)	Seismic, wells, cuttings and core data	Seismic mapping, tectonostratigraphy, structural restoration and geochemistry	Wintershall, EBN, Sterling Resources, Spectrum and Dutch Ministry of Economic Affairs	2017-2018	Until 2021

Table 7: Overview of recent and ongoing Joint Industry Research Projects conducted by TNO in the North Sea Basin (part 2).

Project	Title	Stratigraphic interval	Geographic context	Data used	Disciplines	Partner	Periods	Confi-dentiality
COMMA	Understanding Jurassic sands along the complex	Middle Jurassic to Lower Cretaceous	Dutch Offshore, Terschelling Basin	Seismic, well and core data	Seismic mapping, tectonostratigraphy, biostratigraphy, paleogeography	Dutch Ministry of Economic Affairs, ONE, EBN	2016	Public
FOCUS	Upper Jurassic Sandstones: Detailed sedimentary facies analyses, correlation and stratigraphic architectures of hydrocarbon bearing shoreface complexes in the Dutch offshore.	Middle Jurassic to Lower Cretaceous	Dutch Offshore (Blocks A to M)	Seismic, well and core data	Seismic mapping, tectonostratigraphy and biostratigraphy	Dutch Ministry of Economic Affairs, EBN, Wintershall, Sterling Resources and ONE	2014-2016	Public
Sweet Spot 1 and 2	Improved Sweet Spot Identification and smart development using integrated reservoir characterization	Lower Jurassic	On-and offshore UK, Netherlands	Outcrop, well, core data	Petrography, sedimentology, geochemistry and biostratigraphy	Total, EBN, ENGIE and Wintershall	2013-2016	Public
Northern Offshore	New Petroleum plays in the Dutch Northern Offshore	Namurian to Permian	Dutch Offshore (Blocks A to F) and neighboring areas	Seismic, well, core data	Seismic mapping, stratigraphic correlation, petrography, petroleum system modeling	Centrica, Total, Fugro, NAM, Petrogas, Wintershall and Dutch Ministry of Economic Affairs	2013-2015	Public
JUSTRAT	New stratigraphic framework for the Upper Jurassic-Lower Cretaceous in the southern North Sea using integrated novel techniques	Middle Jurassic to Lower Cretaceous	Dutch Offshore (Blocks A to Q)	Well, core and cuttings	Stratigraphy, biostratigraphy, geochemistry	Centrica, Petrogas, Sterling Resources and Dutch Ministry of Economic Affairs	2014-2015	Public
Shallow Gas	Anatomy of the Cenozoic Eridanos Delta hydrocarbon system	Plio-Pliestocene	Dutch Offshore (A, B and F Blocks)	Seismic, core, cuttings, wells	Seismic mapping, stratigraphy, chronostratigraphy, biostratigraphy	EBN, ONE, Chevron, Dana, Total	2011-2013	Public

4 BASELINE DATA FOR HARMONIZATION

Seismic and well information are the principal baseline data for 3D geological modelling and the shared access to these data is vital for cross-border harmonization issues. However, 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. The following section summarizes the disparity of national laws and their consequences for sharing subsurface data within the GeoERA project.

4.1 Legal constraints on sharing subsurface data

Data on the deep subsurface tend to derive from high investment exploration and production (E&P) activities, mainly for oil and gas. Seismic surveys and deep wells are thus subject to business interests and mostly are classified as company secrets. The duration of confidentiality is, however, determined differently by the legislation in each country (Table 8):

- In the Netherlands, a new Mining Law came into force on 1st January 2003. Before this date, there was no legal regulation for the release of onshore well and seismic data, whereas offshore data remained confidential for 10 years. Since the new Mining Law was established, geological data becomes publicly available after 5 years. An exception are multi-client seismic surveys whose confidentiality was extended in early 2016 from 5 to 10 years.
- In Denmark, subsurface data that companies have compiled under licenses granted in pursuance of the Danish Subsoil Act are generally protected by a five-year confidentiality clause. However, the confidentiality period is limited to two years if the license has expired or been relinquished.
- In Germany, most exploration data are classified as confidential, no matter how old they are and whether or not the concession still exists. To use these data an approval of the owner is required.

Further, the provision of subsurface data is handled in a slightly different manner in the participating countries:

- In the Netherlands, non-confidential well and seismic data are usually available free of charge and can be accessed e.g. through the Netherlands Oil and Gas Portal (NLOG). A small processing fee, however, will be charged for the provision of larger seismic datasets.
- In Denmark, certain well data are available free of charge (completions reports, deviation data & lithostratigraphical formations tops). Further well and seismic data are sold via GEUS' webshop Frisbee or can be ordered for a fee from GEUS' Subsurface Archive.
- In Germany, the data of E&P campaigns are stored at the companies and in the archives of the state authorities in charge. In the case of the North Sea, by mutual consent between the Federal Government and the Federal State of Lower Saxony, the Office for Mining, Energy and Geology (LBEG) of Lower Saxony is responsible. Released data are generally provided by the LBEG, whereas confidential data have to

be requested either by the BVEG (Bundesverband Erdgas, Erdöl und Geoenergie e.V.) or for data from non-BVEG companies individually at the data owners. Seismic data acquired by the BGR are made available free of charge via the Geo-Seas webpage.

The current legal situation in Germany, as well as the differences in providing released well and seismic data, impedes the exchange of subsurface information among the participating partners. Although publicly available 3D geological models in the German North Sea are partly evolved from confidential data, BGR cannot easily share these baseline data for harmonization purposes with the other GSOs. Restricted data from the German offshore sector can be provided only after approval of the data owner, while derived interpretations that do not allow any conclusions to be drawn about the source data can be shared with the other project partners without restrictions. A further complication for sharing data is that GEUS is partly financed by the sale of subsurface data and therefore free access to this data is not always guaranteed for GSOs of neighboring countries. TNO is the only project partner that can provide the baseline data for the cross-border harmonization without any restrictions.

Table 8: Legal regulations accessing subsurface data in the Netherlands, Germany and Denmark.

<table>
<tr><th>Country</th><th>Confidentiality period</th><th>Data type</th><th>Accessing the data</th></tr>
<tr><td rowspan="4">Netherlands</td><td rowspan="3">5 years
(after acquisition)</td><td>Well data</td><td rowspan="4">Released well and seismic data can be ordered or downloaded via the following links:

www.nlog.nl
www.dinoloket.nl.

Free of charge: Selected seismic lines and surveys can be downloaded for free (providing the total size does not exceed 200MB/1GB).

A fee, however, will be charged for any work done by the TNO Service desk.</td></tr>
<tr><td>Seismic data</td></tr>
<tr><td>Reprocessed seismic surveys</td></tr>
<tr><td>10 years
(after acquisition))</td><td>Multi-client seismic surveys</td></tr>
<tr><td>Germany</td><td>everlasting</td><td>Well and seismic data</td><td>Subsurface information remain confidential and the initial owner must give approval for subsequent access.</td></tr>
<tr><td rowspan="3">Denmark</td><td rowspan="3">5 years
(after acquisition)</td><td>Well data</td><td>Released data are sold as “well data packages“ via GEUS’ webshop Frisbee

Free of charge: completion reports, deviation data & lithostratigraphical Formation Tops</td></tr>
<tr><td>2D seismic data</td><td>Purchase of released 2D seismic data and other geophysical data (e.g. CSEM) is handled by GEUS’ Subsurface Archive</td></tr>
<tr><td>3D seismic data</td><td>Released 3D data (processed or re-processed) are sold via GEUS’ webshop Frisbee</td></tr>
</table>

4.2 Data coverage

4.2.1 Well data

Figure 8 gives a general overview about existing well data in the Dutch-German-Danish offshore border region. Almost all wells in the German sector of the North Sea are classified as confidential, whereas most wells in the Netherlands and Denmark are publicly available. The overview illustrates further the good coverage with well data in the Entenschnabel working area, but also the low data density in the Horn Graben region.

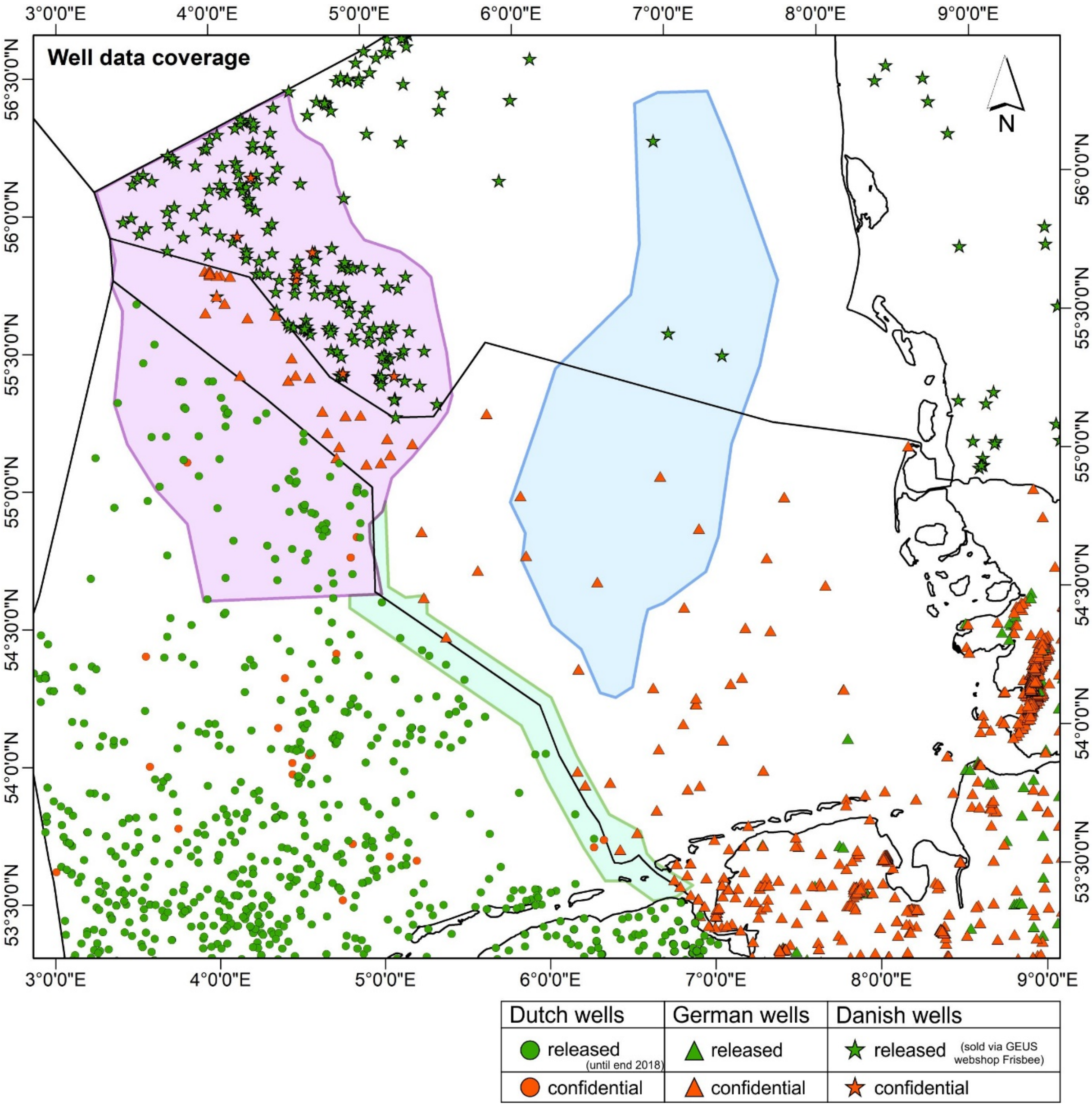

Figure 8: Released and confidential deep (> 100 m) wells in the Dutch-German-Danish offshore border region with working areas indicated by colored polygons (purple: Entenschnabel region; green: Dutch-German offshore border area; blue: Horn Graben region). (Status: Dutch data – June 2019; German data – June 2019; Danish data – June 2019).

4.2.2 Seismic data

Figures 9 and 10 give a general overview about existing 2D/3D seismic surveys in the Dutch-German-Danish offshore border region. The distribution of released and confidential seismic data shown in these figures nicely reflects the different legal regulations accessing subsurface data in the participating countries. In Germany, most seismic data are confidential, no matter how old they are and whether or not the concession still exists, whereas in the other participating countries a large number of seismic surveys have been made available to the public.

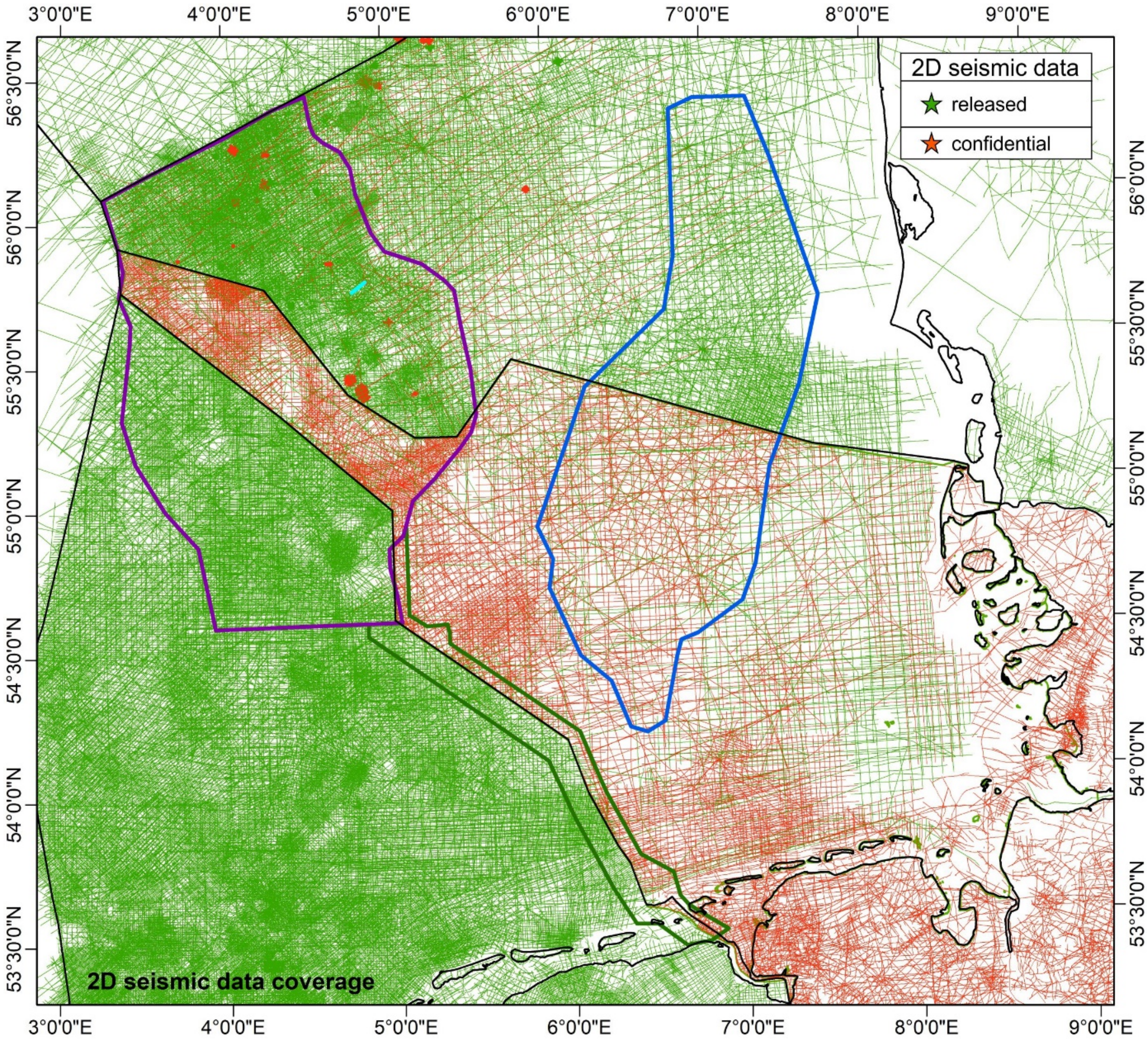

Figure 9: Released and confidential 2D seismic surveys in the Dutch-German-Danish offshore border region with working areas indicated by colored polygons (purple: Entenschnabel region; green: Dutch-German offshore border area; blue: Horn Graben region). (Status: Dutch data – June 2019; German data – June 2019; Danish data – June 2019).

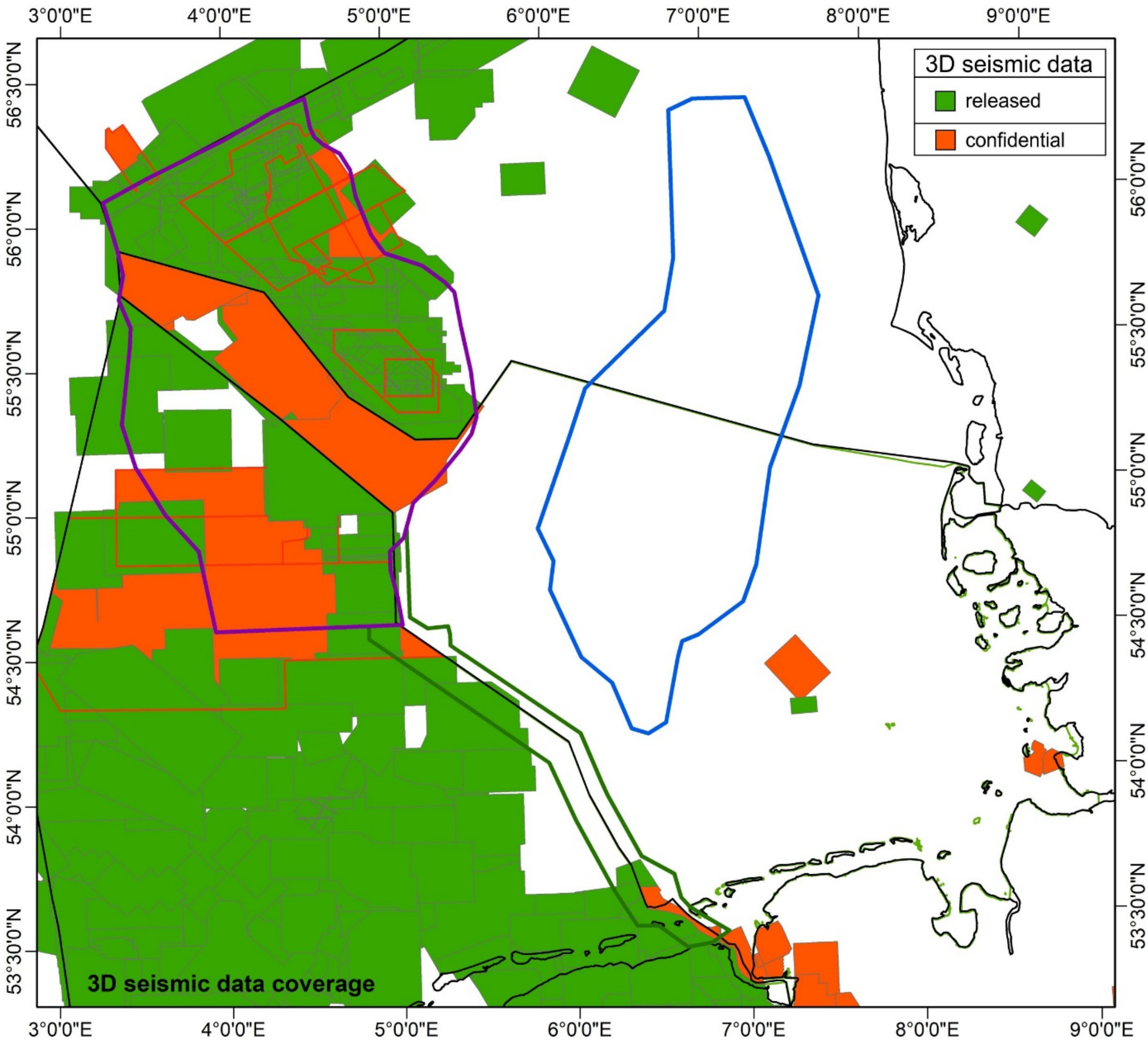

Figure 10: Released and confidential 3D seismic surveys in the Dutch-German-Danish offshore border region with working areas indicated by colored polygons (purple: Entenschnabel region; green: Dutch-German offshore border area; blue: Horn Graben region). (Status: Dutch data – June 2019; German data – June 2019; Danish data – June 2019).

5 CROSS-BORDER HARMONIZATION

5.1 Shared subsurface models

TWT (Two-Way Travel time) horizon grids of various model sources were provided by the participating GSOs in an initial phase of the project in order to identify possible cross-border discrepancies of existing 3D models. These initially shared grids are listed below for the Entenschnabel region in Table 9 and for the working area along the Dutch-German offshore border area in Table 10. No subsurface interpretations have been shared so far for the Horn Graben region, as GEUS is currently carrying out a seismic re-interpretation of the Danish part of the Horn Graben.

Table 9: Currently shared TWT horizons grids in the Entenschnabel region and their sources.

Key horizons		Entenschnabel region					
		Dutch North Sea		German North Sea		Danish North Sea	
		Grid name	Grid source	Grid name	Grid source	Grid name	Grid source
1	Near MMU	NU_2D3D_base_grd	DGM-deep v5.0	01_tmiR_MMU	«Eridanos delta» model (GPDN)	MMU_BSeqE_TWT_d200_14_80Ma_XYZ	GEUS current structural database
2	Near Base Cenozoic	N_2D3D_base_grd	DGM-deep v5.0	05_tpao_T1	3D model Entenschnabel (GPDN)	Top_CHALK_TWT_d200_61_60Ma_XYZ	GEUS current structural database
3	Base Upper Cretaceous	CK_2D3D_base_grd	DGM-deep v5.0	06_kro_Kr2	3D model Entenschnabel (GPDN)	Base_CHALK_TWT_d200_100_50Ma_XYZ	GEUS current structural database
4	Near base Lower Cretaceous	KN_2D3D_base_grd	DGM-deep v5.0	07_kru_Kr1	3D model Entenschnabel (GPDN)	BCU_TWT_d200_140_75Ma_XYZ	GEUS current structural database
5	Near base Upper Jurassic	S_2D3D_base_grd	DGM-deep v5.0	08_jo_J3	3D model Entenschnabel (GPDN)	Base_UppJuraPSS_9_TWT_d200_161Ma_XYZ	GEUS current structural database
6	Near base Middle Jurassic	**no data**		09_jm_J2	3D model Entenschnabel (GPDN)	**no data**	
7	Near base Lower Jurassic	AT_2D3D_base_grd	DGM-deep v5.0	10_ju_J1	3D model Entenschnabel (GPDN)	Base_Jura_PSS_1_TWT_d200_201Ma_XYZ	GEUS current structural database
8b	Near base Middle Triassic	RN_2D3D_base_grd	DGM-deep v5.0	12_so_Tr3	3D model Entenschnabel (GPDN)	**no data**	
8	Base Lower Triassic	RB_2D3D_base_grd	DGM-deep v5.0	Tr1_Base	3D model Entenschnabel (GPDN)	base_Triassic_TWT	GEUS current structural database
9	Base Zechstein	ZE_2D3D_base_grd	DGM-deep v5.0	Z_nearbase	3D model Entenschnabel (GPDN)	Base_Zech_TPZ_TWT_d200_256Ma_XYZ	Top pre-Zechstein (Britze et al., 1995)

Table 10: Currently shared TWT horizons grids along the Dutch-German offshore border area and their sources.

Key horizons		Dutch-German offshore border area			
		Dutch North Sea		German North Sea	
		Grid name	Grid source	Grid name	Grid source
1	Near MMU	NU_2D3D_base_grd	DGM-deep v5.0	01_tmiR_MMU	«Eridanos delta» model (GPDN)
2	Near Base Cenozoic	N_2D3D_base_grd	DGM-deep v5.0	05_tpao_T1	Preliminary grids (TUNB project)
3	Base Upper Cretaceous	CK_2D3D_base_grd	DGM-deep v5.0	06_kro_Kr2	Preliminary grids (TUNB project)
4	Near base Lower Cretaceous	KN_2D3D_base_grd	DGM-deep v5.0	07_kru_Kr1	Preliminary grids (TUNB project)
5	Near base Upper Jurassic	S_2D3D_base_grd	DGM-deep v5.0	08_jo_J3	Preliminary grids (TUNB project)
6	Near base Middle Jurassic	**no data**		09_jm_J2	Preliminary grids (TUNB project)
7	Near base Lower Jurassic	AT_2D3D_base_grd	DGM-deep v5.0	10_ju_J1	Preliminary grids (TUNB project)
8b	Near base Middle Triassic	RN_2D3D_base_grd	DGM-deep v5.0	12_so_Tr3	Preliminary grids (TUNB project)
8	Base Lower Triassic	RB_2D3D_base_grd	DGM-deep v5.0	Tr1_Base	Preliminary grids (TUNB project)
9	Base Zechstein	ZE_2D3D_base_grd	DGM-deep v5.0	Z_nearbase	Preliminary grids (TUNB project)

5.2 Possible focus and type of harmonization

Several cross-border discrepancies of defined key horizons (Figure 2) became apparent during the comparison of the initially shared horizon grids (Tables 10 & 11) and are described in detail for the different working areas in the appendix. Based on the differences identified, possible focuses and the type of the planned cross-border harmonization were discussed during a GeoERA WP3 meeting held in Hannover (27.-29. May 2019). The priorities envisaged for the harmonization and the challenges presumably associated with them are briefly outlined below.

5.2.1 Harmonization of structural interpretations

The model horizons compared in the time domain (see Appendix) show generally a good fit along the national borders when viewed on a larger scale. Existing cross-border discrepancies often emerge in areas of high structural complexity such as in the vicinity of salt dome flanks and tops or along major faults like the Coffee Soil / Schillgrund Fault zone at the eastern boundary of the Central Graben. The reasons for such discrepancies are not always obvious and may be caused by a combination of independent factors. In general, structural interpretation especially in areas of high structural complexity is subject to uncertainty, which can be seen as a function of data distribution and the structural complexity experience and bias of the interpreter (e.g., Bond et al., 2007). Moreover, structural interpretation based on seismic data is often performed in a resolution much higher than it is possible to be represented in a 3D model. Therefore, subsequent to seismic interpretation, a suitable generalization is usually required, which reduces the structural elements included in the 3D model and, at the same time, maintains the model constraints. The approach and the degree of generalization, however, is rarely the same and can therefore differ considerably. In order to find and test efficient workflows to overcome these challenges, harmonization of the Coffee Soil / Schillgrund Fault zone at the eastern border of the Central Graben is regarded as an appropriate example by the participating partners as it runs through all countries.

5.2.2 Evaluation of major horizon discrepancies

In the western part of the Entenschnabel region (Outer Rough Basin & High / Step Graben), major discrepancies in distribution and thickness of certain stratigraphic intervals (e.g. near bases of the Lower Cretaceous, Upper Jurassic and Lower Triassic) were identified during the initial cross-border comparison of the shared horizons models (see Appendix for details). These misfits are probably related to national differences in lithostratigraphic, seismic stratigraphic and interpretational concepts (e.g., Arfai et al., 2011). In general, the stratigraphic subdivision of the North Sea Basin has evolved from regional approaches and reflects the complex basin evolution featuring laterally varying sedimentary cycles. Grown historically different nomenclatures and subdivisions on the detailed scale are therefore used. Thus, working cross-border requires also a semantic harmonization and the alignment of stratigraphic peculiarities to allow the correlation of a uniform lithostratigraphic column with the prominent seismic reflectors traceable over the entire basins. A closer evaluation of the observed discrepancies and their causes is an important step in this process and will be a focus of upcoming work.

5.2.3 Cross-border velocity model

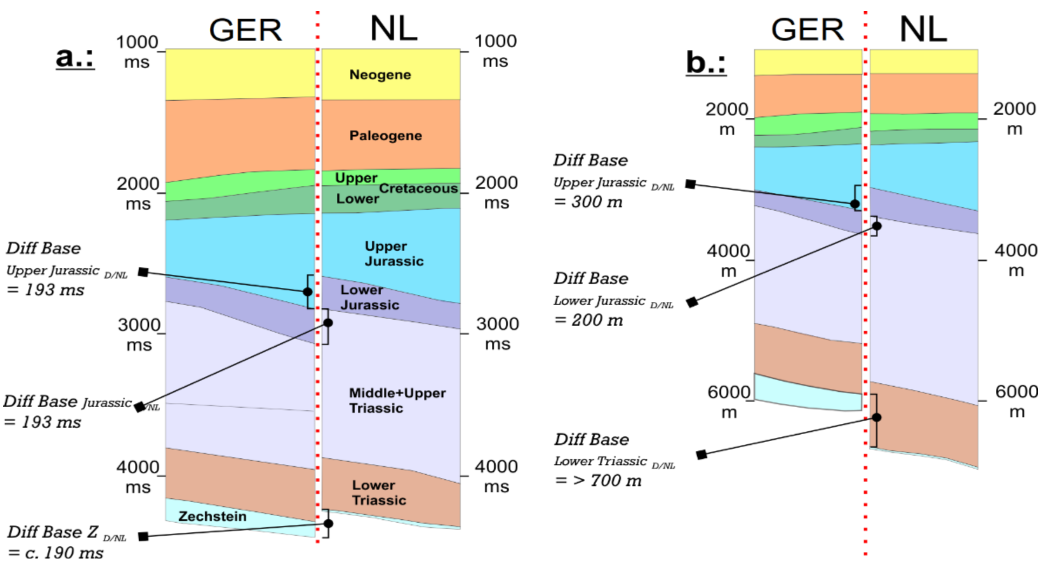

Figure 11: Cross-border comparison of horizon models between offshore GER and NL in the southeastern Entenschnabel in time (a) and depth (b) domain. (a) Differences in TWT are mainly the result of differences in seismic stratigraphic concepts, raw data or structural interpretation. Concerning the GER/NL offshore border region, major differences are visible for the Mesozoic to Paleozoic. (b) Differences observed in TWT interpretation may be increased or decreased by time-depth conversion, depending on differences in the velocity model used for conversion. Note increase in vertical difference in the Lower Triassic after depth conversion.

Differences observed in TWT-interpretation may be increased or decreased by time-depth conversion, depending on differences in the national velocity model used for conversion (Arfai et al., 2014; Groß, 1986; Japsen, 1993; van Dalfsen et al., 2006). Especially in the deeper graben systems where the rock intervals are not supported by drilling data sometimes major discrepancies across border can be observed (Figure 11). In addition to the above-mentioned challenges, an essential step for the planned cross-border harmonization in WP3 will be therefore the development of a transnational velocity model (see Appendix of Deliverable D3.2).

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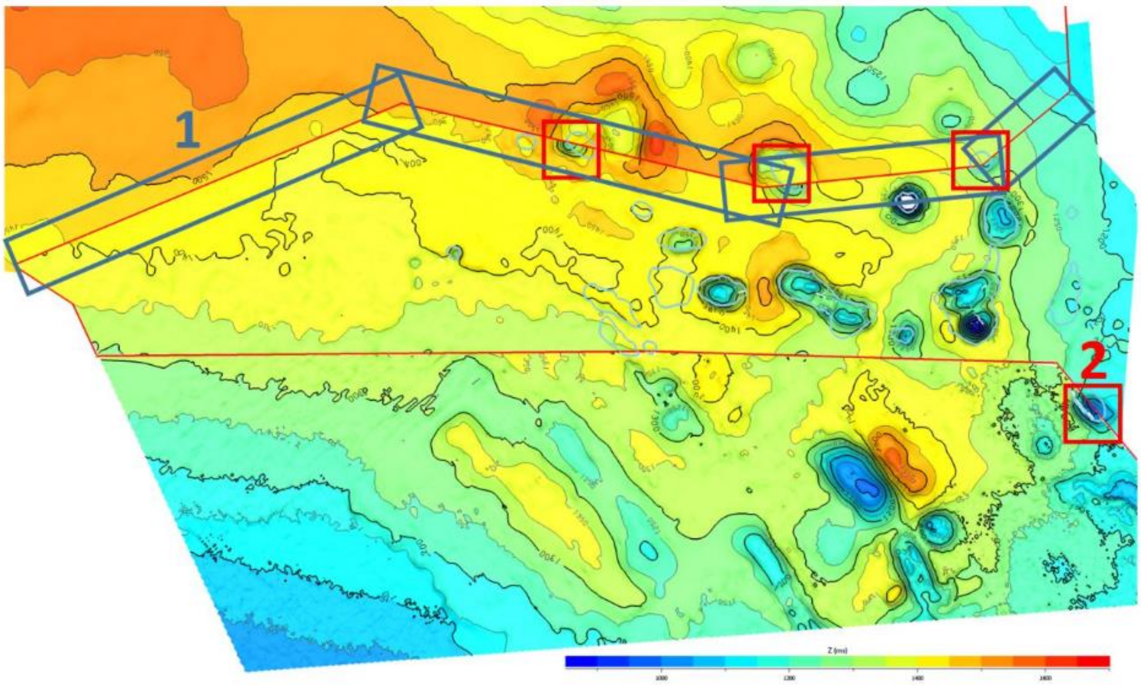
7 APPENDIX

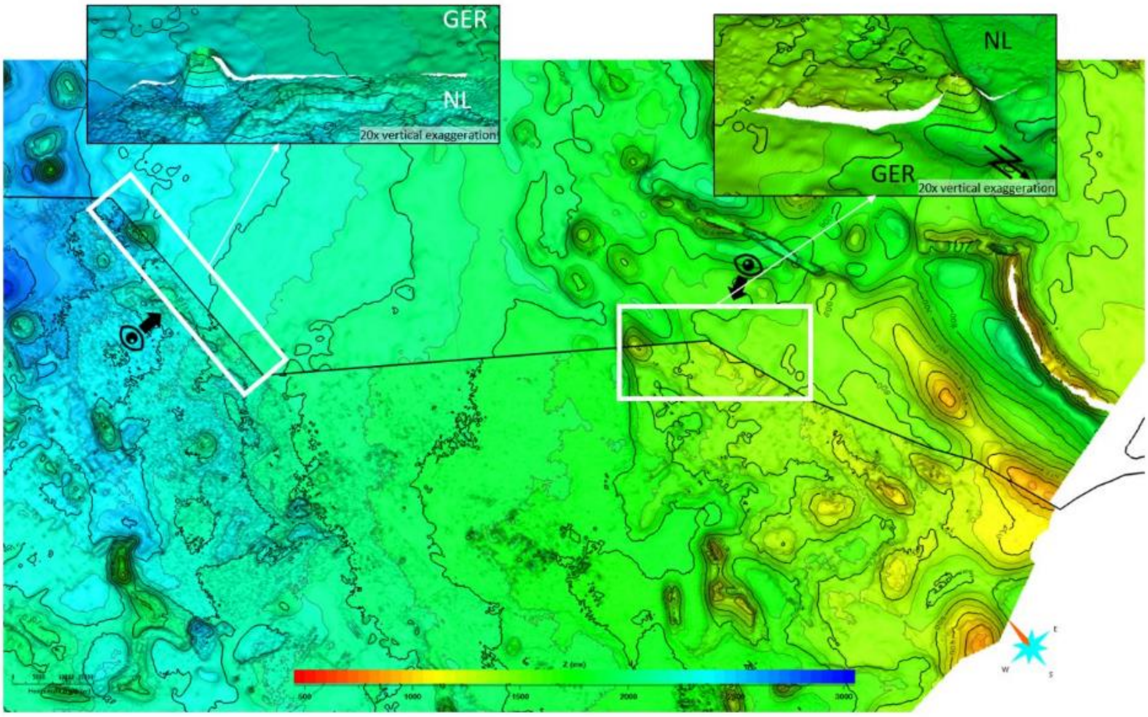
7.1 Cross-border discrepancies of key horizons

In an initial phase of the project, TWT horizon grids of various model sources were provided by the participating GSOs in order to identify possible cross-border discrepancies of existing 3D models. The observed cross-border discrepancies of this initial analysis are summarized below for the defined key horizons (Figure 2).

7.1.1 Near Mid Miocene Unconformity

<table>
<tr><td>Horizon name</td><td>Near Mid Miocene Unconformity</td><td>Horizon Nr.</td><td>1</td></tr>
<tr><td>Working area</td><td colspan="3">Entenschnabel region</td></tr>
<tr><td colspan="4">
</td></tr>
<tr><td colspan="4">Discrepancies and their possible reasons</td></tr>
<tr><td colspan="4">(1) Misfits around 50 ms along the DE-DK border (bluish rectangles)
(2) Differences > 50 ms atop of salt structures crossing the borders (red squares)
Possible reason:
o Misfits due to difference in seismic horizon definition
o Differences in seismic data quality
o Gridding issues</td></tr>
</table>

Horizon name	Near Mid Miocene Unconformity	**Horizon Nr.**	1
Working area	Dutch-German border region		



Discrepancies and their possible reasons

(1) generally good fit with minor bulk shift

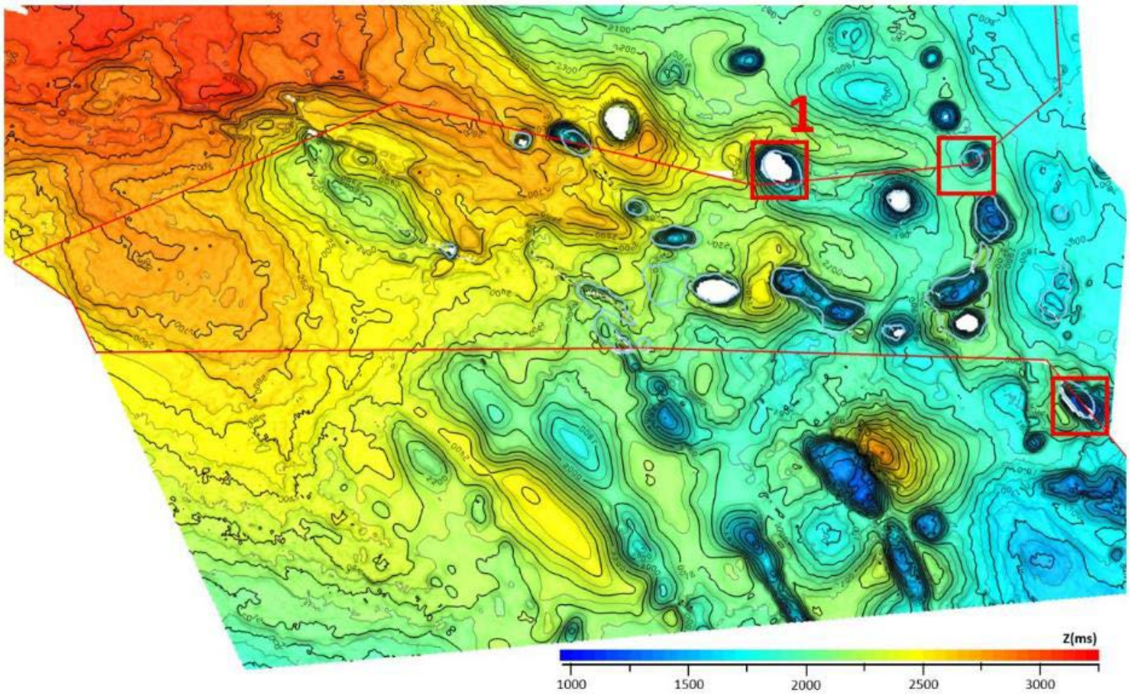
(2) locally major differences, e.g. G+L-platforms (**right zoom-in**)

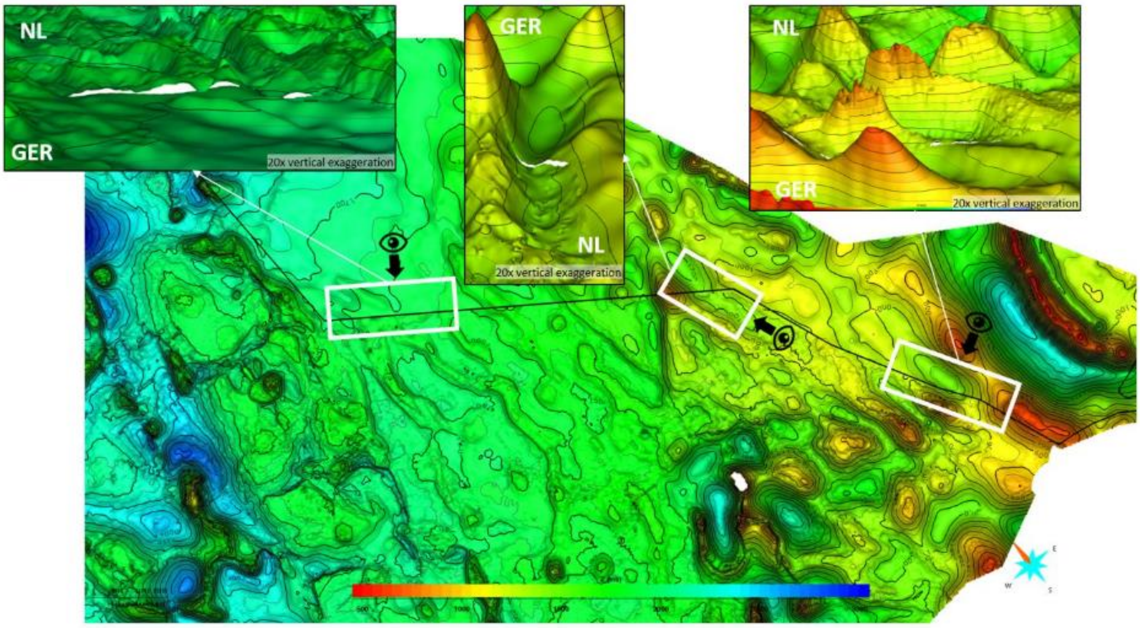
(3) Differences >50 ms atop of salt structures (**left zoom-in**)

Possible reason:

- Misfits due to difference in seismic horizon definition
- Differences in seismic data quality
- Gridding issues

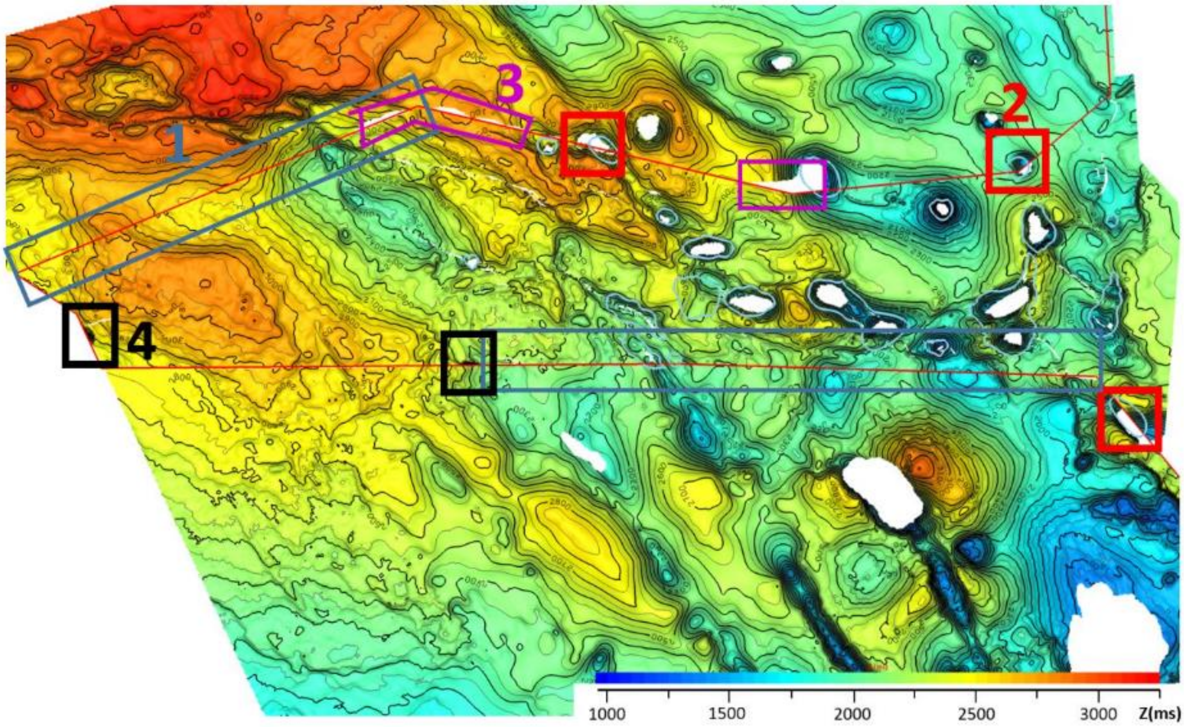
7.1.2 *Near base Cenozoic*

<table>
<tr><td>Horizon name</td><td>Near base Cenozoic</td><td>Horizon Nr.</td><td>2</td></tr>
<tr><td>Working area</td><td colspan="3">Entenschnabel region</td></tr>
<tr><td colspan="4">
</td></tr>
<tr><td colspan="4">Discrepancies and their possible reasons</td></tr>
<tr><td colspan="4">(1) Differences > 50 ms atop of salt structures crossing the borders (red squares)
Possible reasons:
o Misfits due to difference in seismic horizon definition
o Differences in seismic data quality
o Gridding issues</td></tr>
</table>

<table>
<tr><td>Horizon name</td><td>Near base Cenozoic</td><td>Horizon Nr.</td><td>2</td></tr>
<tr><td>Working area</td><td colspan="3">Dutch-German border region</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="4">Discrepancies and their possible reasons</td></tr>
<tr><td colspan="4">(1) generally good fit with minor bulk shift; NL grid higher roughness
(2) some vertical gaps of approx. 20 ms between grids (zoom-ins); vertical gaps, at least in some locations, associated with interpretation of salt structures
Possible reasons:
o Misfits due to difference in seismic horizon definition
o Differences in seismic data quality
o Gridding issues</td></tr>
</table>

7.1.3 Base Upper Cretaceous

Horizon name	Base Upper Cretaceous	**Horizon Nr.**	3
Working area	Entenschnabel region		



Discrepancies and their possible reasons

(1) Differences in time gids of 50-100 ms (**bluish rectangles**)

(2) Differences > 50 ms atop of salt structures crossing the borders (**red squares**)

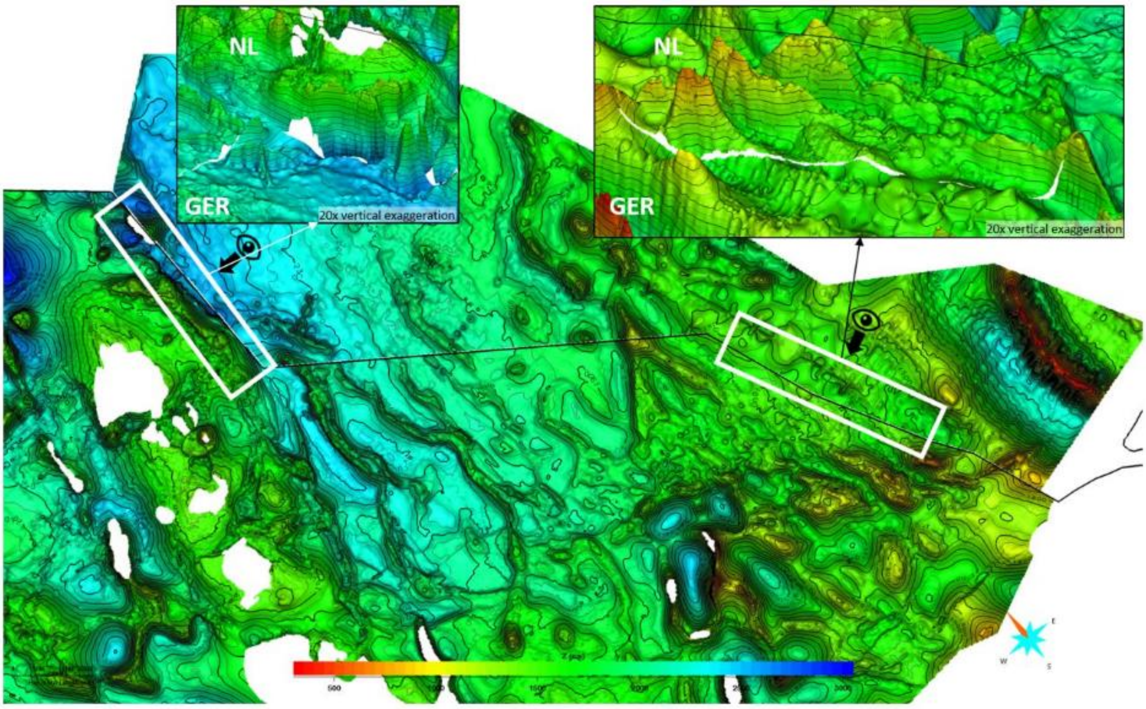
(3) Gaps in (picks) or gridding artefacts (**purple polygons**)

(4) Gridding artefacts (**Black squares**)

Possible reasons:

- Misfits due to difference in seismic horizon definition
- Differences in seismic data quality
- Gridding issues

Horizon name	Base Upper Cretaceous	Horizon Nr.	3
Working area	Dutch-German border region		



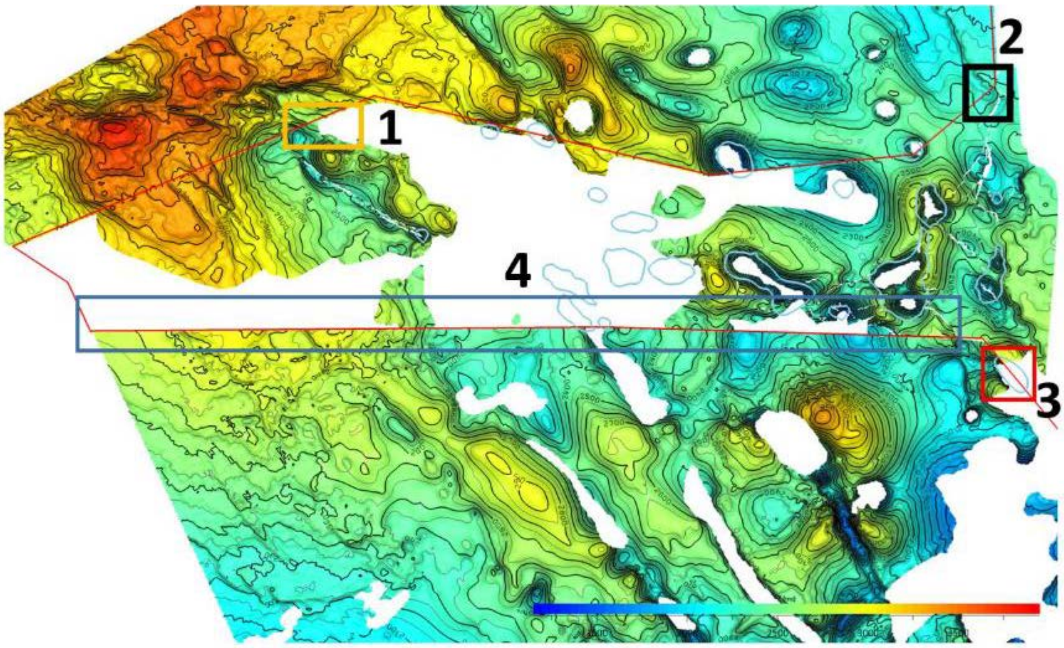
Discrepancies and their possible reasons

(1) some major differences in time of 50-100 ms (due to differences in interpreted horizons / fault interpretation) in transition between Dutch Central Graben and German Schillgrund-Hoch (**left zoom-in**)

(2) constant gap (approx. 10-20 ms) in southern part (NL Schillgrund & Ameland Platforms, GER: G+L-Platform) (**right zoom-in**)

7.1.4 Near base Lower Cretaceous

Horizon name	Near base Lower Cretaceous	**Horizon Nr.**	4
Working area	Entenschnabel region		



Discrepancies and their possible reasons

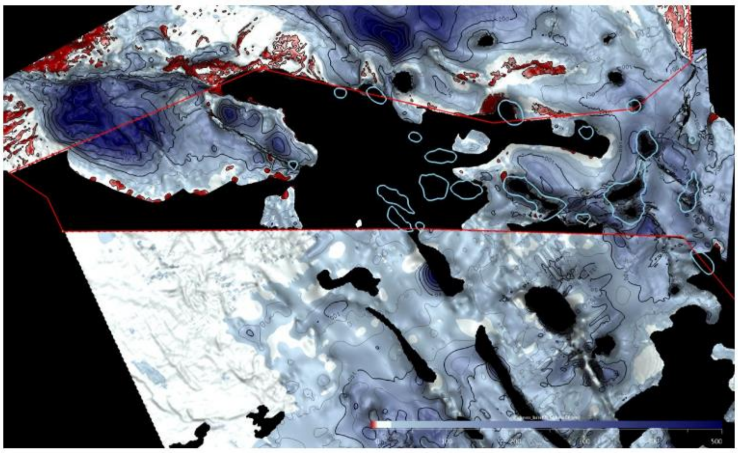
General note: Good fit between DK and DE. Less well fit between DE and NL (issues concerning definition of a ”base Cretaceous” horizon (Wealden, Ryazanian, …)).

(1) Trend of DE grid not well constrained due to low data density (**orange rectangle**)

(2) Gridding artefacts (**black square**)

(3) Differences in structural picking concepts (**red square**)

(4) Differences in horizon definition (“Base Cretaceous” definition) (**bluish rectangle**).



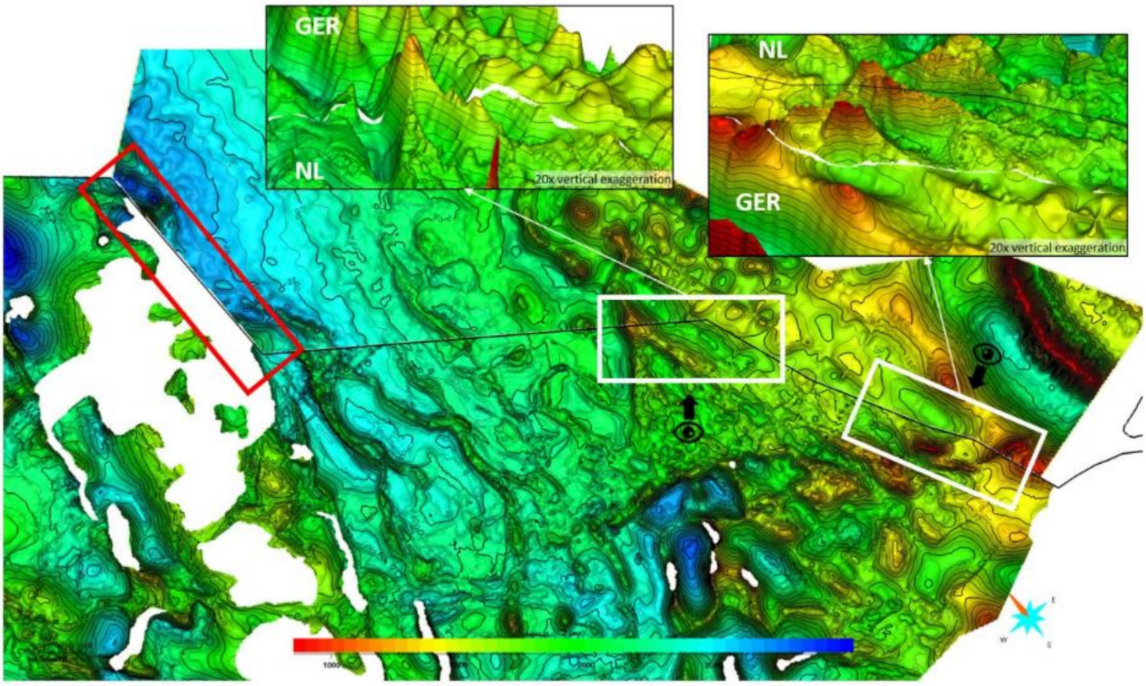
Thickness map (Lower Cretaceous)

Distribution pattern indicate strong differences in NL, DE and DK interpretation of the Lower Cretaceous.

However, thickness maps reveal that differences are small, in most cases below 20ms.

Areas with very low thickness in DK and NL correspond well with regions of non-distribution in GER.

Horizon name	Near base Lower Cretaceous	**Horizon Nr.**	4
Working area	Dutch-German border region		



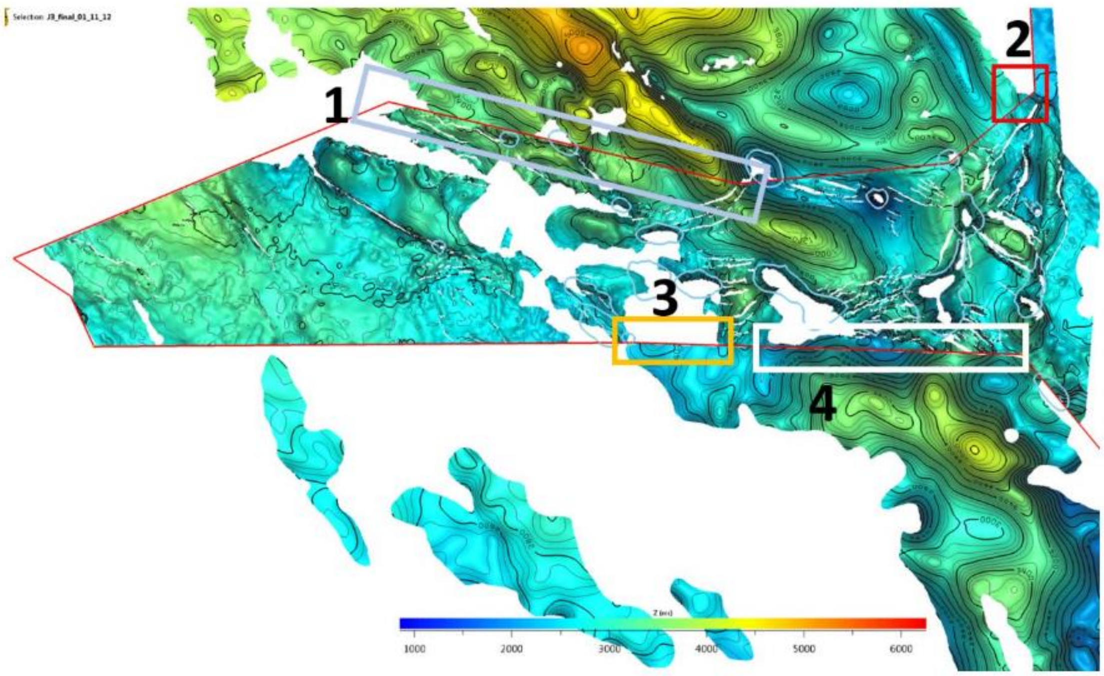
Discrepancies and their possible reasons

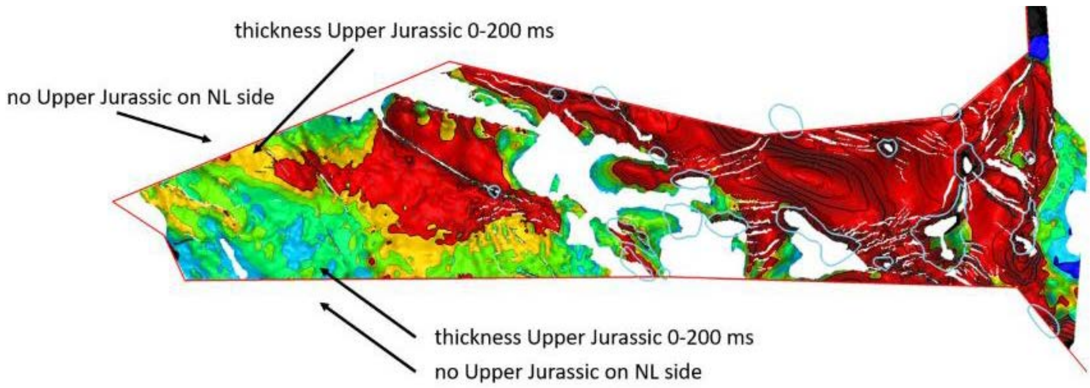
(1) Strong contrast in distribution of Lower Cretaceous strata in transition of Dutch Central Graben and German Schillgrund High (**red rectangle**)

(2) “bulk shift” vertical gap (differences in picked seismic reflector?) (**zoom-ins**)

7.1.5 *Near base Upper Jurassic*

Horizon name	Near base Upper Jurassic	**Horizon Nr.**	5
Working area	Entenschnabel region		





TWT thickness map (Upper Jurassic)

Discrepancies and their possible reasons

<u>NW part of the working area:</u>
No Upper Jurassic on DK and NL side, but up to 200ms TWT Upper Jurassic strata in GER (see figure below). The distribution and thickness of Upper Jurassic strata in GER is, however, evidenced by data from several wells.

<u>SE part of the working area:</u>

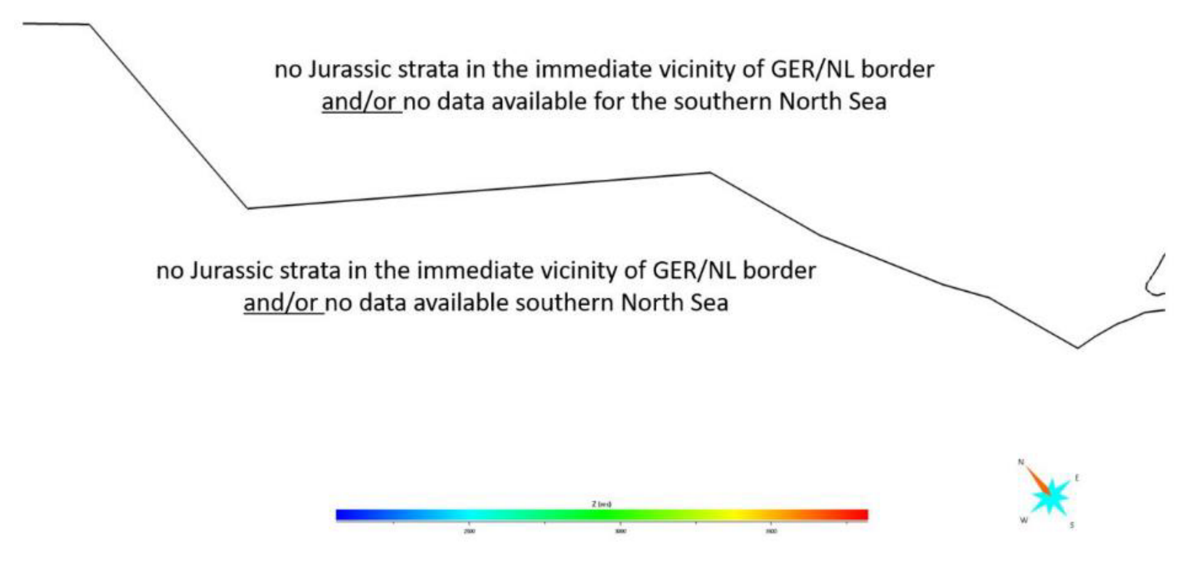
(1) Differences in structural trends on DK and GER sides. Differences of up to 600ms TWT can be observed. Differences decreasing to the SE, where DK and GER likely use the same data source (Fugro ES2002 3D-Survey). (**greyish rectangle**)

(2) Area of high structural complexity, and decreasing seismic resolution along Schillgrund / Coffee Soil Fault (**red square**)

(3) Differences in interpretational concepts. On GER side, region interpreted as structural high, subjected by Upper Cretaceous inversion and erosion by deep incision of Upper Jurassic strata and erosion of Lower Cretaceous to Upper Jurassic strata. (**orange rectangle**)

(4) Different structural gradients resulting in differences >100m; NL grids are based on 2D seismic data while GER grids are based on 3D seismic data (**white rectangle**)

Horizon name	Near base Upper Jurassic	**Horizon Nr.**	5
Working area	Dutch-German border region		



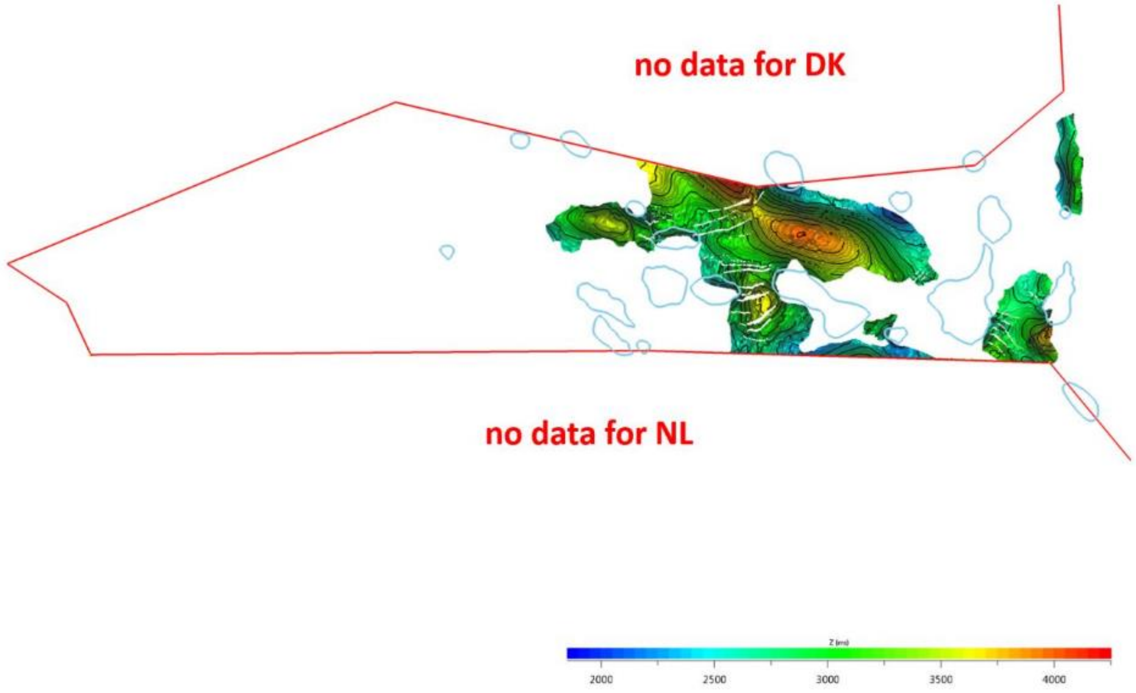
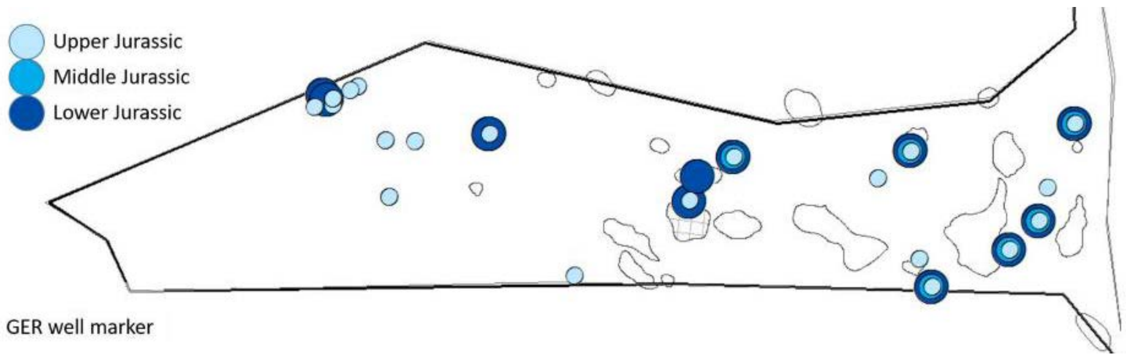
Discrepancies and their possible reasons

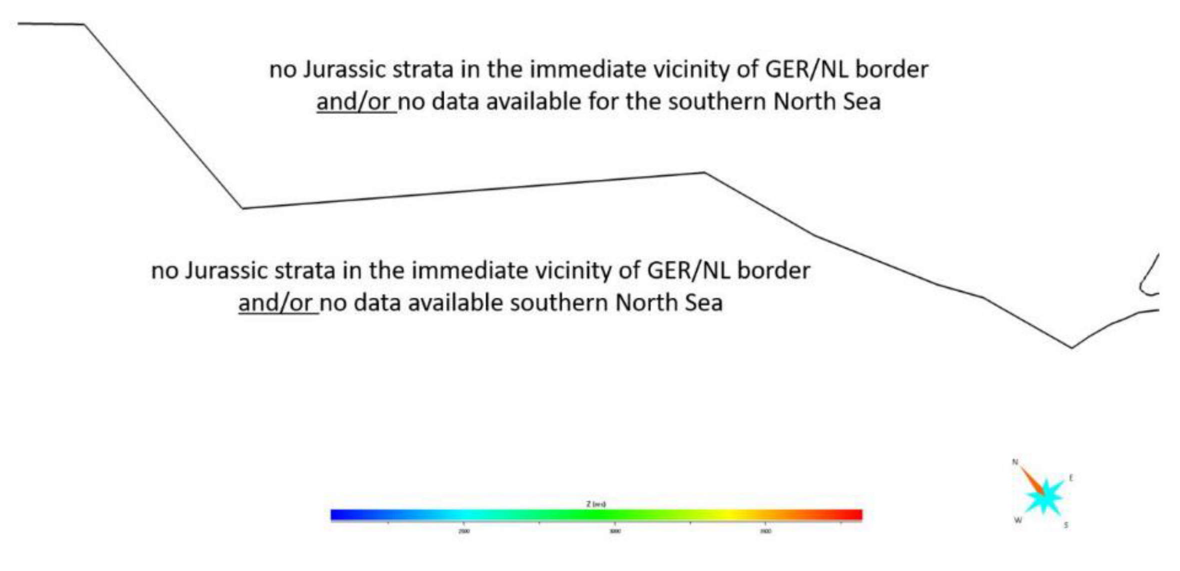
(1) No Jurassic strata in direct vicinity of the GER/NL border.

General note:

In the NW-part of the German North Sea (Horn Graben and its branches, southern Schillgrund High, parts of the G+L-platform) parts of the youngest Upper Jurassic strata might be preserved as in form of thin greensand-layers (as indicated by findings from some wells). However, due to the similarities in lithology (greensands) of the Uppermost Jurassic and Lowermost Cretaceous, these strata was not mapped as “Jurassic” but considered as Lowermost Cretaceous “Wealden”.

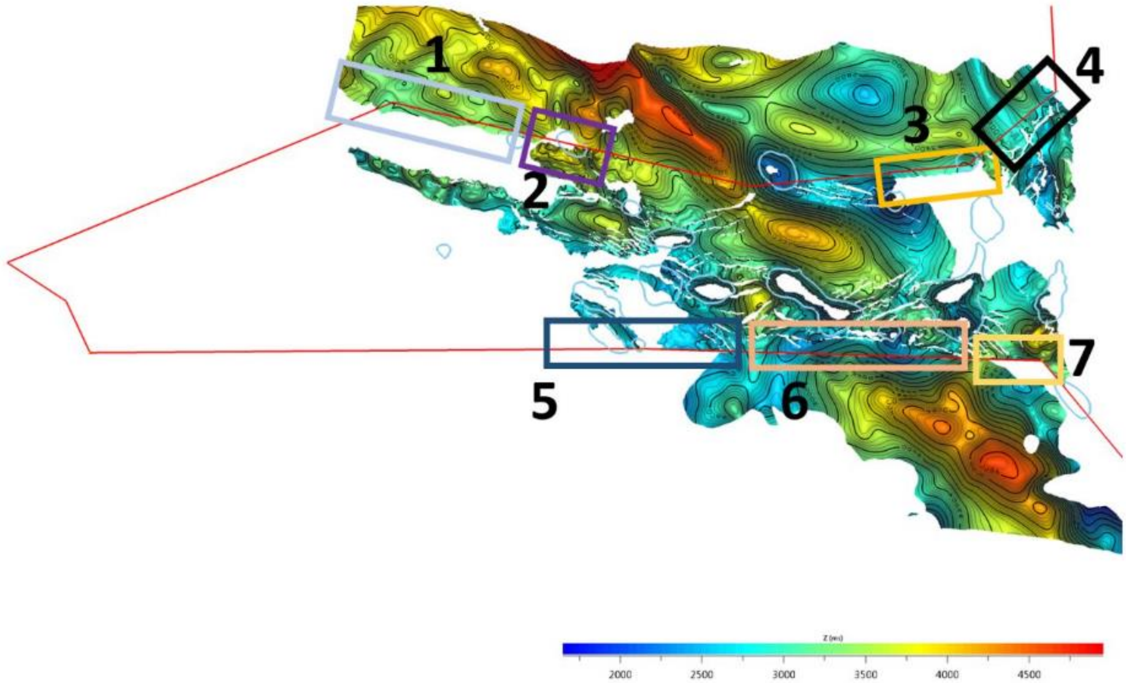
7.1.6 Near base Middle Jurassic

<table>
<tr><td>Horizon name</td><td>Near base Middle Jurassic</td><td>Horizon Nr.</td><td>6</td></tr>
<tr><td>Working area</td><td colspan="3">Entenschnabel region</td></tr>
<tr><td colspan="4">
</td></tr>
<tr><td colspan="2">Discrepancies and their possible reasons</td><td colspan="2">(1) No data for DK and NL available.</td></tr>
<tr><td colspan="4">
</td></tr>
<tr><td colspan="4">Wells in the German part of working area show evidence of Middle Jurassic along the border regions to DK and NL.</td></tr>
</table>

Horizon name	Near base Middle Jurassic	**Horizon Nr.**	6
Working area	Dutch-German border region		
			
Discrepancies and their possible reasons	No Jurassic strata in direct vicinity of the GER/NL border.		

7.1.7 Near base Lower Jurassic

Horizon name	Near base Lower Jurassic	**Horizon Nr.**	7
Working area	Entenschnabel region		



Discrepancies and their possible reasons

(1) Low (negative or near zero) thickness on DK side, non-distribution on GER side (**greyish rectangle**)

(2) Different structural trends (**purple rectangle**)

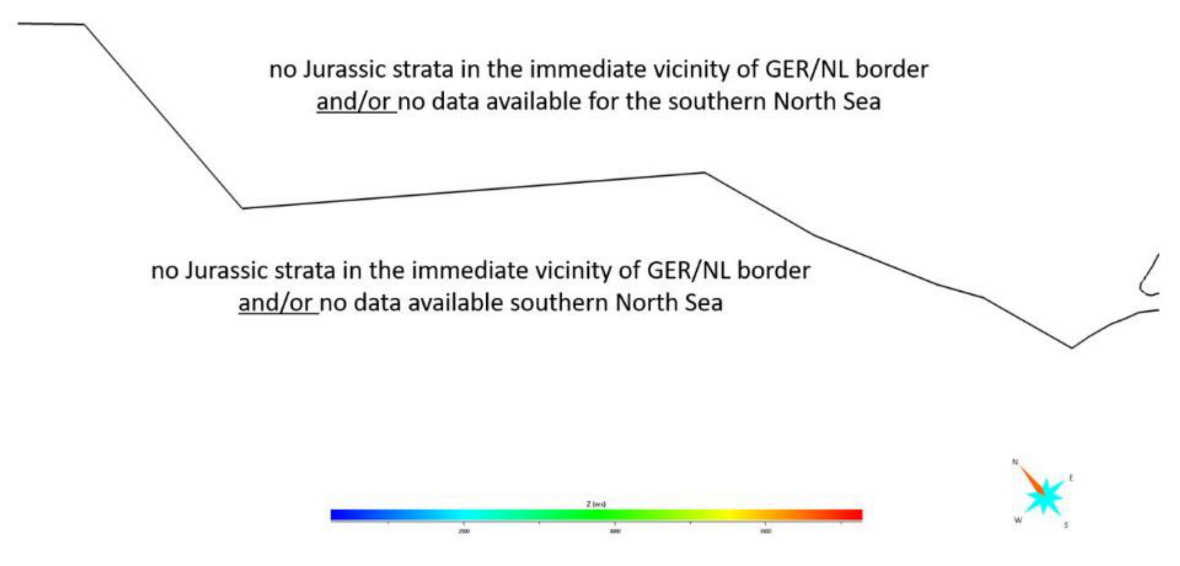
(3) No Lower Jurassic on GER side interpreted due to deep incision of Upper Jurassic in this region down to the Triassic (Keuper) (**orange rectangle**)

(4) Decreasing seismic data quality in structural complex region near the Coffee Soil Fault (**black rectangle**)

(5) Issues due to salt structure rim syncline interpretation and data quality issues (2D on NL side vs. 3D on GER side) (**bluish rectangle**)

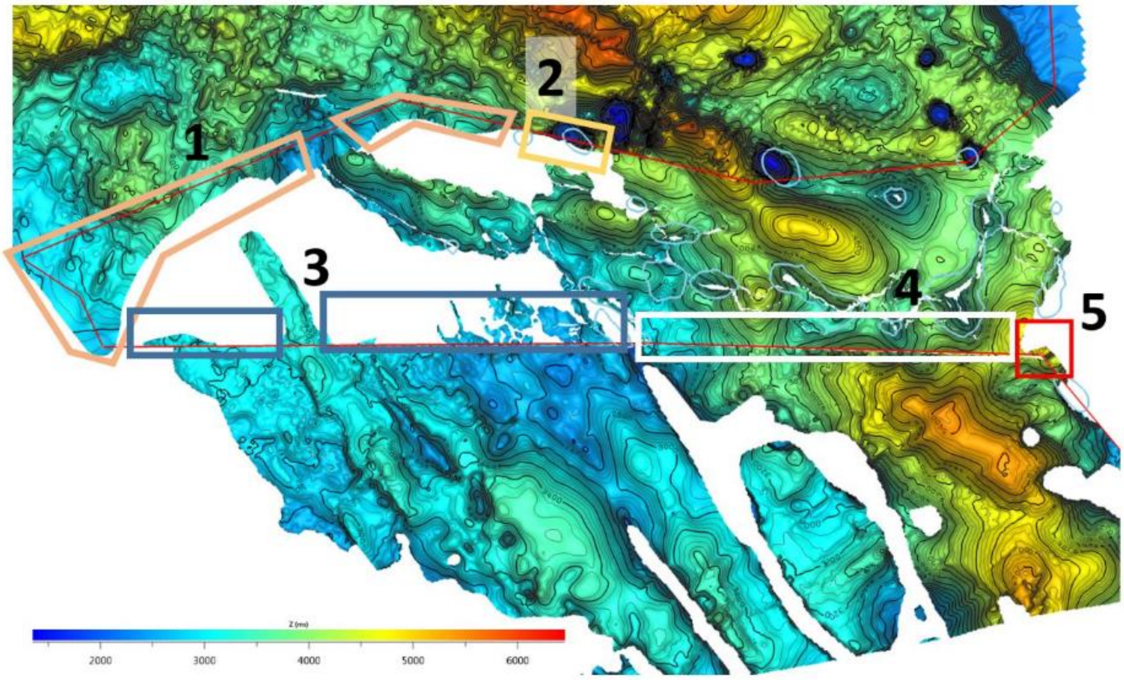
(6) Differences in structural trends. Differences due to different seismic stratigraphic concepts? (GER top of reflector band; NL base on a reflector band, Altena Group/Rhät problem?). (**light brown rectangle**)

(7) Decreased resolution of seismic data? GER grids are based on 3D seismic data while NL grids are based on 2D seismic data (**yellow rectangle**)

<table>
<tr><td>Horizon name</td><td colspan="2">Near base Lower Jurassic</td><td>Horizon Nr.</td><td>7</td></tr>
<tr><td>Working area</td><td colspan="4">Dutch-German border region</td></tr>
<tr><td colspan="5">
</td></tr>
<tr><td colspan="2">Discrepancies and their possible reasons</td><td colspan="3">No Jurassic strata in direct vicinity of the GER/NL border</td></tr>
</table>

7.1.8 Base Lower Triassic

Horizon name	Base Lower Triassic	**Horizon Nr.**	8
Working area	Entenschnabel region		



Discrepancies and their possible reasons

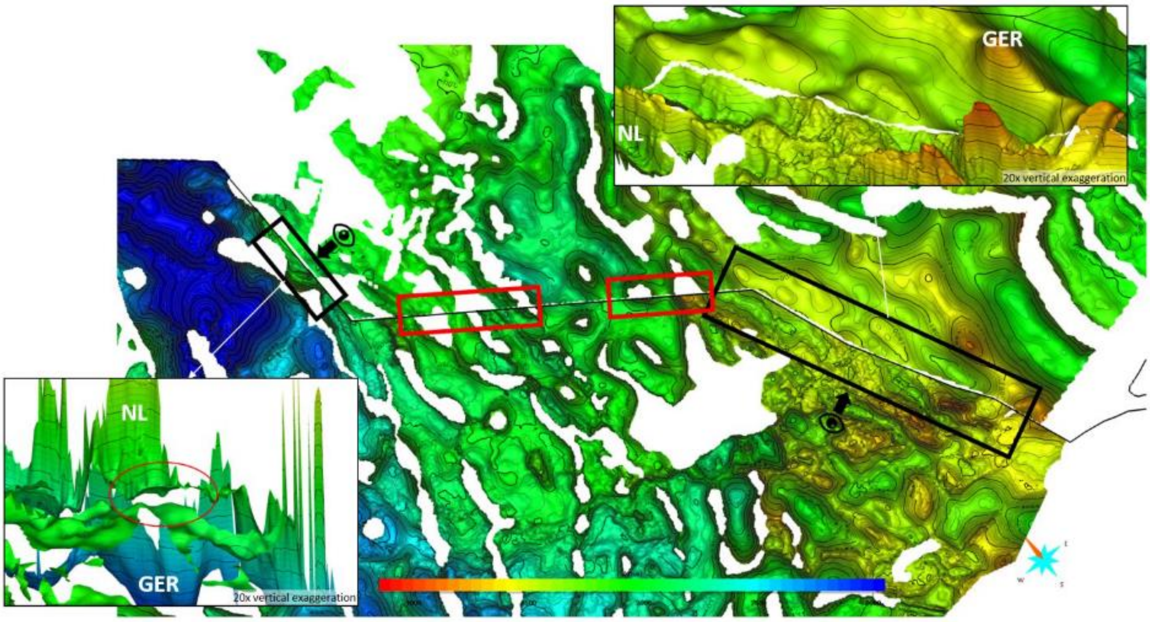
(1) On GER side, no Lower Triassic strata (except inside Graben structures or as highly isolated, residual deposits) due to Mid/Upper Jurassic and Upper Cretaceous erosional events (oldest Upper Cretaceous in this region is Campanian-Maastrichtian) (**light brown polygons**)

(2) Lot of gridding artefacts, grid very rough in this region on DK side. The Base Triassic is merged with the Top of salt structures in order to produce a closed surface. As consequence, the top of salt-structure does not equal with "true" Lower Triassic distribution (yellow rectangle)

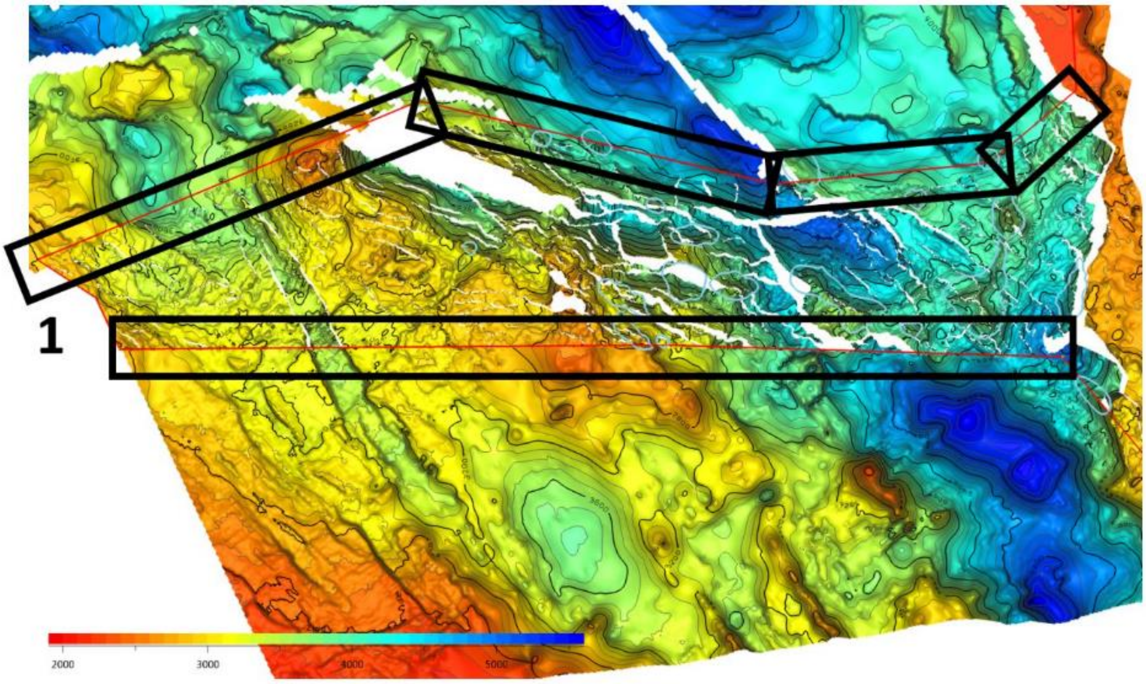
(3) Only residual distribution of Lower Triassic in DE. Triassic is here capped by Mid-Upper Jurassic erosional events (**bluish rectangles**)

(4) Generally good fit. Minor differences due to gridding artefacts on NL side? (**white rectangle**)

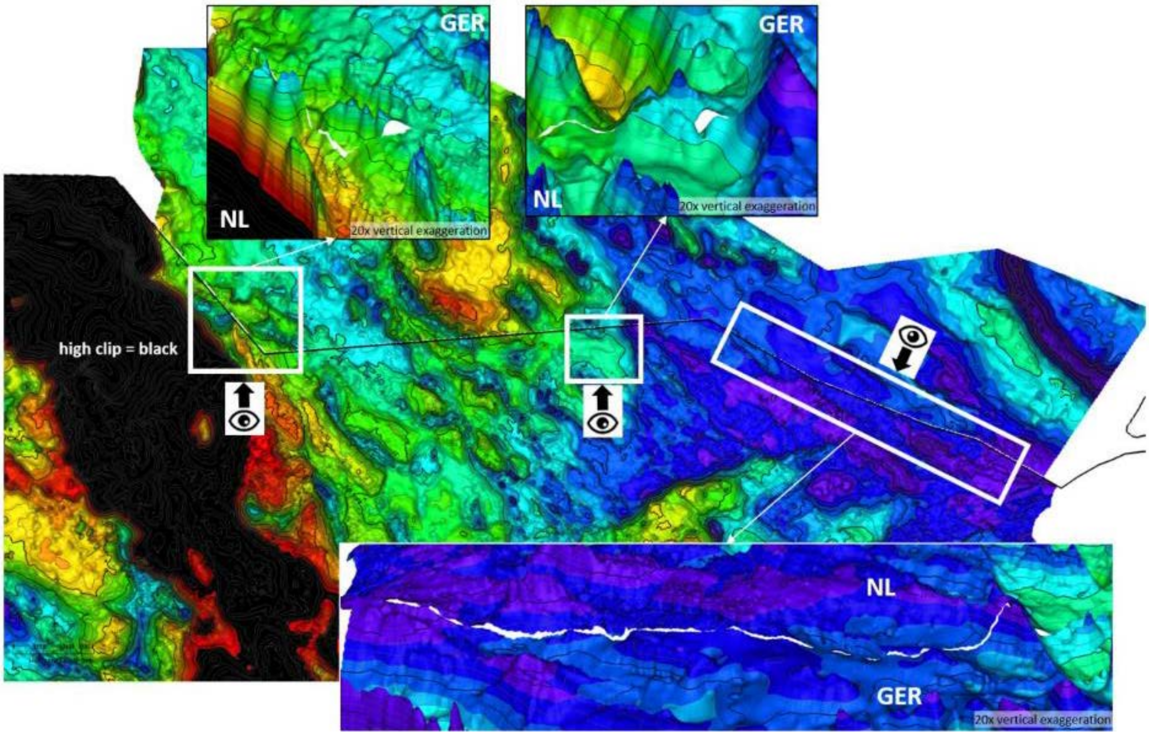
(5) Differences in the structural gradient/trend (**red square**)

<table>
<tr><td>Horizon name</td><td>Base Lower Triassic</td><td>Horizon Nr.</td><td>8</td></tr>
<tr><td>Working area</td><td colspan="3">Dutch-German border region</td></tr>
<tr><td colspan="4">
</td></tr>
<tr><td colspan="4">Discrepancies and their possible reasons</td></tr>
<tr><td colspan="4">(1) bulk shift vertical gap (NL: Schillgrund & Ameland Platforms, GER: G+L Platform) (right zoom-in)
(2) Strong contrast in distribution of Lower Triassic strata in transition of Dutch Central Graben and German Schillgrund High (most issues related to salt structures) (left zoom-in & red rectangles)</td></tr>
</table>

7.1.9 Base Zechstein

Horizon name	Base Zechstein	**Horizon Nr.**	9
Working area	Entenschnabel region		
			
Discrepancies and their possible reasons	Variable but mostly minor differences		

Horizon name	Base Zechstein	Horizon Nr.	9
Working area	Dutch-German border region		



Discrepancies and their possible reasons

(1) Variable but mostly minor differences (almost constant bulk shift along Schillgrund, Ameland and G+L-Platforms. Most probably due to different reflectors used for mapping)(**right zoom-in**)

(2) minor gaps probably due to differences in structural picking concepts (**left & middle zoom-in**)

7.2 Project TUNB – recent R&D work in the German North sector

7.2.1 Current research topics (Part 1: Subsurface potentials)

Bundesanstalt für Geowissenschaften und Rohstoffe

GEOZENTRUM HANNOVER

Project TUNB North Sea - An overview of recent R&D work in the German North Sea sector (part 1: Subsurface potentials)

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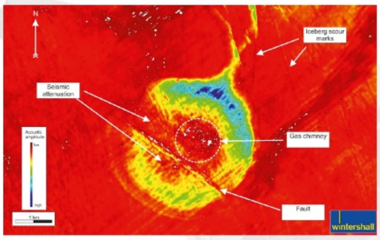
Introduction

Within the project „Subsurface potentials for storage and economic use in the North German Basin" (german acronym TUNB), the Federal Institute for Geosciences and Natural Resources (BGR) and the geological surveys of the northern German federal states are developing a 3D model of the North German Basin harmonised across the state borders.

Along with model construction, the BGR performes research and development work in the German North Sea area. Here, we present an overview of the current research topics in regard to the assessment of subsurface potentials for storage and economic use.

Seismic mapping of amplitude anomalies (shallow gas)

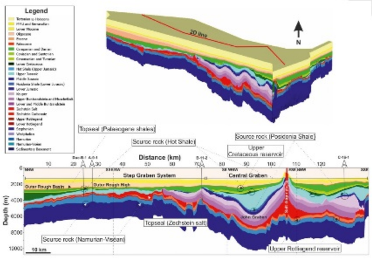
The presence of shallow amplitude anomalies in seismic reflection data are likely due to the presence of gas. The most prominent and easy-to-recognize indicators are high-amplitude anomalies, or "bright spots", that are widespread within the southern North Sea (Müller et al. in review).



Horizontal amplitude grid along a bright spot horizon. The slice is located at ~ 700 ms (TWT). High-amplitude bright spots stick out of the low-amplitude background. The semicircle shape of the bright spots is due to the separating NW-SE trending fault and the structure of the anticline. Iceberg scour marks indicate an arctic paleo-climate during sedimentation. Seismic data courtesy of Wintershall Holding GmbH.

Petroleum system modelling

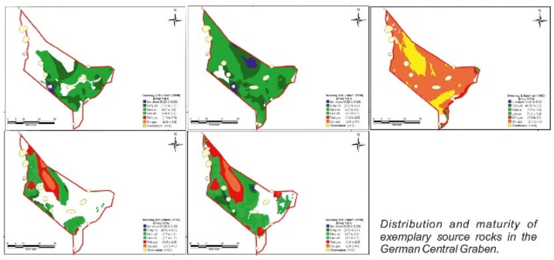
Structural data from the Entenschnabel (NW German North Sea) is used for a 3D reconstruction of the burial and temperature history, source rock maturity, and timing of hydrocarbon generation. The study is focused on the Jurassic and Lower Carboniferous.



3D basin and petroleum system modelling of the NW German North Sea (Entenschnabel) was performed to reconstruct the thermal history, maturity and petroleum generation of potential source rocks (Arfai and Lutz 2017).

Seismic mapping of source rocks in the NW German North Sea

Potential source rocks like the Clay Deep Member, the Posidonia Shale Formation and Visean coals were mapped in detail for the first time in the German North Sea and integrated within the Petroleum model of Arfai and Lutz (2017).



Distribution and maturity of exemplary source rocks in the German Central Graben.

References

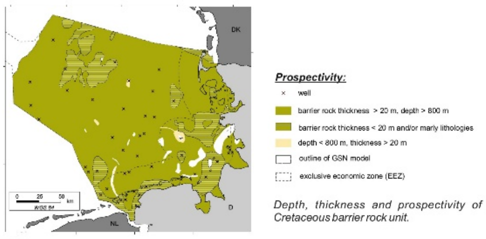
Arfai J, Lutz R (2017) 3D basin and petroleum system modelling of the NW German North Sea (Entenschnabel). Geological Society, London, Petroleum Geology Conference series 8.

Bense FA, Jähne-Klingberg F (2017) Storage potentials in the deeper subsurface of the central German North Sea. Energy Procedia 114:4595-4622.

Müller S, Reinhardt L, Franke D, Gaedicke C, Winsemann J (in review) Shallow gas accumulations in the German North Sea.

Assessment of CO_2 storage potentials

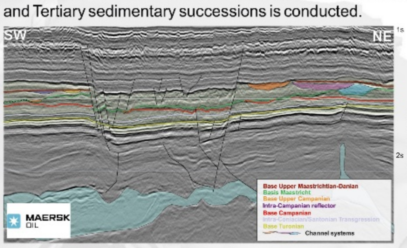
The potentials for subsurface storage in the Central German North Sea are assessed in a reconnaissance scale, investigating specific stratigraphic units based on the standardised criteria lithology, spatial distribution and thickness. By site screening, the most promising areas for CO_2 storage ("prospective areas") are highlighted, while those that do not meet basic criteria are eliminated from consideration. The study shall also provide data for future assessment steps like site selection and initial characterisation as well as storage capacity estimations (Bense & Jähne-Klingberg 2017).



Depth, thickness and prospectivity of the Lower Cretaceous barrier rock unit.

Seismic mapping

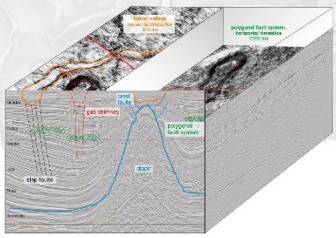
Detailed mapping and stratigraphic analysis of Triassic, Jurassic, Cretaceous and Tertiary sedimentary successions is conducted.



SW-NE oriented seismic section striking subparallel to the step fault system of the Horn Graben. Note channel systems of various scales and stratigraphic position in the Maastrichtian successions. Seismic data provided by Maersk Oil, interpretation from BGR.

Spatial superposition of structural elements

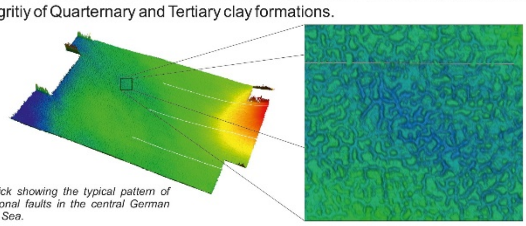
Structural elements, such as tunnel valleys, polygonal fault systems, faults and salt structures, may have high impact on barrier integrity, especially in regions where these structures are in superposition to each other. There, they may form network-like fluid pathways connecting deeper reservoirs and the seafloor.



Spatial superimposition of structural elements, e.g. polygonal fault systems, tunnel valleys, crestal faults and mesozoic step fault systems. When features are structurally linked, fluid pathways may be formed which have a high impact on the barrier integrity of geological seals.

Distribution of polygonal fault systems

Polygonal fault systems (PFS) are networks of layer-bound small normal faults, mainly found in fine-grained sediments. In the Tertiary of the German North Sea, PFS are widely developed, and of special significance concerning the barrier integritiy of Quarternary and Tertiary clay formations.



3D pick showing the typical pattern of polygonal faults in the central German North Sea.

Poster presentation at the Joint Meeting of DGGV and DMG in Bremen (GeoBremen, September 24-29, 2017)

7.2.2 Current research topics (Part 2: Fundamental research)

Bundesanstalt für Geowissenschaften und Rohstoffe

GEOZENTRUM HANNOVER

Project TUNB North Sea - An overview of recent R&D work in the German North Sea sector (part 2: Fundamental research)

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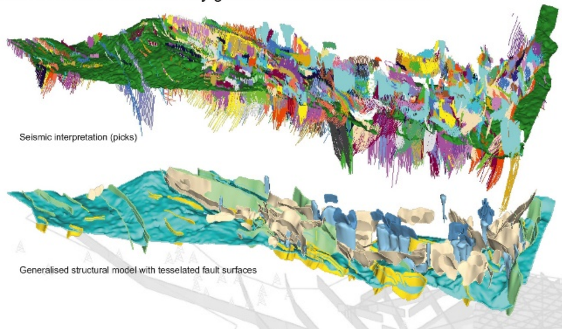
Introduction

Within the framework of the TUNB project the BGR performes research and development work in the German North Sea area. Here, we present an overview of the current research in regard to fundamental research topics concerning the structural and sedimentological development, style and inventory of the German North Sea sector.

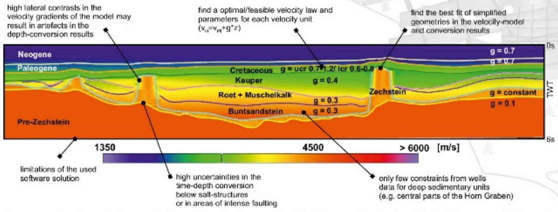
Interpretation and generalisation of faults and salt structures

High-resolution seismic mapping of faults and salt structures not only provide more detailed insights into the structural development of a region but also the basis of consistently generalized structural models.



Seismic velocity modelling

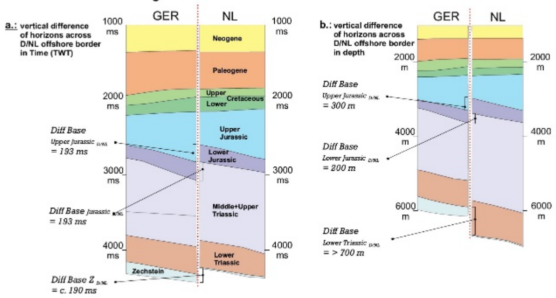
A seismic velocity model is necessary to calculate depth and thickness of geological layers interpreted from seismic reflection images. Depth conversion is also a way to remove the structural ambiguity inherent in time interpretation.



Cross-section through the preliminary 3D velocity model of the German North Sea, illustrating some of the main challenges in regional velocity modelling and depth conversion.

Cross-border harmonisation

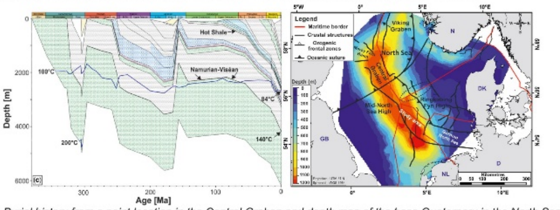
Cross-border harmonisation of stratigraphy, seismic interpretation, velocity models and modelling workflows.



Cross-border comparison of horizon models between offshore GER and NL in the southeastern Entenschnabel in time (a) and depth (b) domain. (a) Differences in TWT are mainly the result of differences in seismo-stratigraphic concepts, raw data or structural interpretation. Concerning the GER/NL offshore border region, major differences are visible for the Mesozoic to Paleozoic. (b) Differences observed in TWT interpretation may be increased or decreased by time-depth conversion, depending on differences in the velocity model used for conversion. Note increase in vertical difference in the Lower Triassic after depth conversion.

Subsidence analysis

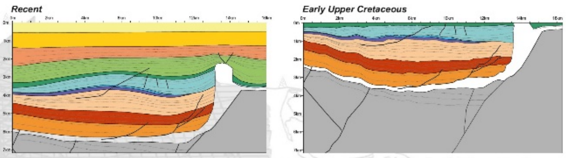
The analysis of subsidence through time provide insights into basin dynamics and may allow conclusions on associated geodynamic processes.



Burial history from a point location in the Central Graben and depth map of the base Quaternary in the North Sea area, highlighting the Quaternary subsidence anomaly.

Mesozoic rifts

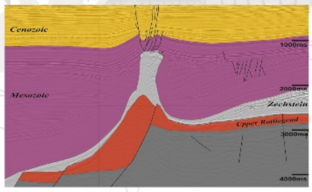
Mesozoic rift structures (e.g. southern Central Graben, Horn Graben) played a major role in the structural development of the German North Sea region. Especially structural and kineamtic modelling may provide valuable information for the general understanding of this region.



Preliminary modelling results for the retro-deformation of inversion movements along the Schillgrund Fault (eastern Central Graben).

Rotliegend halotectonics

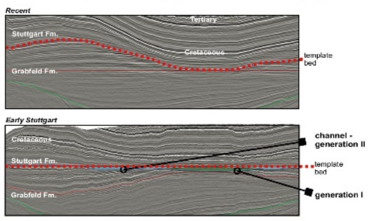
Investigation of the timing, spatial distribution and mechanisms of halo-tectonic deformation of Late Rotliegend sedimentary successions in the central and southern German North Sea.



Triassic salt diapir at the eastern flank of the Horn Graben. The Zechstein and Upper Rotliegend formations show strong thickness variations across the salt structure.
The extend of Rotliegend diapirism is generally masked by strong lateral changes in the seismic velocity (between evaporites of the salt diapir and surrounding sediments), causing e.g. velocity pull-ups.

Erosional valleys

Mapping of the spatial distribution and investigation of the evolution of sedimentary features (e.g. erosional valleys) visible in seismic data.



Seismic section showing erosional features along the base of the Middle Triassic Stuttgart Formation. Erosional structures within the Stuttgart Formation are super-imposed by later deformation events and a strong late Jurassic - early Cretaceous erosional event. Backstripping to the stage Early Stuttgart highlights the former geo-metry of erosional valleys of different generations.

Workflow development

To handle heterogeneous, multi-age and multi-survey seismic, well and interpretation data, proper data processing and 3D modelling workflows are required. For example, the ubiquitous use of seismic interpretation software require the vectorisation of numerous printed paper seismic lines into SEG-Y files.

Poster presentation at the Joint Meeting of DGGV and DMG in Bremen (GeoBremen, September 24-29, 2017)