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Final report incl. lessons learned

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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) intented to integrate existing national (and regional) geomodels into a harmonized, consistent cross-border geomodel of the North Sea area.

The following report will summarize the results of the WP3 study, discuss best practices and lessons learned, all leading to recommendations how to generate Pan-European 3D-models.

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1 INTRODUCTION

1.1 Objectives and study area

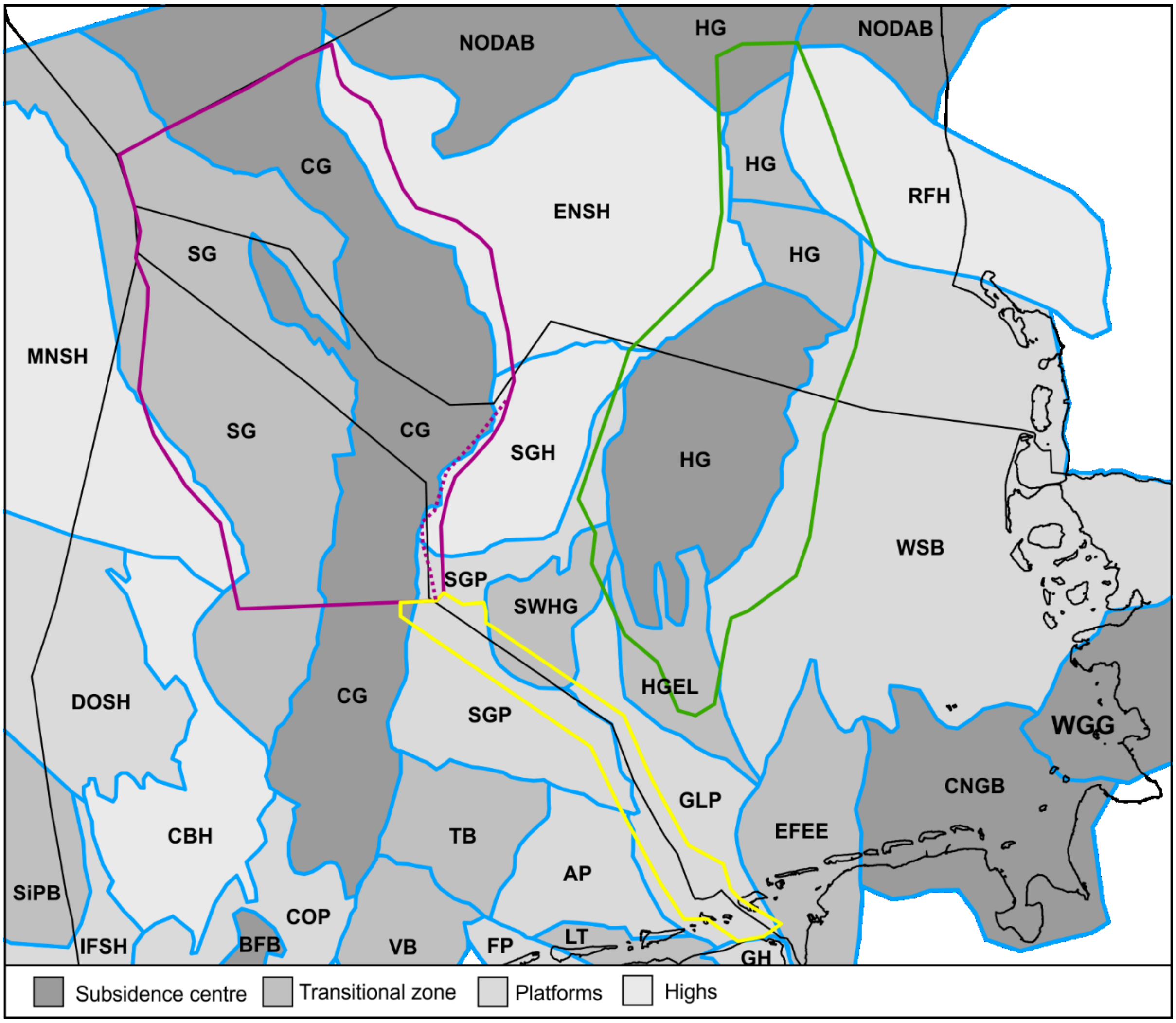

Figure 1: Structural element map (preliminary draft) compiled in 3DGEO-EU WP3 for the area of the Dutch, German and Danish North Sea sectors showing the location of working areas defined by the project partners for harmonization purposes in WP3 (yellow= NL-GER offshore border area / purple = Entenschnabel region / green = Horn Graben region).

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 / WGG – Western branch Glückstadt Graben / DOSH = Dogger Shelf / CBH = Cleaver Bank High / COP = Central offshore Platform / VB = Vlieland Basin / TB = Terschelling Basin / BFB = Broad Fourteens Basin / FP = Friesland Platform / AP = Ameland Platform / LT = Lauwerszee Trough / GH = Groningen High / SIPB = Silver Pit Basin / IFSH = Indefatigable Shelf / NODAB = Norwegian-Danish Basin.

The GeoERA research project "3D Geomodeling for Europe (3DGEO-EU)", which started in July 2018, aimed to show on the example of cross-border pilot areas, how harmonization of geological data and subsurface models can be established across political borders. One of the pilot areas selected as a showcase for harmonization and worked on in work package 3 (WP3) of the project spanned thereby the offshore cross-border North Sea area between the Netherlands, Germany and Denmark (Figure 1). 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) pursued the objective to integrate existing national (and regional) geomodels into a harmonized, consistent cross-border geomodel of the North Sea area. One of the main tasks in this context was to find and exemplarily test efficient workflows for this purpose with the final goal to recognize and eliminate inconsistencies between the national geomodels along the borders. Furthermore, the methodologic advantages (agreements on best practices, optimized workflows, etc.) and the gain in experience on cross-border harmonization were intended to serve as a keystone for future Pan-European harmonization projects.

The harmonization approach chosen to pursue the above mentioned objectives of WP3 (Chapter 1.2), the challenges and problems encountered with it (Chapter 1.3), and finally the resulting products achieved in WP3 will be summarized briefly (Table 3, Chapter 2). For a more detailed description, the reader is referred to the deliverables created in WP3 (Table 4, Chapter 2). The experiences and lessons learned from the harmonization work are then discussed in Chapter 3, followed by recommendations on how to generate consistent Pan-European 3D-models (Chapter 4). A good picture of the whole process of harmonizing the geology across borders with the aim to reach a consistent interpretation is illustrated in the attached poster (Appendix 1; Thöle, 2021b).

1.2 Harmonization approach

Harmonizing existing national (and regional) subsurface models across borders and establishing efficient workflows for this purpose, as envisaged in 3DGEO-EU WP3 for the North Sea area between the Netherlands, Germany and Denmark, requires first and foremost a proper knowledge of the reasons for model inconsistencies. However, evaluating this can be a challenging task in the harmonization process, as the reasons for cross-border discrepancies are not always immediately obvious and might be caused by a combination of independent factors. In the case of 3DGEO-EU WP3, the subsurface models developed by the participating GSO´s over the last decades in the North Sea area and provided for harmonization purposes are mainly based on the interpretation of 2D and 3D seismic data, supplemented by well information. Here, cross-border discrepancies may arise 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. Moreover, differences in the national velocity models, in the scale and detail of a model, or in the type of generalization may lead to inconsistencies among national subsurface models. Because the reasons for cross-border discrepancies can be so diverse, a broad harmonization approach addressing the various potential sources of model inconsistencies is generally advisable and was therefore pursued in 3DGEO-EU WP3 (Thöle, 2021b).

The main steps in the process of the cross border harmonization in 3DGEO-EU WP3 have been explored and are listed in Table 1. During the various (sub-)activities of the harmonization process several questions have been raised and discussed.

Differences and similarities in the nationally defined (litho-)stratigraphic formations and their boundaries were, for example, elaborated in Deliverable 3.3 and presented in harmonized stratigraphic charts for the North Sea area. The challenges and limitations encountered in harmonizing (litho-)stratigraphic units across borders were addressed later in more detail for certain stratigraphic levels in Deliverable 3.4, and detailed log-correlations as a way for harmonization were presented and discussed. The seismic stratigraphic and interpretational concepts applied by the participating GSO´s were compared further in detail for the first time in Deliverable 3.5 and, when possible, existing disparities were harmonized across borders. Building upon the findings from the previous deliverables, a harmonized time horizon model for the Entenschnabel region was constructed and presented in Deliverable 3.6, and the corresponding harmonization steps like seismic re-interpretation in the border regions were described. The establishment of a transnational velocity model for the time-depth conversion in the study area was a further essential step to ensure successful harmonized cross-border 3D models in WP3 and is described in Deliverable 3.7. Finally, in Deliverable 3.8 a consistent, harmonized depth model of the Entenschnabel region and a fault model of a segment of the Coffee Soil Fault was constructed as well as concepts for defining structural elements across borders were presented and discussed.

Table 1: Steps in the process of cross-border harmonization and possible questions.

No	Steps in harmonization process	Activity or issue	Delive-rable	Possible questions
1	**Overview of existing cross-border discrepancies**	Basic data used	D3.1	How to solve the discrepancies if differences in data density or data type are present: e.g., 2D/3D seismics, potential field data etc.
		Data confidentiality	D3.1	How to solve the problems arising if on one side of the border the data are confidential?
		Coordination system	D3.1	After transformation of a national model to another coordinate system, the original model should not be distorted?
		Model date	D3.1	To what extend is all current knowledge and data incorporated in the models of each country?
		Degree of generalization	D3.1	How to solve scale differences? Looking to the aim of the study in which scale or detail will be mapped and modelled?
		Exploration aim and concepts	D3.1	Why is the aim for exploration different (HC, geothermal energy, groundwater, minerals…) and why are different concepts used?
		Knowledge of project partners	D3.1	What are the knowledge gaps of partners and how to use special knowledge of partners?
		Making a rough preliminary cross-border model	D3.2	First trial to combine national models and showing model discrepancies at the border
2	**(re)Processing of raw data (seismics, well logs,..) and reinterpretation**	Not part of the project		
3	**Agreement on seismic stratigraphic concept**	Stratigraphical names and nomenclatures	D3.3	How to pick the same horizon on both sides of the border?
		Seismic reflector characterization	D3.5	How to pick the same reflector on both sides of the border?
4	**Agreement on structural concept**	Interpretation and modelling of faults	D3.8	How to interpret and model a fault(zone)?
		Definition of structural element	D3.8	How to define (the boundary of) a structural element?
5	**Modelling method**	velocity	D3.7, D3.8	Which t-d conversion method is the best?
		horizons	D3.5, D3.6	Which available modelling techniques for horizons are the best?
		faults	D3.8	Which available modelling techniques for faults are the best?
6	**Reservoir assessment**	Mapping reservoirs (resulting in detailed models)	D3.4	What are good reservoirs? How to harmonize reservoirs cross-border?
		Basin modelling	GARAH D3.7, D3.8	What was the geological history of the area? (source, reservoir, seal, migration)
		Volumes calculations	Not part of this project	

1.3 Challenges and problems

During the harmonization process of cross-border modelling in WP3 the following problems and challenges have been assessed (Table 2).

Table 2: Problems and challenges during the harmonization process of cross-border modelling in WP3

Problems associated with	Challenges	Evaluated and discussed
DATA BASE 1. Accessibility/confidentiality 2. Data quality and density 3. Scale differences 4. Uncertainties data projection and transformation procedure	To get an overview of data and its differences per partner and define what data can be used and at what level the cross-border modelling can be done.	D3.1; D3.2 The way forward needs a gathered data base to define what and how a harmonization can be carried out.
INITIAL MODEL TYPES 1. 2D/3D seismic of different vintage 2. Resolution/scale differences 3. Coordination system 4. Different model/grid formats	How to harmonize a heterogeneous partly inconsistent data set	D3.2 The solution was to examine the possibility to establish a rough preliminary cross border model.
GEOLOGY 1. Different basin development and complexity 2. Structural variability across borders 3. Different stratigraphy and stratigraphic nomenclature	To identify the differences and establish a reference platform	D3.3; D3.4; D3.8 The national classifications can't be harmonized but a detailed correlation can be established
INTERPRETATION/MODELLING 1. Horizon definition 2. Velocity modelling 3. Fault interpretation 4. Exploration aim and concepts 5. limitations of software 6. limitations due to available working time	To find the best starting point for implementation of the national horizon, velocity and fault interpretation in order to establish regional maps and models	D3.5; D3.6; D3.7; D3.8 Adjustment and fine-tuning of horizon picking, fault interpretation and velocity data are needed due to the different approaches and methodologies

2 EXECUTED WORK

The harmonization work conducted in WP3 and the resulting products are summarized in nine deliverables, which are listed in Table 3. A brief description of each deliverable is provided in Table 4, along with information on where they can be accessed.

Table 3: List of deliverables compiled in WP3 with summary on lead participant, product type, dissemination level, originally planned and realized delivery month, and associated reference. (PU = public).The project started on July 1, 2018 (M1=Month 1) and ended on October 31, 2021 (M40= Month 40).

Delive-rable no.	Deliverable name	Lead parti-cipant	Type	Dissemi-nation level	Originally planned delivery month	Realized delivery month	Reference
D3.1	State of the Art Report	BGR	Report	PU	M6	M12	Thöle et.al. (2019)
D3.2	A generalized 3D depth model of the Entenschnabel region	TNO	Digital data (3D depth model) + supporting document	PU	M6	M10	Doornenbal et al. (2019)
D3.3	Harmonized stratigraphic chart for the North Sea area NL-DE-DK	GEUS	Report	PU	M18	M20	Jakobsen et al. (2020a)
D3.4	Lithostratigraphic/ chronostratigraphic correlation profiles through the study area	GEUS	Report	PU	M18	M23	Jakobsen et al. (2020b)
D3.5	Harmonized seismic stratigraphic concepts - A base for consistent structural interpretations	BGR	Report	PU	M24	M29	Thöle et.al. (2020)
D3.6	Harmonized time model of the Entenschnabel region	BGR	Digital data (3D TWT model) + report	PU	M24	M35	Thöle et.al. (2021)
D3.7	A harmonized cross-border velocity model	TNO	Report	PU	M24	M34	Doornenbal et al. (2021a)
D3.8	Harmonized depth models and structural framework of the NL-GER-DK North Sea	BGR	Digital data (3D depth models, velocity cubes) + report	PU	M30	M39	Thöle et al. (2021)
D3.9	Final report incl. lessons learned	all	Report	PU	M36	M39	Doornenbal et al. (2021b)

Table 4: Brief description of compiled WP deliverables, along with information on where they can be accessed.

Deliverable	***D3.1 "State of the Art Report"***
Short description, remarks	*This report provides an overview of existing model and map data of the North Sea primarily developed by the project partners in the last decades. Recent research activities of the project members are summarized and legal constraints in sharing subsurface data among the different national project partners are evaluated. Furthermore, the results of an initial analysis of cross-border discrepancies between existing geomodels are presented in an annex.*
Availability	*Link to GeoERA website:* *https://geoera.eu/3DGEO-files/3DGEO-EU-D3.1-State-of-the-art-report.pdf*
Deliverable	***D3.2 "A generalized 3D depth model of the Entenschnabel region"***
Short description, remarks	*The 3D depth model of the Entenschnabel region, that has been built during July 2018 to March 2019, is a generalized model which has been used within the GARAH-project. The model is based on 8 seismically interpreted horizons.*
Availability	*Link to GeoERA website:* *https://geoera.eu/3DGEO-files/3DGEO-EU-D3.2-Supporting-Document.pdf* *xyz model:* *https://geoera.eu/3DGEO-files/3DGEO-EU-D3.2-TVDgrids-Zmap-14042019.7z* *https://geoera.eu/3DGEO-files/3DGEO-EU-D3.2-TVDgrids-CPS3-14042019.7z* *EGDI platform: http://www.europe-geology.eu/*
Deliverable	***D3.3 "Harmonized stratigraphic chart for the North Sea area NL-DE-DK"***
Short description, remarks	*Harmonized stratigraphic charts for the NL-DE-DK North Sea area have been created, that are providing an overview of the relationship of Dutch, German and Danish North Sea lithostratigraphy. The results from this report are fundamental to ensure a successful harmonized cross-border 3D model.*
Availability	*Link to GeoERA website:* *https://geoera.eu/wp-content/uploads/2021/11/3DGEO-EU_D3.3_Harmonized-stratigraphic-chart-for-the-North-Sea-area-NL-DE-DK.pdf*
Deliverable	***D3.4 "Lithostratigraphic/ chronostratigraphic correlation profiles through the study area"***

Short description, remarks	*In this report correlations of the Jurassic and the Rotliegend successions in the NL-DE-DK North Sea area are used to illustrate the stratigraphic variation in the study area and to identify the most essential parameters needed to ensure a successful harmonized cross-border volume or reservoir model. The report gives an exemplary insight into further necessary detailed harmonization work in order to be able to derive open questions about resources and potentials of the deep subsurface from the models.*
Availability	*Link to GeoERA website:* *https://geoera.eu/wp-content/uploads/2021/11/3DGEO-EU_D3.4_Correlation-profiles-through-the-study-area-North-Sea.pdf*
Deliverable	***D3.5 "Harmonized seismic stratigraphic concepts - A base for consistent structural interpretations"***
Short description, remarks	*This report provides information about seismic stratigraphic definitions on horizons that have been selected by the project partners for harmonization purposes. 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 enables different interpreters within or outside the geological surveys to use the same interpretation concepts or have a basis for further discussions. The understanding of the seismic stratigraphy concepts presented should ensure the easy harmonization of existing and future interpretations.*
Availability	*Link to GeoERA website:* *https://geoera.eu/wp-content/uploads/2021/11/3DGEO-EU_D3.5_Harmonized-seismic-stratigraphic-concepts.pdf*
Deliverable	***D3.6 "Harmonized time model of the Entenschnabel region"***
Short description, remarks	*This report is a documentation of the harmonization work conducted in order to create a harmonized time model of the Entenschnabel region. The harmonized time model incorporates 8 key stratigraphic horizons from the base of the Zechstein to the Cenozoic and covers the northwestern part of the German North Sea sector and the adjacent areas in Denmark and the Netherlands. The challenges and problems encountered with the harmonization as well as the revisions made to harmonize the national time horizon models across the borders are described in detail.*
Availability	*Link to GeoERA website:* *https://geoera.eu/wp-content/uploads/2021/11/3DGEO-EU_D3.6_Harmonized-time-model-of-the-Entenschnabel-region.pdf* *xyz model:*

	https://geoera.eu/wp-content/uploads/2021/11/3DGEO-EU_D3.6_TWT-Model-Entenschnabel_data.zip *EGDI platform: http://www.europe-geology.eu/*
Deliverable	***D3.7 "A harmonized cross-border velocity model"***
Short description, remarks	*The report provides information about the production of a harmonized cross-border velocity model covering main parts of the UK, Danish, German and northern part of the Dutch North Sea. This velocity model has been used for time-depth conversion of the main seismic interpreted time horizons that have been selected by the project partners for harmonization purposes.*
Availability	*Link to GeoERA website:* *https://geoera.eu/wp-content/uploads/2021/11/3DGEO-EU_D3.7_A-harmonized-cross-border-velocity-model.pdf*
Deliverable	***D3.8 "Harmonized depth models and structural framework of the NL-GER-DK North Sea"***
Short description, remarks	*This report presents a harmonized horizon depth model of the Entenschnabel region and a cross-border fault model of a segment of the Coffee Soil Fault (eastern boundary of the Central Graben). The harmonization work conducted to create the fault model is described in detail. This includes also the steps involved in building seismic velocity volumes for time-to-depth conversion. Furthermore, concepts for defining structural elements across borders are presented and discussed.*
Availability	*Link to GeoERA website:* *https://geoera.eu/wp-content/uploads/2021/11/3DGEO-EU_D3.8_Harmonized_depth_models_and_SF.pdf* *xyz models and structural framework:* *https://geoera.eu/wp-content/uploads/2021/12/3DGEO-EU_D3.8_Harmonized_models_and_SF.zip* *EGDI platform: http://www.europe-geology.eu/* *NLOG: https://www.nlog.nl/en*
Deliverable	***D3.9 "Final report incl. lessons learned"***
Short description, remarks	*This report summarizes the results of the WP3 study, discussing the best practices and lessons learned, all leading to recommendations how to generate Pan-European 3D-models.*
Availability	*Link to GeoERA (3DGEO-EU) website:* *https://geoera.eu/projects/3dgeo-eu/*

3 EXPERIENCES AND LESSONS LEARNED FROM EXECUTED WORK

The experiences and lessons learned from each deliverable compiled in 3DGEO-EU WP3 will be summarized in the following sections.

3.1 Deliverable 3.1 “State of the Art Report”

The intention of the first deliverable was to provide an overview of publicly available subsurface models covering the offshore border areas of the participating countries and to describe the general aspects of the planned cross-border harmonization within 3DGEO-EU WP3. Part of this was to define what is meant actually by a harmonized, consistent cross-border geomodel, which areas should be actually harmonized and which software, data formats and coordinate systems should be used in the project. Specifying these issues is generally not a major problem, but should be precisely defined at the beginning of each cross-border harmonization project. Another aspect discussed with an impact on the way of harmonization can be conducted across borders concerns the shared access of the principal baseline data of the subsurface models to be harmonized. As mentioned before, seismic data supplemented by well information are the principal baseline data for the subsurface models primarily developed by the participating GSO´s over last decades in the area of the North Sea. Because most of these data tend to derive from high investment exploration and production (E&P) activities, they are subject to business interests and are initially mostly classified as company secrets. The duration of confidentiality is, however, determined differently by the legislation in each country and this 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 impeded the exchange of data among the participating partner countries. A brief overview of the legal constraints of Germany, The Netherlands and Denmark was given in Deliverable 3.1. 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 work conducted in 3DGEO-EU WP3, however, were still affected by the more restrictive regulations. A further complication for sharing data was that GEUS is partly financed by the sale of released subsurface data and therefore free access to this data is not always guaranteed for GSOs of neighboring countries. TNO was the only project partner that could provide released data for the cross-border harmonization issues without any major restrictions.

The disparity of national laws and their consequences for sharing subsurface data should be considered in future cross-border harmonization projects and, if possible, data sharing opportunities should be addressed in advance through appropriate transnational data agreements.

3.2 Deliverable 3.2 “A generalized 3D depth model of the Entenschnabel region”

A preliminary generalized 3D depth model of the Entenschnabel region has been built during July 2018 to March 2019, as part of WP3 of the 3DGEO-EU project and was meant as input for burial studies within the GARAH-project. The model is based on 8 seismically interpreted horizons (NU to ZE). For time-depth conversion of the Cenozoic to Triassic units a layer cake

method (V_0-K) has been used, which assumes that the acoustic velocity of a unit increases linearly with depth under the influence of burial and compaction. For the Zechstein unit the interval velocities have been modelled based on a velocity - thickness (or ΔT) relation. In general, Zechstein unit with limited thickness show the relative high abundance of high velocity carbonate layers and Zechstein unit with high thickness show influence of the interval-velocity of halite (=4500 m/s).
A subdivision of the velocity dataset in three structural elements (Mid North Sea High, Step Graben and Central Graben) has been examined but did not show clear difference in characteristics, so global K-values (whole study area) were chosen for the Cenozoic to Triassic units.
Most of the horizons (i.e., KN, S, TR) could not be well harmonized in depth at the country borders because of discrepancies in time pick during seismic horizon interpretation (see the anomalies on distribution, depth, thickness and V_0 maps shown in Deliverable 3.2).
Because the locations of the German well data were not public, extra steps in the working process had to be made, which was not ideal. Additional steps in the working process, not only related to cross-border issues, were also needed in merging the time grids. To prevent a cumbersome process of coherently stacking layers and QC of the time model it is advisable that all time grids to be merged and delivered by the different countries, have comparable quality in terms of areal coverage and truncation status.

A considerable amount of time was spent on building a coherently stacked depth model based on existing not (yet) well harmonized data, because an important objective was to provide a depth model fit for input in burial studies within the GARAH-project early in the GeoERA program. This finding shows that it is advisable to carefully think through, if in an early phase of a harmonization project all these modelling steps are needed to highlight harmonization issues and plan further actions. Alternatively, it may also be considered to take modelling even one step further and also incorporate a preliminary evaluation of mis-ties of well markers based on, e.g., a more rough version of the trial model, provided well data can be shared without restrictions. In this study the latter was not explored because of the confidentiality restrictions in sharing the well data.

3.3 Deliverable 3.3 “Harmonized stratigraphic chart for the North Sea area NL-DE-DK”

The cross-country comparison of the lithostratigraphy is not always straight forward due to differences in nomenclature, differences in detailed subdivision of the stratigraphic intervals and differences in basin development. Additional complications for a comparison of the lithostratigraphic charts arose from different timescales used as well as from differing geographical orientations of the charts.
The lithostratigraphic charts clearly mirror the differences in the national interest in different stratigraphic intervals. Because of the thick and predominant Triassic in the German sector, the Triassic succession is subdivided and studied in more detail in Germany. The focus in the Danish offshore lies on a detailed description from the Jurassic up to the Cenozoic. In the Netherlands offshore emphasis have been made in addition to the Jurassic on the siliciclastics of the Rotliegend play, Permian level.

The comparison of the lithostratigraphic charts show much resemblances across the country borders but it is also evidence that there is a limitation for harmonization. Especially diachronous units are by nature difficult to correlate. The local distribution and diachronous appearance of specific lithofacies show that a detailed cross-border comparison is often only possible after time-consuming well log correlations applying sequence stratigraphy.
An example of a detailed log-correlation is shown in the Report D3.4: “Lithostratigraphic/ chronostratigraphic correlation profiles through the study area” where a log correlation of the Jurassic & Rotliegend succession in the Danish, German and Dutch Central Graben has been generated.

Another value of Tectonostratigraphic charts that should not be underestimated is that it provides a relatively clear representation of the subsurface structure. Therefore, these charts, especially if they are regionally differentiated, are useful for planning further exploration of the subsurface. In the context of this study, regionally differentiated tectonostratigraphic charts were also produced for the first time for the German North Sea. Even if the rough framework of such charts is valid after compilation, detailed findings of later detailed investigations on lithofacies, paleogeography, chronostratigraphy and structural design should be integrated continuously.

3.4 Deliverable 3.4 “Lithostratigraphic/ chronostratigraphic correlation profiles through the study area”

The comparison of the lithostratigraphic charts (Jakobsen et al., 2020a) indicates a limitation for harmonization of the lithostratigraphy across country borders. Especially diachronous units are difficult to correlate and may only be identified from detailed log correlations applying sequence stratigraphy.
A detailed correlation of the Jurassic and the Rotliegend successions across the country borders have been carried out in order to identify the distribution and the diachronous appearance of specific lithofacies.
The correlation of the Jurassic is based on a detailed sequence stratigraphic subdivision of the Jurassic succession. The log correlation displays a basin development giving rise to divergent facies distribution and distribution of sandstone deposits. The outcome of this correlation is a time related distribution of the sedimentary units. Based on the correlation it has been possible to discriminate local units and put it into a stratigraphic context. A time stratigraphic chart for the Jurassic elucidates stratigraphic similarities and discrepancies between the three countries and is very helpful for harmonization purposes.
The correlation panel of the Rotliegend shows a complex stratigraphic and structural setting with a limited contribution to the harmonization across the country borders. The change from clastic dominated deposits in the Netherlands to prevailing volcanics and volcanoclastics in the Danish and German sector make it difficult to correlate the lithology across the borders.

The findings of such detailed parameter studies form the basis for a creation of harmonized and parameterized volume & reservoir models of the subsurface based on harmonized structural models (D3.6 – D3.8). Any investigation and evaluation of the subsurface for e.g., geothermal use, CO_2 sequestration or oil and gas is based on such volume models. This detailed study makes it clear that, in addition to the harmonization of sub-regional to regional structural models for the application of the results, further harmonization work must also be carried out in detail. Harmonization as well as generalization is always bound to the respective scale of observation and the respective case of application.

3.5 Deliverable 3.5 "Harmonized seismic stratigraphic concepts - A base for consistent structural interpretations"

In Deliverable 3.5, the seismic stratigraphic interpretation concepts applied by the participating GSOs in the area of the North Sea were compared and discussed 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, allowing both similarities and differences in the national seismic interpretation concepts to be easily highlighted. The intention behind this was to evaluate whether disparities in nationally mapped horizons already stem from differences in the applied seismic stratigraphic interpretation concepts, or whether other reasons might play a role and have to be considered in the harmonization process. In this context, each project partner also 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 sections and synthetics compiled the differences in the nationally mapped seismic horizons were evaluated and, if possible, existing disparities were harmonized across borders. In general, the following conclusions and lessons can be drawn from the comparison of the seismic stratigraphic interpretation concepts:

For most key stratigraphic horizons selected for harmonization, the seismic reflectors mapped by the participating GSOs differed only slightly from each other along the cross-border seismic sections, often by only a single reflection. The minor differences observed rely thereby in part on different assumption regarding the acoustic impedance contrast to be expected at the stratigraphic horizon, slightly different mapping concepts (top vs. base), but partly the seismic interpretations differ solely for practical reasons, since the best traceable reflector was mapped in each country. However, despite the fact that the mapped seismic reflectors differed only negligibly, it became clear during the project that for several horizons selected for harmonization in WP3, a comprehensive cross-border harmonization and definition of a common seismic mapping approach was finally not feasible to establish. The reasons why it was not always possible to finally harmonize the seismic stratigraphic interpretation concepts of the three countries differed thereby partly from horizon to horizon. For example, the harmonization of the seismic stratigraphic concept for the Near base Lower Jurassic was generally hampered by the different nationally-defined lithostratigraphic boundaries and the impedance contrasts associated with them. Furthermore, in the case of the Near base Lower Triassic, it is generally difficult to predict the seismic polarity of the base reflector throughout the study area due to existing lateral changes in depositional facies across the Zechstein/Triassic boundary and the changing acoustic characteristics associated with them. Consequently, it was also difficult to decide which nationally mapped seismic reflector is closest to the actual base of the Lower Triassic and should be integrated in the national interpretation concepts. Regardless these uncertainties, however, it could be stated that an adaptation of the nationally mapped reflectors was usually not required for the planned regional scale harmonization due to the minor differences in the mapped seismic reflectors and that other reasons like misinterpretations of structural geometries, or the low significance of seismic data used for the horizon interpretation in certain areas play a more important role for the observed cross-border discrepancies among the national horizon models.

Since a comprehensive harmonization was usually not feasible, however, it is even more important to be aware of these differences and therefore this information was compiled in a clear form in Deliverable 3.5, ensuring that different interpreters within or outside the geological surveys can easily follow and reproduce the former interpretations made in the respective countries.

3.6 Deliverable 3.6 “Harmonized time model of the Entenschnabel region”

In Deliverable 3.6, the harmonization work conducted to create a harmonized time model of the Entenschnabel region was described. The model incorporates eight key stratigraphic horizons from the base of the Zechstein to the Upper Cenozoic and covers the north-western part of the German North Sea sector and the adjacent areas in Denmark and the Netherlands. Prior to cross-border harmonization, several disparities in the nationally mapped horizons became apparent along the national borders. These discrepancies were largely related to differences in the seismic picking concepts, misinterpretations of structural geometries, or the low significance of seismic data used for the horizon interpretation in certain areas. The most obvious discrepancies observed in the time horizon grids initially provided for harmonization by the project partners were addressed and could be removed by seismic re-interpretation, whose temporal scope, however, was significantly underestimated in the project planning. However, there remain disparities in the national horizon models which could not be fully resolved within the timeframe of the project for a variety of reasons. In the German horizon model, for example, most faults exhibiting horizon offsets were mapped and are represented by gaps in the current horizon grids. Contrary to this, only major faults, i.e., faults with large offsets and faults that are important for the definition of structural elements, are usually considered in the Danish and Dutch horizon models. Therefore, their horizons partly coincide with fault planes and also locally e.g., with salt dome flanks. A harmonization of fault traces across borders, however, can be time-consuming and is generally hampered by the fact that most faults occur in structurally complex regions, and here the national horizons tend to be highly generalized. In light of this generalization, a re-interpretation of horizons would often be unavoidable to ensure a geologically plausible harmonization, but this is generally not feasible for the entire study area due to time constraints.

3.7 Deliverable 3.7 “A harmonized cross-border velocity model”

The velocity model for the study area is created for a minimal lithostratigraphic unit configuration as the dataset appeared to be too limited for a detailed unit configuration. Finally, seven main stratigraphical intervals have been selected for building the transnational velocity model: N, CK, KN, S, AT, TR and ZE.
During the determination of the K-factor (V_{int}-Z_{mid} analysis), various filtering criteria have been applied such as acceptable interval velocities within a minimum and maximum range, thickness of the interval (>5 ms), completeness of the interval and the source of the data (preference for calibrated sonic logs). Similar filtering criteria were also used by the determination of the V_0-values. By paying a lot of attention to these filtering criteria the final velocity model of D3.7 was improved in comparison with the preliminary velocity model that was made for deliverable D3.2.

For the Cenozoic and Mesozoic intervals, it is generally assumed that the acoustic velocity increases linearly with depth under the influence of burial and compaction (V_0-K method).
After analysing the results of the V_0-K method for the study area as a whole or splitting it in structural elements, structural element types or a combination of structural elements, finally the following K-values have been used:

- regionalized K values (inside / outside CG+SG) for N and CK intervals and
- a global K value (whole study area) for KN, S, AT and TR intervals

In general, for the Cenozoic and Mesozoic intervals, lower velocities occur within the main depocenter region as the Central Graben + Step Graben (CG+SG), where the sediments are characterized by a more relative faster subsidence, resulting in under compaction. Also, within the depocenter region ("CG+SG") a poor velocity-depth correlation has been found for the older Mesozoic intervals (KN, S, AT, TR), which could be caused by changes in facies distribution, strongly differential uplift during Late Cretaceous basin inversion and differences in formation pressure.
To further investigate the characteristics of the Cenozoic (N), this unit was subdivided in two intervals: NU and NLM. It could be concluded that for NU a 'global K for the whole study area' gave the best results and that for NLM (similar to the N interval) it is better to assume for the main depocenter region a vertical constant V_{int} or a velocity trend with a much smaller K value than the region outside the main depocenter.
In contrast to the Cenozoic and Mesozoic layers, the Zechstein (ZE) interval velocity is not a function of depth and compaction. The lithological composition of the interval is the most dominant factor for the interval velocity and the influence of compaction on the interval velocity is considered very minor. For this project, the Zechstein velocities are modelled based on an interval velocity - thickness (or ΔT) relation. The method presented does not prevent a pull down when modelling saltdomes: three solutions have been presented to correct for this effect.

Thoroughly evaluating and organizing velocity data based on geological concepts, as was done in this study by structural element separation, can give better insight in the data at hand and may provide a guidance for parameter settings in velocity gridding. The full effect of choices made, however can only be evaluated in an iterative process with depth converting the horizons and evaluating mis-ties of the well marker depth with the horizon depth. The final velocity model selected may vary depending on structural complexity and areal extend of the model area.
A regionally consistent seismic velocity model is one of the essential conditions for a sound investigation of the deeper subsurface. Therefore, it is surprising that exactly such studies for large areas of Europe are not available for scientific research also outside of national state authorities. This may be due to the fact that the parameter of the seismic velocity at first sight does not have a direct economic benefit. But any depth model that relies on seismic, and that is the majority in the sedimentary basin area, needs consistent intensive processing for seismic velocity distribution in the subsurface. The North Sea study clearly demonstrates how information on the subsurface of neighboring countries can also help increase the consistency of national subsurface models.

3.8 Deliverable 3.8 “Harmonized depth models and structural framework of the NL-GER-DK North Sea”

Besides the presentation of a harmonized horizon depth model for the Entenschnabel region and a discussion on unresolved horizon modelling issues in this region, D3.8 mainly focussed on various sub-aspects related to the cross-border harmonization of structural models/elements of different scales. For example, a segment of the Coffee Soil Fault (eastern boundary of the Central Graben) was modeled in detail to demonstrate how a main fault can be harmonized across borders and how uncertainties in structural interpretations can be represented in such fault models. The implemention of a harmonized cross-border velocity model usable for time-to-depth conversion played thereby a critical role for developing a reliable cross-border fault model, as it allowed to interpret and analyze the fault segment based on depth converted seismic sections. This is crucial because angular relationships between horizons and faults or basic geometric properties, which act as indications for fault kinematics, are generally skewed in the time domain. Depth conversion allows to circumvent the structurally ambiguity inherent in time and thus to create a more realistic fault model than is possible in the time domain. The challenges associated with the depth conversion and the steps towards a velocity model which can be used to consistently transfer data to the depth domain without distortions are described in detail in D3.8.

Even though the offshore border region of the Dutch, German and Danish North Sea is probably one of the best studied in Europe, little has been done to categorise and harmonise the structural inventory of the subsurface across borders. In D3.8, the challenges and uncertainties associated with the creation of a harmonized, sub-regional scale Structural Framework of the Central North Sea based on existing map data is discussed in detail using illustrative examples. Furthermore, a first harmonized structural element map is presented, which refers in part to the findings and developed working methods of the GEOERA project GeoConnect 3D. However, due to the enornous challenges and uncertainities associated with the harmonisation of subsurface structures, the presented work can only be regarded as a first entry into the very work-intensive harmonization and modeling of transboundary structures.

In general, consistent structural interpretation and modeling requires intensive study of cross-border structural genesis. Especially due to the ambiguity of geophysical data (seismic, potential field methods or well logs) in the vicinity of strongly faulted areas (e.g. Malz et al., 2021; Deliverable 5.2) both the structural modeling and special models and simulations derived from them are massively subject to interpretational bias. In order to better assess these influences, more efforts should be made to capture and visualize uncertainties of interpretations (e.g. Zehner et al., 2021; Deliverable 4.1 & 4.2).

4 RECOMMENDATIONS

The interpretation and modelling of horizons and faults is an essential (combined) step during the process of 3D geological modelling. The harmonization of horizons and faults, especially in cross-border areas, is a challenging task. Heterogeneous data sets, independent exploration concepts, technical limitations and legal restrictions often exclude the existence of a uniform data base. Consequently, inconsistent data, variable processing techniques as well as interpretational and regional geological concepts provide various challenging issues for cross-border model harmonization.

In the following general recommendations are made for future work not only in the cross-border study area of WP3 (Entenschnabel region in the North Sea), but also in areas crossing boundaries within a country or crossing national borders within Europe.
To perform an efficient cross-border model harmonization project the following questions have to be clarified during an early phase of the project:
(1) Are there any legal restrictions or technical discrepancies between the project partners? If raw data and large parts of existing models can be exchanged across political borders, this information can be made available for all partners. Hence, all partners are enabled to check the consistency of their interpretations, data and modelling results across borders.
(2) Which situation and state of knowledge exist in each project partners research at the beginning of the harmonization process? Are there any discrepancies in the stratigraphical nomenclatures and/or nomenclature of structural elements? If geological interpretations were performed individually, often geological horizons were picked differently and/or various kinds of fault interpretations exist.
(3) Which kind of raw data is available on both sides of the border? How was the data processed and interpreted? In many cross-border areas the target for exploration and thus used methods (e.g., detailed seismic reflection vs. potential geophysics) and data acquisition (e.g., different target horizons for prospection) strongly differs. In such scenarios it would be best to only use raw data and, first, establish unified and harmonized processing algorithms (e.g., cross-border harmonized velocity models usable for time-depth conversion of seismic data). Nevertheless, such unified algorithms need much effort, especially if several hundreds of seismic sections must be analyzed and reprocessed.
(4) Are there any discrepancies between interpretational and regional geologic concepts across borders? In some cases, political borders even follow regional geologic boundaries. Hence, significant changes in interpretational and regional geologic concepts probably become obvious in cross-border areas. The most efficient solution to overcome these issues is an enhanced transfer of knowledge across borders. Only, if all partners are able to understand the geological situation on both sides of a border, unified and harmonized interpretations are possible.
(5) Is building a pilot depth model in an early phase of a harmonization project an essential step in gaining insight and exchanging knowledge of the 3D distribution of cross border issues? In the current project a lot of effort went into modeling details which required a considerable time investment not necessarily contributing to the geological understanding or highlighting cross border issues. In fact, a lot of the issues were already highlighted by the pilot time horizons or became apparent when addressing the various harmonization topics in more detail.

Further, timewise, in a more final harmonized model iteratively testing and evaluation of time-depth conversion solutions are more effectively performed.

As shown in this 3DGEO-EU WP3 there is a wide range of challenges for model harmonization. All these issues typically evolve from independent data sets, interpretations and concepts and are hampered by legal restrictions and technical limitations. Only if an efficient exchange of data and, if the latter is not possible, a transfer of knowledge is enabled, cross-border model harmonization can be performed successfully. Thereby, model harmonization across political borders strongly depends from technical, interpretational and legal limitations. An efficient harmonization thus needs a huge amount of communication, the possibility of data and knowledge exchange, scientific independence across borders and political decisions and frameworks, which help to establish cross-border to pan-European research areas where scientists can come together to perform joined and integrated research projects without political limitations.

Since a comprehensive harmonization was usually not feasible in our study area, however, it is even more important to be aware of differences (in national classifications and nomenclatures, in seismic stratigraphical interpretation, in used concepts etc.) and to compile this information in such a manner, that different interpreters within or outside the geological surveys can easily follow and reproduce the former interpretations made in the respective countries.

One main question to be answered is whether our experiences actually could be transferred to other regions in Europe and finally could be used to generate pan-European 3D-models. All our efforts actually show that the harmonization steps strongly depend on the data basis, as well as the geological complexity and outcrop situation. Therefore, we can only give recommendations for basin areas comparable with our WP3 study area and that owe a comparable similar good data base and coverage. The harmonization work executed in WP3 is a great example how many discrepancies and thus problems have been encountered crossing borders, finally to generate a consistent geological model for the whole area.
After development of a harmonized (in some essential points) regional model for the Entenschnabel area within Central North Sea, it could be concluded that in Europe we are still at a starting point for generation of pan-European 3D-models. Since the national geological services deal mainly with national issues the border harmonization has not a high priority and often also there is not enough capacity. Also for the region presented in WP3, a large number of aspects could not yet be considered in the model harmonization. Thus, both the Cenozoic/Quaternary and Pre-Zechstein were only marginally considered in the model harmonization. Also, far-reaching harmonization could only be achieved for a small part of the DK/GER/NL border region. Due to the very work-intensive analysis, harmonization of structures could only be carried out on an exemplary basis, and rock properties could only be correlated on the basis of selected transects. But these studies are actually critical for later applications of subsurface models for resource estimates or process simulations.

In order to ultimately achieve the goal of a harmonized geological database across Europe, the EU should start and promote exactly here. At the national Geological Surveys there is a strong need to promote exactly such cross-border harmonization projects and to integrate these activities into a European framework, for example through concepts like the semantic concept used for building an European Fault Database (HIKE) and the concept used to generate a structural framework for a larger area (GeoConnect3D). To maintain the harmonization of models as knowledge is gained (additional data, more detailed interpretations, etc.), it is also necessary to continuously promote cross-border exchanges between national services and research institutions and to consider capacities on both sides of a border for model maintenance.

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