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GEO-ENERGY

3D Geomodeling for Europe

Project number: GeoE.171.005

Deliverable 8.5

Summary of project work and results

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Several authors from different 3DGEO-EU partner institutions have contributed to this report. The work package (WP) specific sub-chapters 3.1 to 3.7 have been written by WP leads/WP participants. Chapter 4 is a group effort with opinions and statements on lessons learned from various authors/ WPs.

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GENERAL INTRODUCTION

This summary report provides an overview of the work and main results of the project „3D Geomodeling for Europe (3DGEO-EU)". The rationale and the general approach of the project is shortly described in chapters 1 and 2. In chapter 3, for each of the seven technical Work Packages (WP), the results are briefly presented, including information on WP specific approaches and challenges/problems the WP partners had to cope with.

In chapter 4, lessons learned and conclusions based on the experiences and results from the work in the WPs are provided. As the project had a special focus on cross-border harmonization of 3D geomodels, the lessons learned concerning thematically related issues are most prominent, yet other tackled project issues like visualization of uncertainties of geological 3D models and workflows for 3D reconstruction of the subsurface are discussed as well.

The detailed project results are described in various WP-specific deliverable reports. This summary report does not replace any of the deliverable reports, instead it is meant to be a guidebook that helps the reader to find the project results of interest and therefore provides in chapter 3 links to the WP-specific deliverables, like 3D geomodel data and technical deliverable reports.

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1 INTRODUCTION

Ambitious greenhouse gas reduction targets enhance the need of European countries for sustainable energy supply, which also increases the need for reliable assessments of subsurface geo-energy potential in the European Union. Such assessments might include conventional, unconventional, and renewable energy resources as well as storage options for energy carriers and CO_2. A good evaluation of subsurface resources in Europe requires up-to-date geological basic information that is consistent across European country borders in order to adequately inform stakeholders and decision makers. For this an appropriate provision and presentation of subsurface parameters and the 3-dimensional arrangement of geological strata, rock and fault properties are required, as it is provided by 3D geomodels.

Consistent and reliable results of resource assessments across borders can only be achieved if the used geodata and 3D geomodels are harmonized across borders, i.e. exhibit no border discontinuities. However, as a matter of fact, geodata and 3D subsurface information is often inconsistent across borders. Adjoining geomodels for example quite often do not fit across borders, i.e. exhibit border discontinuities like a different depth of a geological horizon (Figure 1). Such inconsistencies hamper reliable assessments of cross-border subsurface potentials.

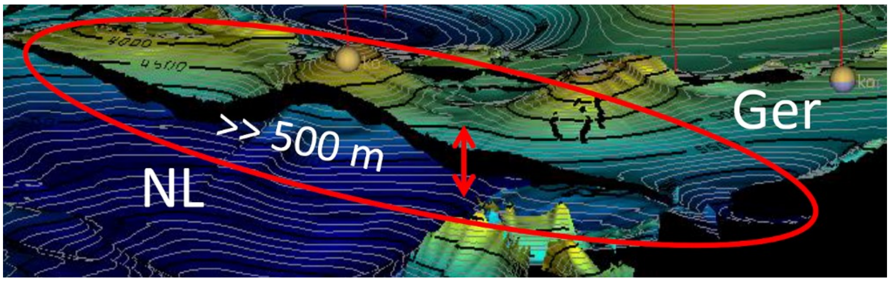

Figure 1: Example of a border discontinuity (North Sea area).

The reasons for cross-border inconsistencies are e.g. different definitions of stratigraphical horizons, heterogeneous geological base data, different levels of geological exploration, or different approaches and methods used by the Geological Survey Organizations (GSO) on both sides of a border. The project 3DGEO-EU addressed this important issue as it mainly dealt with the harmonization of geological data and 3D geomodels across international borders. Yet, cross-border issues are not the only difficulties to be faced when producing reasonable 3D geomodels of the subsurface. Therefore the project has also investigated selected geomodeling topics regarding (i) the visualization of uncertainties of geological 3D models, (ii) regarding modeling of geological faults, and (iii) regarding optimized workflows for 3D reconstruction of the subsurface.

In 3DGEO-EU, 11 national and regional GSO from 7 countries (Table 1, Figure 2) have worked together and strived to find some solutions helping to overcome cross-border differences and aspired towards achieving best methods and (optimized) workflows for cross-border harmonization and 3D geomodeling, which could be applied in other regions and geological settings in Europe.

Table 1: Project participants

#	Participant Legal Name	Institution	Country
1	Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) [Project Coordinator]	**BGR**	**Germany**
2	Ceska Geologicka Sluzba – Czech Geological Survey (CGS)	**CGS**	**Czech Republic**
3	Geological Survey of Denmark and Greenland (GEUS)	**GEUS**	**Denmark**
4	Landesamt für Bergbau, Geologie und Rohstoffe Brandenburg (LBGR)	**LBGR**	**Germany**
5	Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern (LUNG)	**LUNG**	**Germany**
6	Landesamt für Bergbau, Energie und Geologie Niedersachsen (LBEG)	**LBEG**	**Germany**
7	Landesamt für Geologie und Bergwesen Sachsen-Anhalt (LAGB)	**LAGB**	**Germany**
8	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek TNO	**TNO**	**Netherlands**
9	Polish Geological Institute – National Research Institute (PGI-NRI)	**PGI**	**Poland**
10	Instituto Geológico y Minero de España (IGME-Spain)	**IGME**	**Spain**
11	State Research and Development Enterprise State Information Geological Fund of Ukraine	**GEOINFORM**	**Ukraine**

2 GENERAL APPROACH OF 3DGEO-EU

The general approach of the project was to set-up international cross-border pilot areas (work packages 1-3) that served as showcases to develop and test methods for the cross-border harmonization of geological 3D models (Figure 2). Accompanying the work in the pilot areas and to support cross-border harmonization, three additional work packages (4-6) have investigated selected geomodeling topics like the visualization of uncertainties of geological 3D models, modeling of geological faults, or the optimization of 3D subsurface reconstructions. Furthermore, work package 7 governed the interactions with the GeoERA Information Platform Project (GIP-P), thus managed all kinds of communication and data exchange between 3DGEO-EU and GIP-P, and was responsible to upload results (spatial data) to EuroGeoSurvey's web portal EGDI (European Geological Data Infrastructure).

The main research and technical work happened in the work packages 1-6:

Cross-border pilot areas

- WP1 Pilot area in onshore Dutch-German cross-border region
- WP2 Pilot area in onshore German-Polish cross-border region
- WP3 Pilot area in offshore cross-border North Sea region between the Netherlands, Germany and Denmark

Selected geomodeling topics

- WP4 Uncertainty in geomodels
- WP5 Faults
- WP6 Optimizing reconstructions of the subsurface to reduce structural uncertainty in 3D models

The WPs were partly connected, especially a "vertical" connection from WP4-6 to the cross-border pilot areas WP1-3 was established in order to derive mutual benefit from it. For example, the pilot areas partners could provide test data to WP4 regarding uncertainty visualization, or allowed cross-border modelers to apply a WP6 workflow for 3D reconstruction based on gravimetric, structural and petrophysic information in the Northern German-Polish border region.

Furthermore, the project was connected with other GeoERA research projects, especially with GARAH and HIKE. For GARAH ("Geological Analysis and Resource Assessment of selected Hydrocarbon systems") a generalized cross-border 3D depth model of the 'Entenschnabel' region in the North Sea was built (D3.2) that was used for Petroleum System modelling. The connection to HIKE ("Hazard and Impact Knowledge for Europe") was close as well, as WP5 "Faults" was set up as a direct interface between both projects, communicating standard and requirements set by the Fault Database of HIKE.

In the first phase of the project, the cross-border work packages (WP1-3) covered the inventory of existing geodata, 3D models, and model concepts in the considered pilot areas. The partners evaluated the differences across borders and examined necessary steps to prepare harmonized geomodels. This state-of-the-art is documented in inventory reports (Deliverables D1.1, D2.1, D3.1), setting an important milestone for the project, because harmonization work cannot begin until the cross-border inconsistencies are identified. Based on the state-of-the-art, the partners developed their strategies for the modelling and harmonization work. As such quite time-consuming fundamental work like covering the state-of-the-art and especially identifying and describing the inconsistencies was necessary, the work on cross-border harmonization and actual geomodels mainly started later on in the second phase of the project.

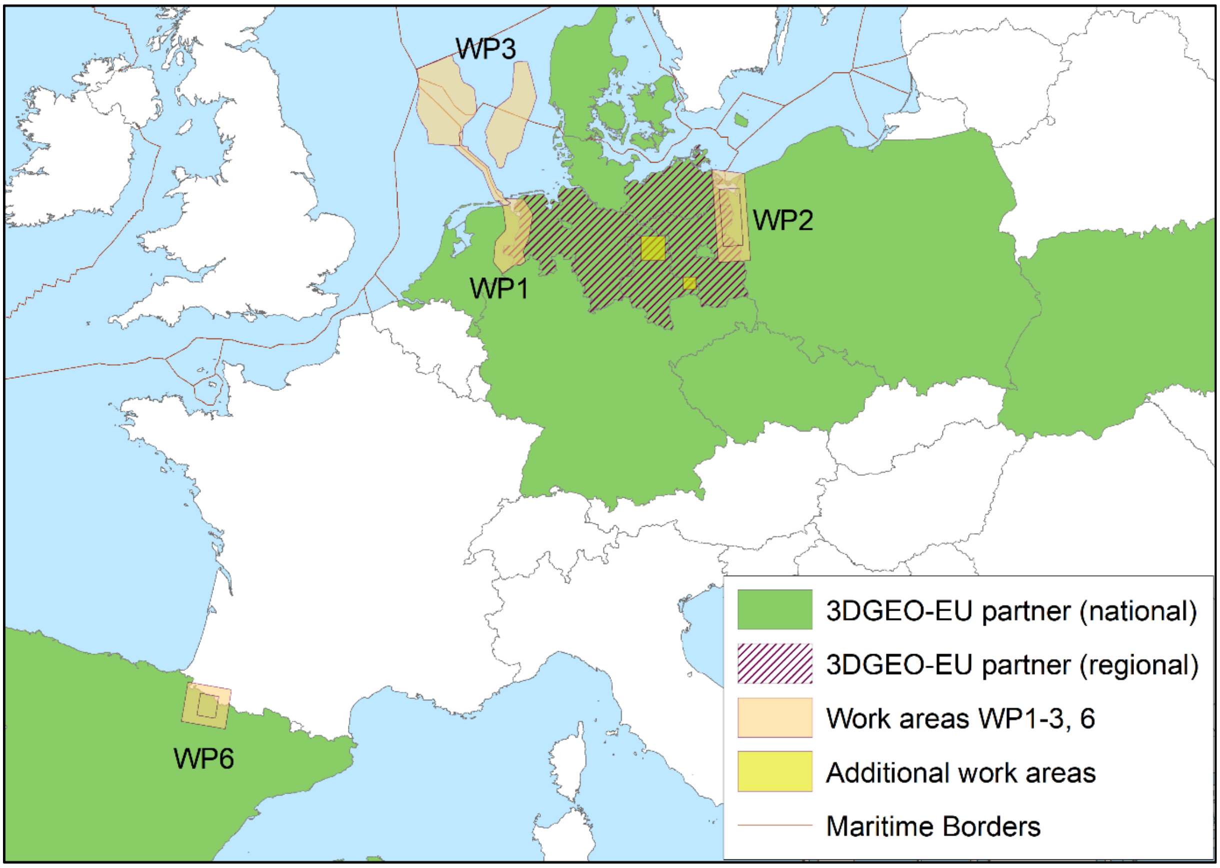

Figure 2: Partner countries and work areas of 3DGEO-EU.

Investigating the state of the art included to analyze and discuss the possibilities and restrictions of data exchange within partner countries. Often, the exchange of primary geophysical data from wells or seismics was limited or even impossible because of legal restrictions. So the workflow for cross-border harmonization was then mainly based on interpreted data.

3 WORK PACKAGES

In this chapter, for each of the seven technical work packages, the WP-specific work (approaches) and results are briefly presented. Also some information on challenges/problems is provided there. These sub-chapters shall give an overview of what happened in the WPs and what has been achieved. Further profound information on the work and results is provided in several WP-specific deliverable reports, which can be accessed via links to the GeoERA 3DGEO-EU webpage.

3.1 WP1

Work Package title:

<u>Harmonization of Cenozoic and Mesozoic layers in the northern onshore Dutch-German cross-border region for assessment of underground usage</u>

Objectives

“Overcoming a national border, which has no relevance in geosciences” was the vision of WP1 in 3DGEO-EU. Geology and usage of underground ends not at the national border between Germany (Lower Saxony) and The Netherlands. GeoERA supported the possibility for LBEG and TNO of working together on harmonization of existing 3D models. Both organisations provide detailed 3D models of the geological underground for the states, which end at the border.
A study area of approximately 30km on both sides of the national border was chosen to exam in detail existing 3D models for harmonization of the new cross-border model NLS3D (see Figure 3).

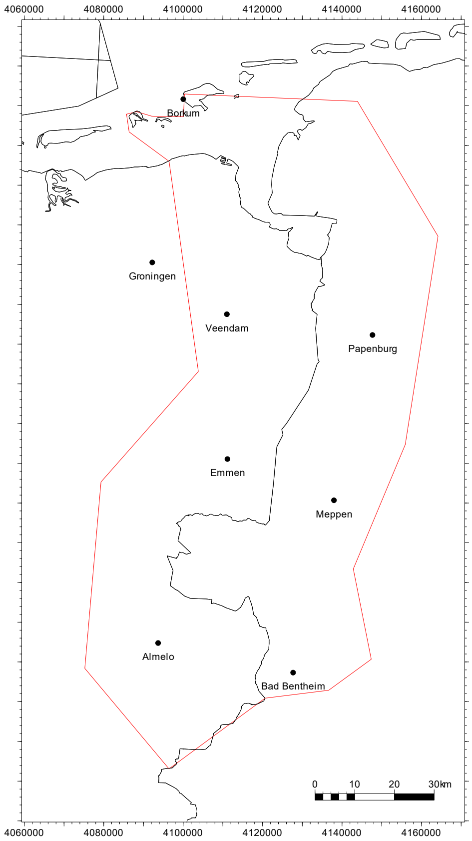

Figure 3: WP1 work area in the Dutch-German (Lower Saxony) border region.

Despite harmonization of corresponding horizons of existing 3D models and development of a methodology for this purpose, also main faults should be harmonized. Following works was focused on Cenozoic units to identify, describe and attribute potential geothermal reservoirs. Another purpose was to derive a decision support map of the Rupel Formation from the harmonized NLS3D model. Therefore remodeling of two Cenozoic horizons was necessary at Lower Saxony side.

Approach and challenges

Three different existing 3D models were examined in detail in task 1.1 to generate a common knowledge base as starting point for harmonization. Based on this knowledge 10 corresponding stratigraphic horizons were identified for generating NLS3D. Corresponding layers were extended for overlapping. For each corresponding horizon depth differences between the two input horizons along the border have been calculated. Difference in depth and the average depth were used to calculate the deviation in percent. For each stratigraphic horizon a fixed deviation percentage was chosen to serve as a threshold for harmonization. Corresponding grids were not harmonized in areas for which the deviation percentage exceeded the horizon specific deviation percentage. These areas are represented by gaps.

Differences in structures were controlled in seismic lines, to decide if harmonization was feasible or not.

NLS3D is compiled of three different existing 3D models, areas were a harmonization was not feasible are represented as gaps along the border. Following reasons were identified:

- Differences in input data of the 3D models.
- Different lithostratigraphic classification of corresponding horizons
- Natural dipping of the sediments towards the centre of the Lower Saxony Basin, with a stronger effect on the German side
- Differences in modeling faults and structures (especially salt structures) in existing models
- Differences in the used velocity models of existing 3D models
- Differences picked seismic horizons
- areas with low document point density towards the border of the model lead to fuzziness and generate deviations due to uncertainty
- Changes in the stratigraphic classification and assignment of individual sediments to certain chronostratigraphic stages over the last 70 years led to the fact that in some cases the horizons from boreholes were assigned to the wrong horizons during modelling.
- Vulnerability of the harmonization method - the method was designed to be able to map and compensate the expected high deviation of the deepest horizons very well. Contrary to expectations, the shallowest horizons showed the greatest deviation in the harmonization in relation to the depth.

Faults in the border area have not been harmonized. An attempt has been made to harmonize the Gronau fault-zone. This fault-zone has been chosen because of its complexity and a working proof of concept would mean a working method for the entire border area. Unfortunately, the basis for a harmonized fault model is thin. It is not possible to harmonize the faults from 3D models, due to the fact that the Dutch 3D model has interpreted and modelled fault-planes in 3D and the fault planes at the GTA3D model had to be reconstructed and deduced from fault-gaps at horizon levels.

Maps of Cenozoic units were derived from NLS3D, originally planned to be used for describing potential geothermal reservoirs. These maps show thickness, and distribution of Cenozoic units, but investigation of geothermal parameters like permeability and porosity was not successful for Cenozoic units. Lithological specificity and thickness of potential geothermal reservoirs (like Vessem-Member / Rupel Basal Sand Member or Brussels Sand

Member / Brüssel Sand Beds) are not very promising for geothermal usage, or need further investigations.

Results

Deliverable 1.1 is a state of the art report, which describes the input 3D models for NLS3D. NLS3D (see Figure 4) as a new cross-border model comes up with a supporting document (Witthöft et al., 2021).

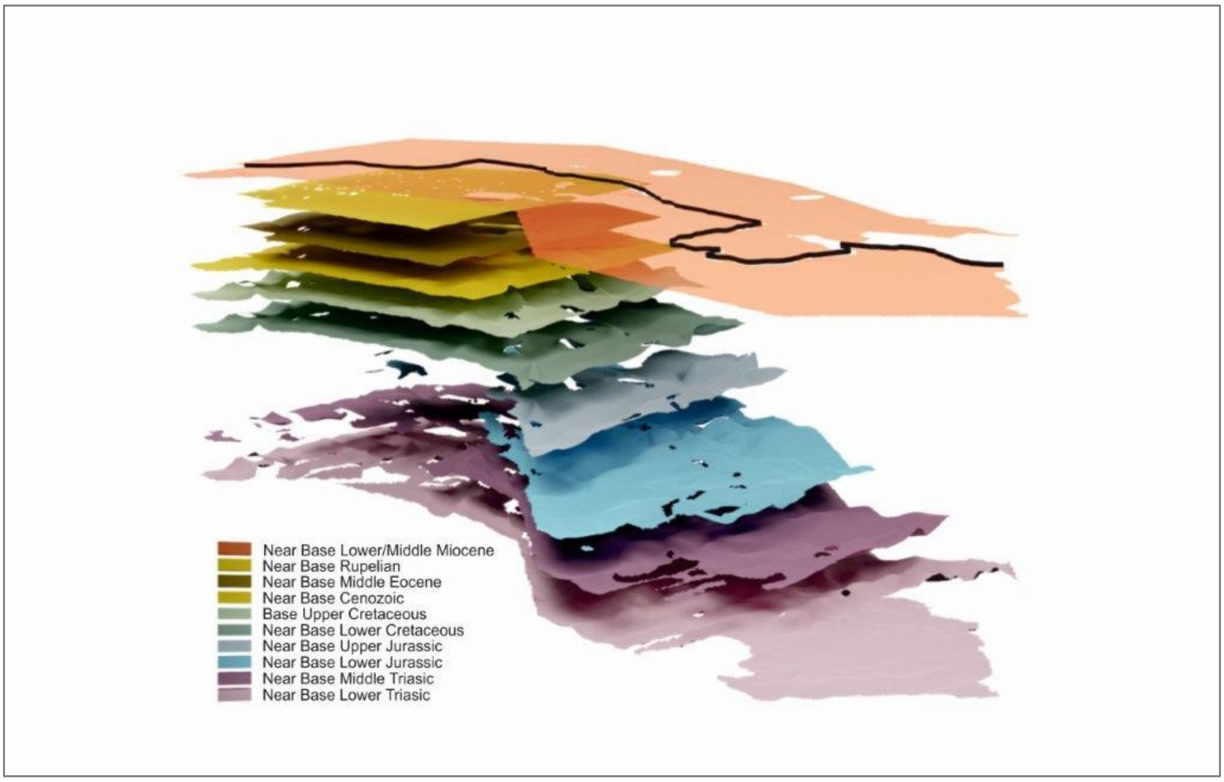

Figure 4: 3D geomodel "NLS3D"; 3D-view into the model.

Cenozoic thickness maps derived from NLS3D give information of thickness, base and distribution of lithostratigraphic units.

The decision support map of the Rupel Formation shows the base and distribution of the barrier between deeper saltwater and freshwater, to be used for decisions of underground usage to protect the freshwater bodies of pollution with saltwater.

An overview of the work, results and lessons learned is presented in Deliverable D1.5 "Final Report incl. lessons learned.

Table 2: Overview of deliverables in work package 1

Deliverable	D1.1: Report including the inventory of existing data and models including a description of the cross-border model concepts and the set of harmonization criteria
Short description, remarks	State of the art inventory of existing 3D models in Lower Saxony and The Netherlands, which were examined for feasibility of harmonization process along the border, which also documents existing maps of Cenozoic reservoir rocks.
Link	Inventory Report
Deliverable	D1.2: NLS3D: A harmonized 3D model of 10 main Cenozoic and Mesozoic horizons with a supporting report
Short description, remarks	NLS3D is a harmonized onshore cross-border 3D model of the northern part of the Netherlands (NL) and Lower Saxony (D). The model contains 10 Cenozoic and Mesozoic lithostratigraphic layers and has been created by using available data and existing depth models on both sides of the border. The base of each lithostratigraphic layer has been harmonized by using a “deviation percentage method”, where corresponding horizons on both sides of the border with a comparable depth within a predetermined range have been harmonized.
Links	Harmonized 3D model - ESRI ASCII Harmonized 3D model - ZMAP Supporting document
Deliverable	D1.3: Harmonized distribution, depth and thickness maps of Cenozoic layers
Short description, remarks	Thickness maps have been derived from the new harminozed cross-border model. These maps show variabilty of thickness in Cenozoic units with a minimun thickness of 5m. Distribution, depth and thickness maps of three Cenozoic units: • nls3d_v2_02_base_rupelian_thickness_3034 • nls3d_v2_03_near_base_middle_eocene_thickness_3034 • nls3d_04_near_base_cenozoic_thickness_3034
Links	Depth Maps Thickness Maps
Deliverable	D1.4: Harmonized map of hydraulic barrier between fresh groundwater and the deep salt groundwater system as a decision support tool for planners
Short description, remarks	For regional planning this decision support map is a reliable base for discussions on competing interests concerning usage of geological underground to derive information about Rupel Formation for detailed investigations.
Links	Map of hydraulic barrier - ESRI ASCII Map of hydraulic barrier - ZMAP
Deliverable	D1.5 Final report incl. lessons learned
Short description, remarks	This report summarizes the work and results of the WP1. It describes work in tasks 1.1 and 1.2 but in detail it documents task 1.3, 1.4 and 1.5 and discusses lessons learned on harmonizing existing 3D models across a national border.
Link	Final Report incl. lessons learned

3.2 WP2

Work Package title:

<u>Cross-border harmonization of selected horizons and structures in the Polish-German border region</u>

Objectives

The major goal of work package 2 (WP2) in the project 3DGEO-EU was the development of harmonized geological 3D models for selected horizons and structures in the Polish-German cross-border region along the river Oder/Odra (Figure 5). These lithostratigraphic horizons, salt structures and faults reflect the evolution of the Central European Basin System, especially in the transition zone between the North German Basin und the Polish Trough. Deposition of sediments, tectonic and halokinetic processes between late Permian to Quaternary are documented and visualized for the project area, which extends from the Baltic Sea in the north to the Lusatian Region in the south. The results will support spatial planning of subsurface uses, e.g. energy storage, geothermal use, and local potential hydrocarbon reservoirs.

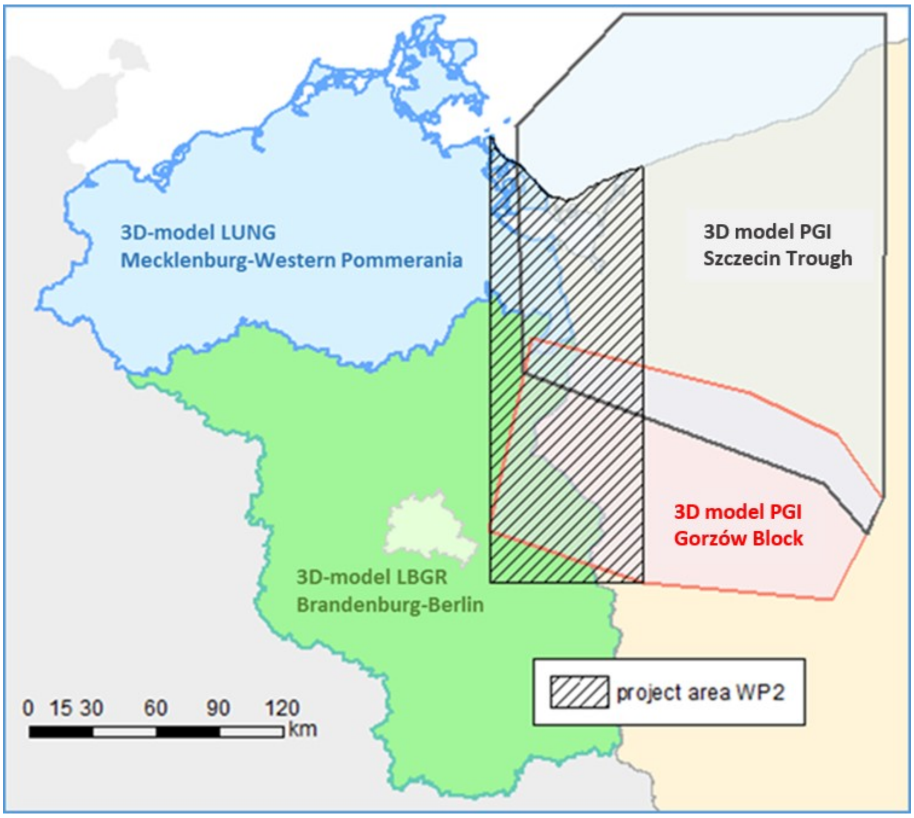

Figure 5: WP2 work areas in the German-Polish border region.

Approach and challenges

Two pilot areas were defined comprising the Gorzów Block and the Szczecin Trough in western Poland and their extension to eastern Germany, thus, in the Federal States of Brandenburg (Uckermark–Barnim and Oderland–Spree) and Mecklenburg-Western Pomerania (Vorpommern-Greifswald). Before the modelling process started, evaluation of national data bases was done. This includes location and depth of deep boreholes, location and results of geophysical data inventories, available maps and 3D models, results of interstate cooperation Eastern Germany/Poland before 1990 and international projects after 1990 with Polish-German participation/cooperation. It showed areas with high data density and with data gaps (deliverable D2.1, submitted in M9).

Well data and seismic lines mainly cover the southern and western parts of the project area. In contrast, the region surrounding Chojna in the center of the project area and the region Szczecin Lagoon – Stargard Szczecinski – Gryfino in the north lack such data. On the German side the seismics is general 2D, on the Polish side 2D and several 3D surveys exist. Therefore, potential field methods (gravimetry) were used in addition to seismic investigations in less explored areas (in cooperation with IGME and 3DGEO-EU, WP6).

Additionally, the possibilities and restrictions of data exchange in both countries were analysed and discussed. The results were that primary data from both countries can be compared and discussed, but usually not be shared and distributed because of legal restrictions (with a few exceptions). So the workflow of cross border harmonization was mainly based on interpreted data, e.g. modelled surfaces and structures on both sides obtained from seismic horizons and well markers.

Modelling was done stepwise beginning in the south (pilot area 1: Gorzów Block in Poland and eastern Brandenburg in Germany) and extending the harmonized model towards the north (pilot area 2: Szczecin Trough in Poland and eastern part of Mecklenburg-Western Pomerania). First of all, a comparison and harmonization of the geological and geophysical interpretations were carried out including well stratigraphy, seismic stratigraphy and velocity models. The picking of main reflectors was compared and discussed in detail using several near-border seismic profiles in time domain. The result was the overall consistence of the stratigraphic correlation and the picking of the reflectors – even if differences exist in some cases due to different interpretation stages and processing of the profiles (especially as at the German side the seismic sections are mostly from the 1980s). In the second step velocity data and models were compared for selected seismostratigraphic intervals. Here also an overall consistence could be recognized.

Results

The first harmonized model of pilot area 1 covers >7.000 km² and comprises the base surfaces of Zechstein, Buntsandstein (= top salt), Muschelkalk, Keuper, Jurassic, Upper Creatceous, Tertiary and Quaternary. The model also included the important fault zones of Guben–Fürstenwalde and Buckow that cross the model area on the German side (Deliverable 2.3a., submitted in M18).

The construction of a similar harmonized model of the pilot area 2 followed, including reworking of the first model and adding a new model horizon, the top surface of the so called Basal Anhydrite in the Lower Zechstein, which separates the basal Zechstein succession, which is mainly composed of anhydrites and carbonates, from the thick rock salt-dominated units above. Finally, all modelled data of pilot areas 1 and 2 were integrated in one GOCAD-SKUA workflow to obtain the final result (Deliverable 2.3b, submitted in M40).

The final harmonized German-Polish 3D model covers an area of about 14.000 km^2. It extends c. 210 km in N–S and c. 70 km in W–E direction. The lowermost base surface of

Zechstein occurs at a depth of 2–3 km in the north and south and goes down to 4–5 km depth in the central part (Figure 6). The overlying horizons follow this major trend. However, the post-Permian horizons show strong undulations caused by formation of salt pillows, especially in the central part of the model area. A salt dome elongated in NNW–SSE direction is visible on the Polish side at the north-eastern margin of the model. All following model surfaces cover nearly the whole project area with exception of the base surfaces of Upper Cretaceous and Tertiary due to a lack of these sediments and erosion at the northern margin.

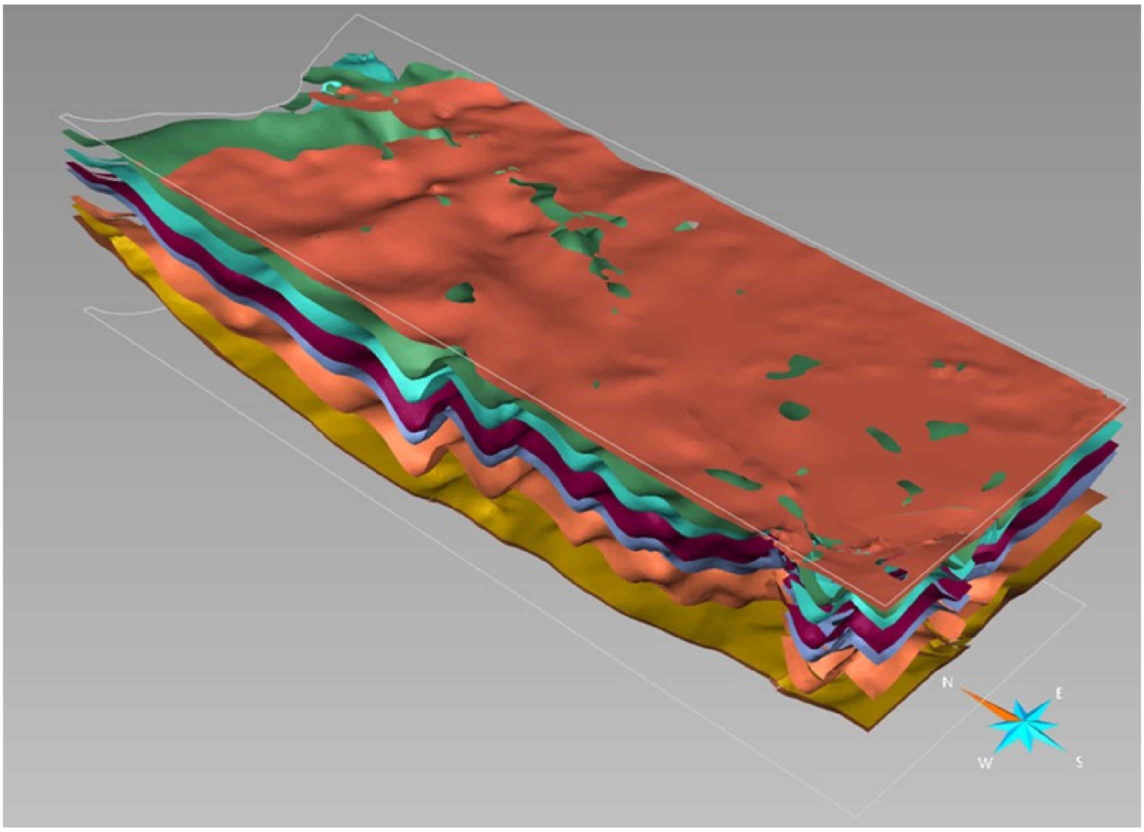

Figure 6: Horizons of the harmonized 3D-model of WP2 in the Polish-German border region from base Cenozoic at the top to base Zechstein (faults are not shown). View from southwest. Vertical exaggeration 1:10

The 3D model contains 120 faults (Figure 7). These faults can be subdivided into faults at the Zechstein base that mainly strike NW–SE. In contrast, faults of the Western Pomeranian Fault System are more NNW–SSE oriented. They occur on both sides of the border and outline discrete graben or halfgraben structures filled with Mesozoic and subordinately with Cenozoic sediments. Due to the orientation parallel to the border in the north, no crossing was observed. In the southern part, the main fault zones either strike NNE–SSW or NW–SE showing also no evidence of crossing the border. The fault modelling and the results are discussed in detail in deliverable 5.2.

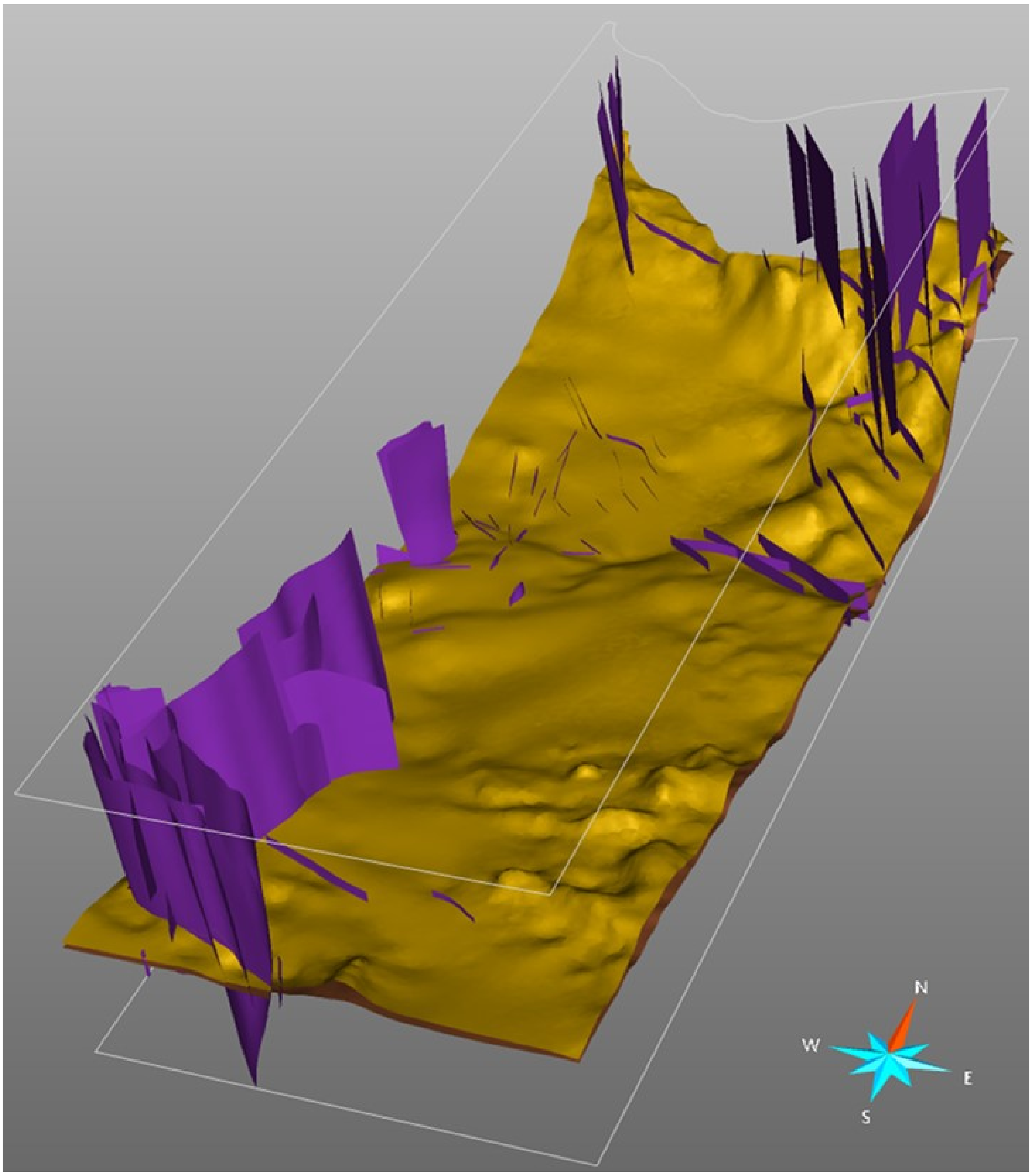

Figure 7: Fault network (violet planes) in the model area and the surfaces Top and Base of Basal Zechstein (ochre and brown). View from southeast. Vertical exaggeration 1:10

The gravimetric data were harmonized and a detailed joint Bouguer map was developed for an extended model area. In addition, a petrophysical model of the rock densities for the modelled strata based on well logs and core data was developed. The information was used in gravimetric modelling in co-operation with WP6 (deliverable 6.3). It could be tested how the modelled structures fit to the gravimetric signal. Furthermore, the gravimetric models were used to constrain basement framework, inaccessible to standard modelling techniques due to limited well depths and very noisy seismic signal below thick Zechstein salt.

Table 3: Overview of deliverables in work package 2

Deliverable	D2.1: Status/State of the Art report on previous work and results in the Polish-German border region at national, interstate and international level
Short description, remarks	This report highlights the existing database along both sides of the Polish-German border (well and seismic data, results of gravimetric and magnetic surveys), the results of former cross-border projects (starting from first co-operations in the 1970s) and the current regulation of sharing data.
Link	State of the Art Report
Deliverable	D2.2: Documentation of harmonization methods, workflows and results for different geological/geophysical datasets and levels of investigation
Short description, remarks	The report describes the methods and techniques of different harmonization workflows for input data of different quality and age. It also shows how anonymized and interpolated data can be used for harmonization processes. Furthermore, it outlines the possibilities to join models from several partners produced by different modelling software.
Link	Documentation of harmonization
Deliverable	D2.3a: Improved and harmonized geological 3D model at the Polish-German border region for the pilot area 1
Short description, remarks	The report document (attached to the model data) describes, how the layers from different models established on the German (eastern Brandenburg) and Polish side (Gorzów Block) could be joint and harmonized. It describes the data bases and challenges in the harmonization process and presents the modelling results of pilot area 1 in the south of the project area.
Deliverable	D2.3b: Improved and harmonized geological 3D model at the Polish-German border region for the pilot area 2
Short description, remarks	The report document (attached to the model data) shortly describes the models that were used for the joint model of pilot area 2 in the north of the project area (model of Mecklenburg-Western Pomerania and model of Szczecin Trough) and the results of the modelling process.
Link	D2.3a + D2.3b: Final joint model with supporting documents
Deliverable	D2.4: Final report including best practices/ lessons learned/ recommendations
Short description, remarks	The report summarizes the major steps and workflows of the final harmonization of the different subsurface models in the Polish-German border regions. It points to difficulties caused by heterogeneous data sets and the inhomogeneous data distribution as well as problems in sharing of primary data. It shows first approaches to overcome the regulation barriers and how data gaps can be filled by using additional information and suitable interpolation procedures. It shortly discusses final results, describes lessons learned during this very enlightening exercise and proposes reccomendations for further actions at the European scale.
Link	Final Report including lessons learned

3.3 WP3

Work Package title:

North Sea area NL-DE-DK

Objectives

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 has been selected as a showcase for harmonization and for working on in work package 3 (WP3) of the project. It spanned the offshore cross-border North Sea area between the Netherlands, Germany and Denmark (Figure 8). 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 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.

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.

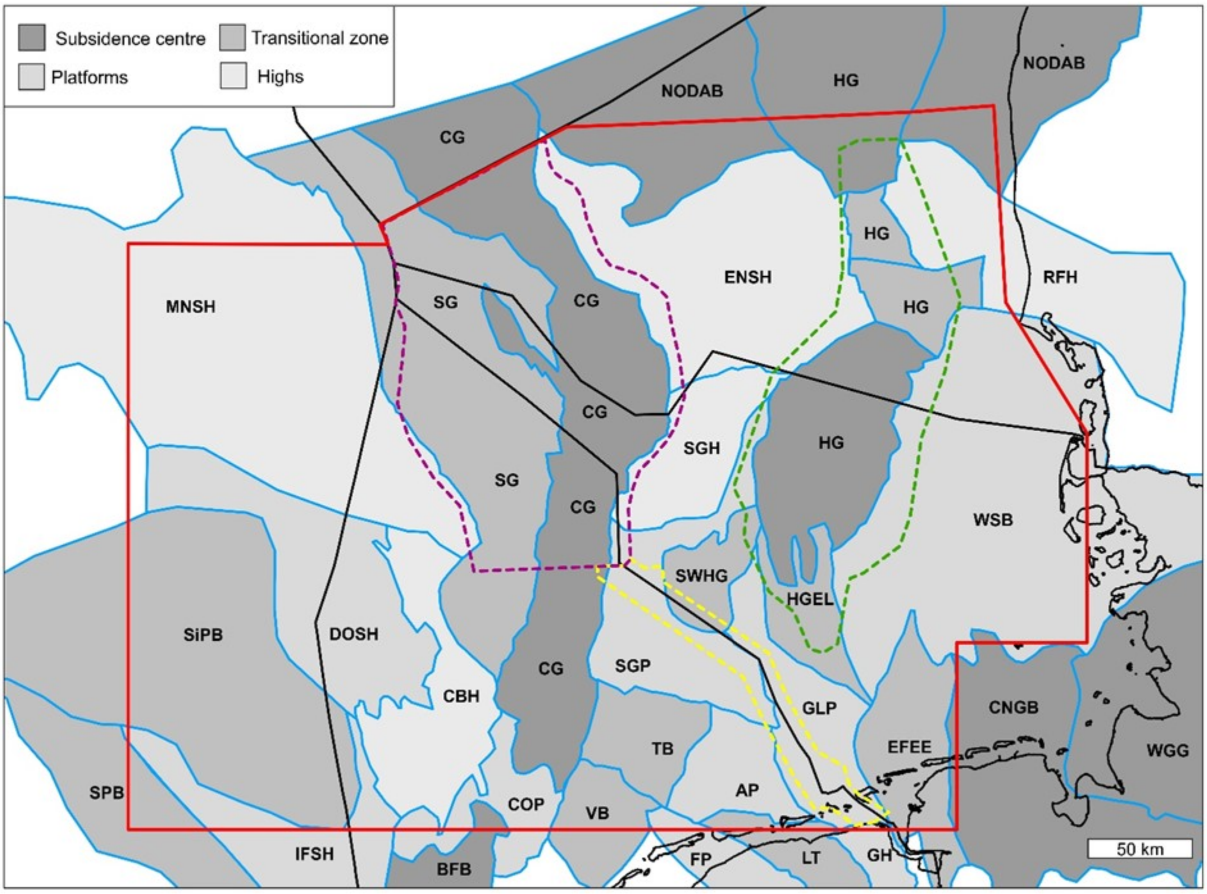

Figure 8: Map of main structural elements in the area of the UK, Dutch, German and Danish North Sea sectors showing the location of the working areas defined in the North Sea for 3DGEO-EU WP3 (yellow= NL-GER offshore border area / purple = Entenschnabel region / green = Horn Graben region). The extent of the transnational velocity model constructed in WP3 is indicated by the red polygon.

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 / SPB = Sole Pit Basin / IFSH = Indefatigable Shelf / NODAB = Norwegian-Danish Basin

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.

Challenges

During the harmonization process of cross-border modelling in WP3 the following problems and challenges have been assessed (Table 4):

Table 4: 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

Results

The harmonization work conducted in WP3 and the resulting products are summarized in nine deliverables, which are listed and briefly described in Table 5.

The experiences and lessons learned from each deliverable compiled in 3DGEO-EU WP3 are summarized in Deliverable D3.9 “Final report incl. lessons learned”. Accordingly, as shown in WP3 there is a wide range of challenges for model harmonization, which typically evolve from independent data sets, interpretations and concepts, technical limitations and legal restrictions. The harmonization work executed in WP3 is an example how many discrepancies and thus problems have been encountered crossing borders, before finally generating a harmonized (in some essential points) geological model for the Entenschnabel area within Central North Sea.

All efforts actually show that the harmonization steps strongly depend on the data basis, as well as the geological complexity and outcrop situation. Therefore, recommendations can only be given for basin areas comparable with the WP3 study area, with a comparable good data base and coverage.

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.

Since a comprehensive harmonization was usually not feasible in the WP3 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.).

Table 5: Overview of deliverables in work package 3

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.
Link	State of the Art Report
Deliverable	D3.2: A generalized 3D depth model of (a part 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. A supporting report about the model is provided as well.
Links	Grids - ZMAP Grids - CPS3 Supporting document
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.
Link	Harmonized stratigraphic chart (Report)
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.
Link	Correlation profiles through the study area (Report)
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 enable 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.
Link	Harmonized seismic stratigraphic concepts (Report)
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.
Links	Harmonized time model of the Entenschnabel region (Report) Harmonized time model of the Entenschnabel region (Model data)

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.
Link	A harmonized cross-border velocity model (Report)
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.
Links	Harmonized depth models and structural framework (Report) Appendix of Report, High Resolution Harmonized models and structural framework - model data and more
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.
Link	Final report incl. lessons learned

3.4 WP4

Work Package title:

Uncertainty in geomodels

Objectives

When constructing 3D regional models of the subsurface, the geoscientist has to deal with a wide range of different types of uncertainty. At the beginning, the uncertainty should already be estimated and assessed during the acquisition and interpretation of the data which later form the basis of the 3D model. The location of markers for faults and horizons that are interpreted from borehole data is uncertain, especially when old logs from the archive have to be used, as the tools to determine the borehole path had, and still have, only a limited precision. When seismic imaging is used, different sources of uncertainty are introduced in the different steps of the seismic processing sequence, especially during the time to depth conversion, as the velocity model can often only be estimated with a limited precision. During the next step, namely the geometrical modelling phase during which the 3D geological model is built, the propagation of the uncertainty that comes from the input data must be assessed and its influence on the final model estimated. Sometimes there are insufficient data available for a large area and the modeller has to provide some kind of model-based interpretation in order to fill the void space in the 3D model. So the modellers have to make a decision on which conceptual models they should apply (e.g. the deformation style? flexure or fracture?) which introduces additional uncertainty. So, as a summary, the geological models involve a considerable amount of uncertainty that the users should be aware of.

While professional geoscientists know the overall geological modelling process and so are aware of these uncertainties, this is often not the case for the stakeholders who use these models, for example as a basis for decision making. Members of the public, who are nowadays quite used to looking at 3D digital mockups presented by architects or car manufacturers, can easily be led to assume that our geoscience models have the same precision as these models. Thus we need to find a way to visualize our models such that they are intuitive and also make the viewer conscious of where the model carries uncertainty and to what degree. This is the basis for later using the generated 3D models for informed decision making. However, in current 3D modeling projects this problem is largely neglected. The uncertainty is mostly not assessed and quantified and the models are visualized in a way as if we know the subsurface with a precision of up to a centimetre.

The aim of the work package was to provide a structured and documented overview on the role that uncertainty plays in the geological modeling process, where it is coming from and how it can be visualized. Further its target was to summarize what is already available for the treatment and visualization of uncertainty and thus to act as a point of transfer for the necessary knowledge and skills from computer sciences to geosciences. Another aim was to suggest some best practices and workflows for how the visualization of uncertainty could be incorporated into the current standard workflows for 3D geological modelling. Finally, it was intended to identify what still needs to be developed and to provide the necessary means, gap identification and corresponding example data sets, to give potential outside partners, such as computer graphics groups at universities, the motivation to do research towards developing the methods lacking.

Approach

The overall idea of the work package ”Uncertainty in geomodels” was to gain an overview on this overall complex and manifold research topic by establishing a network of geological survey organizations (GSOs) and making use of their individual strength. Some of them already had experiences with assessing the uncertainty in their 3D models for sedimentary environments covered by many geophysical data, others where used to cope with crystalline environments where only few data where available and again others had experience with the needed methods in computer graphics and visualization. While some GSOs where more in the role to provide their knowledge, others where more in the role to get an insight what the available options are for future modelling projects.

In order to organize this work, the work package has been structured in terms of four different tasks. During the first phase of the project, the aim of the first two tasks was to establish and document the methods and concepts required. Task 1 captured the state of the art in uncertainty visualization and in this manner also provided information about which type of data we would need to compute in order to be able to display the uncertainty in our models. It thus sheds light on where we might go in terms of visualization and what we will need for it. Task 2 will discuss the different sources of uncertainty and the methods to propagate this uncertainty through the 3D modelling process. Task 3 and 4 in the second phase of the project where intended to do a gap analysis, to define the requirements that the European Geoscience Data Infrastructure should fulfil to make it fit for the use with uncertain geological models and to provide example data, using data sets from the pilot areas of the 3DGEO-EU project.

Challenges

As already said above it was the idea behind the work package to get a broad overview and to structure the knowledge of this complicated topic as a networked team of GSOs who each provide their individual strength, abilities and previous experiences. Clearly this can be done much more efficiently during workshops where individual partners meet than by exchanging texts and having video-conferences – especially as it took some time until all partners installed the necessary technology and internet related problems remained until the end. In summary Corona clearly hampered the work, and so, while the work package was able to achieve its overall goals, even if somehow delayed, it can be assumed that the results would have been better and the established network would have been stronger and more sustainable under normal conditions.

This also intensified the problem that the assessment of uncertainty visualization methods by 3DGEO-EU’s WP4 and the specification of the requirements for the EGDI 3D Viewer by GIP-P happened in parallel. This was inline with the project plan but principally the specification of the requirements regarding the 3D uncertainty visualization should have been available for GIP-P earlier. To overcome this problem a draft version of Deliverable 4.3 has been provided for GIP-P at a much earlier stage. However, also due to resource problems, the necessary infrastructure could not be provided by EGDI in full and some of the requirements that need to be fulfilled by EGDI to use it for storing and visualizing uncertain 3D models could not be implemented in time. However, in cooperation with GIP-P some classes for visualizing the uncertainty of structural models have been implemented by WP4 using the same technologies and libraries as the EGDI 3D viewer. So it will be possible to include these visualization into the EGDI 3D-Viewer in the near future, for example in the context of the planned Coordination and Support Actions (CSAs).

Results

In terms of visualization, viewed from the point of computer sciences, most of what we might need is there and theoretically available, and some further methods have been developed during the project phase. This has been captured in an Open Access article and in Deliverable 4.1 as result of Task 1. As outlined in Deliverable 4.3, especially the basic and most important methods that are needed to show structural uncertainty can be readily used in open source software that is publicly available. However, these necessary methods need to be integrated into the overall workflow which is dependent on the surrounding software architecture of the different GSOs. Further, when more advanced methods will be needed in the future, such as volume visualization or the rendering of uncertain vector fields in hydrogeology, often no implementation will be available that is ready to use. The theoretically available methods have often been developed in the framework of research projects at universities, for example in the framework of a masters or PhD thesis, but have only been implemented on a prototypical basis as proof of concept. The quick implementation of such software in order to present project results would likely be expected too much of individual GSOs and would be a task that needs to be solved by the community, for example in the context of the Strategic Research and Innovation Agenda (SRIAs). The aim would be to make these methods readily available for their use when they are needed.

However, the visualization requires that the 3D models are provided with a quantitative description of their uncertainty. As described in Deliverable 4.2 this requires firstly a quantitative estimation of the uncertainty coming from the input data and its interpretation, such as well logs and seismics, followed by a quantitative assessment of the propagation and distribution of the uncertainty due to the 3D modelling process. While methods for the latter now become more and more available using Monte-Carlo Simulation in commercial and open source software, the quantification of the uncertainty from input data and its interpretation is still a major problem. Often GSOs use data from archives or only get the results of geophysical campaigns and so don't have the necessary information to determine the uncertainty quantitatively, resulting in the use of rough estimates. Further research is needed here.

Table 6: Overview of deliverables in work package 4

Deliverable	D4.1: Report on state of the art of uncertainty visualization in computer graphics
Short description, remarks	The report provides an overview of available methods for uncertainty visualization and shows how they could be used in open source software
Link	State of the art in uncertainty visualization (Report)
Deliverable	D4.2: Report on sources of uncertainties in geomodels and how they can be handled

Short description, remarks	The report provides an introduction where the uncertainty in the 3D models is coming from, mainly with regard to borehole information and seismics as geophysical methods and targeting at structural uncertainty. Further it outlines how the propagation and distribution of this uncertainty during the 3D modelling process can be estimated and gives examples where this has been done by project partners.
Link	Sources of uncertainty in 3D geomodels (Report)
Deliverable	D4.3: Documentation of requirements for the visualization of uncertainties in geomodels which can be used as input for EGDI
Short description, remarks	The report explains what the minimum requirements are for EGDI in order to be used for storing and showing geological models with structural uncertainty. Further it introduces a prototypical example implementation as a proof of concept.
Link	Uncertainty visualization requirements of EGDI (Report)
Deliverable	D4.4: Publicly available data sets/geomodels from the pilot areas (including documentation)
Short description, remarks	Two 3D data sets that are stored in EGDI. These are described in more detail in the supplement – A: a small pilot region for which the uncertainty has been computed using some general assumptions. – B: The WP3 model (Deliverable 3.8) of the cross border region in the Dutch, German and Danish North Sea for which the uncertainty has been computed by TNO for the German and Dutch sector.
Link	Currently geological models with uncertainty can not be shown in the EGDI 3D Viewer – thus no link is available.

Table 7: Article, as an additional result from work package 4

Article	Zehner, B. (2021): On the visualization of 3D geological models and their uncertainty. Open Access, Z. Dt. Ges. Geowiss. (J. Appl. Reg. Geol.), 172 (1), p. 83–98
Short description, remarks	The article deals with issues, regarding the 3D visualization of 3D models, in particular with regard to their uncertainty.
Link	https://dx.doi.org/10.1127/zdgg/2020/0251

3.5 WP5

Work Package title:

Faults

Objectives

Consistent modelling and cross-border harmonization of structural models depend significantly on our knowledge and understanding of the regional geologic setting, the structural inventory and the assessment of lateral discontinuities, which separate individual blocks and regions of the structural model from their adjacencies. Therefore, faults are the most important discontinuities that are relevant for structural modelling. They form mostly planar features in volumes of rocks across which a significant displacement occurred. Moreover, faults never exist individually but rather form a fractal distribution of single fractures ranging from micro- to macroscopic scales. Depending on the level of knowledge, data density and the scale of observation, modelling of faults is always associated with a distinct amount of abstraction. Geologically, faults are important borders of structural blocks or regions that were displaced relative to each other and which likely underwent an individual geological evolution. Hence, faults and fault networks form the essential framework for 3D models and are also possible sources for geological hazards and may act as sealing or leaking structures in deep geological reservoirs.

The main objectives are mentioned in the original 3DGEO-EU Project Plan:

- Consistent cross-border fault mapping- and characterization in all pilot areas (WP's 1, 2 and 3) complying with the standard and requirements set by the Fault Database of the HIKE project.
- Preparation of harmonized fault data for uptake in the IP project (EGDI platform) through WP7.
- Project-to project communication (telcon's and meetings) for synchronization and mutual harmonization.

Approach

The detection and modelling of faults strongly depend on the availability and use of appropriate data sets. The characteristics of these data sets differ depending on the regional geologic setting, the area of interest or territorial or infrastructural conditions. Whereas faults in areas with strong morphological expression are often easy to detect by use of classical geologic mapping, other regions are widely covered by post-kinematic rocks, the water table or infrastructure and thus faults need to be interpreted using subsurface geophysical exploration techniques. In these cases, the most appropriate method must be properly selected in accordance with the geological setting and the distribution of petrophysical parameters. Hence, a high variability of appropriate methods for fault observation and detection exists, which is described in Deliverable 5.1.

A fault modelling workflow is usually described by a series of complex and heterogeneous processes. Depending on the underlying database and supporting information the fault modelling process in general includes poly-dimensional data: one-dimensional points taken from boreholes, two-dimensional polylines taken from maps, cross sections or 2D seismic profiles and even three-dimensional data like point clouds from, e.g., interpreted 3D seismic.

Additionally, regional interpretations and often subjective assumptions on fault kinematics and timing can be integrated in the fault modelling process.

For research areas in the 3DGEO-EU project, fault modelling was always based on heterogeneous data sets, but in general the modelling process focuses on the interpolation of polyline and point information attributed with three-dimensional properties. Therefore, interpreted fault sticks (e.g. from 2D or 3D seismics) or polylines at various estimated depth levels (e.g. surface expressions/fault traces from geological maps, depth maps or interpreted gravity maps) were imported into several modelling environments. In the following, fault modelling was performed individually in all pilot areas and case studies (see Deliverable 5.1).

Challenges

The main challenges during fault modelling and harmonization across borders arise from:

- Political boundaries and legal restrictions (differences between countries)
- Interpretational bias and varible structural regions
- the definition and assignment of structural regions
- differing data processing and interpretation approaches and concepts
- data density and interpolation distances and
- technical limitations

A detailled description of these challenges and limitations is provided in the main report D5.1.

Results

The best practices for fault modelling work, which is executed within various 3DGEO-EU work packages, has been described in a main report D5.1 (see table below). This report also provides some lessons learned on the challenges listed above and finally some conclusive remarks. Accordingly, the various challenges for fault harmonization 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 fault harmonization can be performed successfully. Furthermore, an efficient harmonization needs a huge amount of communication and 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.

Originally in WP5 also a deliverable “3D fault objects with metadata and attributes” was planned as a result for the HIKE project. However, HIKE does not require to receive 3D fault data and the deliverable was discarded. The work on faults has been executed as part of the modelling in the various 3DGEO-EU work packages, and 3D fault objects are included in created models.

Table 8: One deliverable in work package 5

Deliverable	D5.1 ”Methods, bottlenecks, best practices and accompanying descriptions to faults in 3D models”
Short description, remarks	This report provides a more complete overview of best practices for fault modelling and data management and may act as a reference for future fault modelling projects.
Link	Report on methods, bottlenecks, best practices (Faults)

3.6 WP6

Work Package title:

<u>Optimizing reconstructions of the subsurface to reduce structural uncertainty in 3D models</u>

Objectives

3D geological modeling harmonization is one of the main goals of the 3DGEO-EU project. Very often, legal constraints at different levels preclude the access or sharing of information and the building of consistent 3D models and, thus, prevent tackling key challenges of the European Green Agenda as the evaluation of potential structures for CO_2 and Hydrogen storages, deep geothermal reservoirs, etc. The WP6 of the 3DGEO-EU project has focused on potential field geophysics (particularly gravimetrics) and classic structural geology techniques (like balanced cross sections) as quick, cost-effective and efficient methods for 3D modeling, especially useful for the model verification and harmonization of cross-borders regions (applied to a case study in Northern Polish-German border region) or regions with scarce and heterogeneous subsurface information or areas where the access to the subsurface information is restricted (case study from SW Pyrenees).

Two main goals were stablished:

1) To propose an optimized workflow for 3D reconstruction based on gravimetric, structural and petrophysical information. This workflow is based on a deep synthesis, discussion and feedback process among many members of the project team and GeoERA Energy community.

2) To apply and to test this reconstruction workflow in two case-studies: SW Pyrenees and the Northern German/Polish border aiming to aid in the harmonization.

Approach

<u>Workflow for 3D reconstruction using structural, gravimetric and petrophysical data</u>

We have followed the methodological approach extensively described in D6.4 “Optimized 3D reconstruction workflow based on gravimetric, structural and petrophysical data”. This workflow is based on three main pillars; gravimetric data, robust petrophysical (density) data and serial cross sections, and three different levels depending on the data processing can be established (Figure 9):

1) Level 1 considers the raw data from different sources. First, structural, stratigraphic and cartographic elements derived from field work and/or from data repositories are processed and synthetized in GIS platforms (Q GIS and ArcGIS). In second place, gravimetric data is measured in the field and/or harvested from databases (standard reductions are performed in this level). And finally, the petrophysical properties of the lithologies involved are estimated. Data come from field records, from well logging (often non-accessible) or obtained from FAIR databases. Interpretation of seismic sections may be also included in this level.

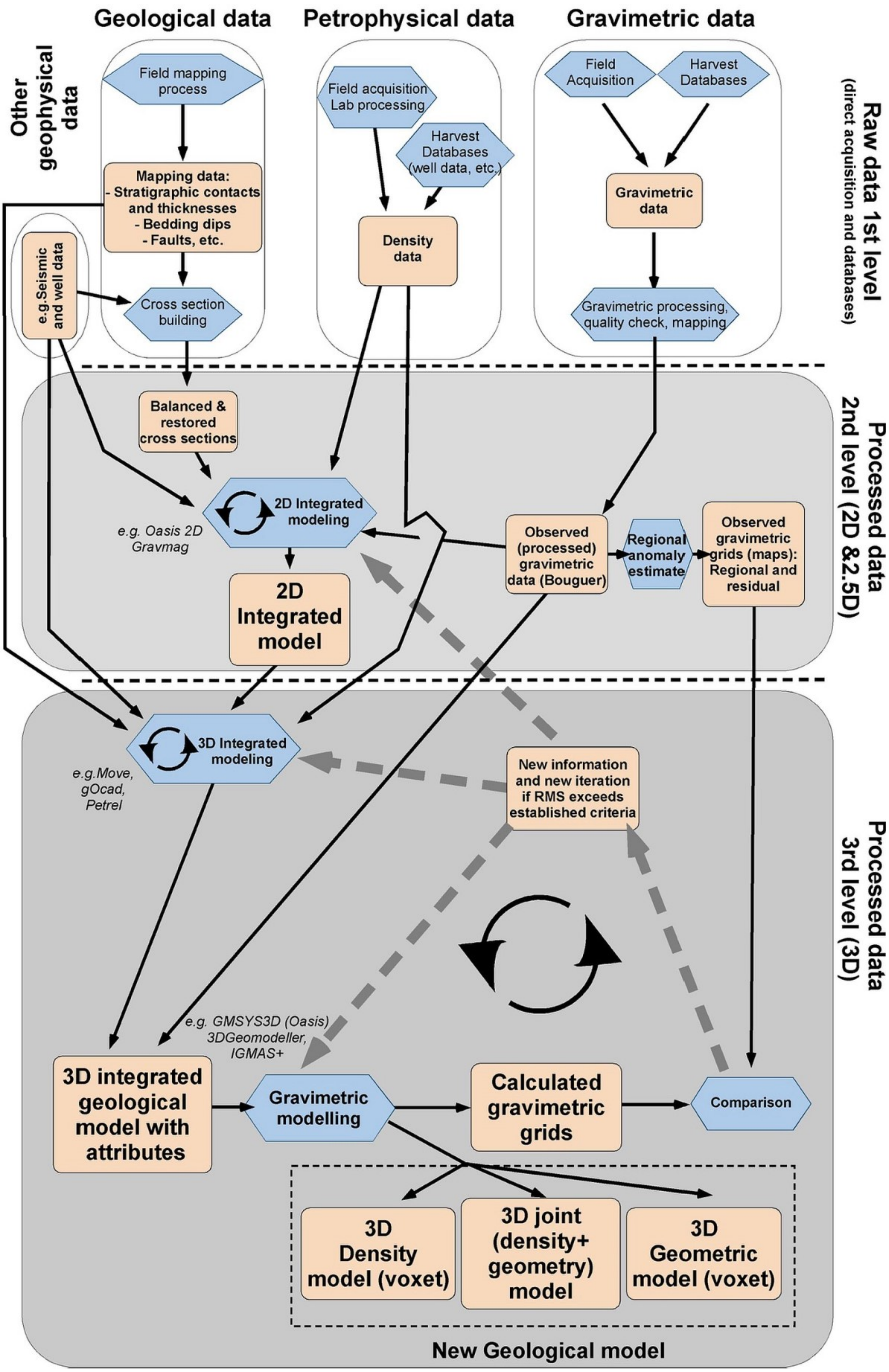

Figure 9: Synthetic 3D reconstruction workflow using gravimetric, structural, petrophysical and (if available) seismic data.

2) Level 2 involves an advanced degree of data processing. The gravimetric data are processed to obtain the Bouguer anomaly as well as regional and residual components or other enhancement techniques (vertical and horizontal derivatives, etc.). Cross sections, balanced and restored, are built from the structural and stratigraphic information as well as from seismic section interpretation (if available). In this level petrophysical data (density) are also grouped and processed together depending upon the final selection of stratigraphic horizons to be modelled.
3) Level 3 is focused in modelling, 2D and/or 3D, sequentially or alternatively (the 2D step may be skipped in areas with extensive or at least sufficient subsurface information). In level 3 an integrated 3D structural model is build merging all data together - the petrophysical and geological data (formation and structural trends, bed dips, stratigraphic thicknesses, etc.) together with the measured gravimetric field. The integration of the geological data to obtain the initial 2D or 3D geological model can be performed in several software platforms. In our case studies we used Oasis (2D and 3D modules) and Move to build the Pyrenean 3D.
4) Further processing during the generation of 3D models with attributes includes the forward modelling and inversion of potential field data. Comparison of misfits after the modeling allows a better constraining and improvement of the model. Oasis was used at this level.

Two case studies where used to test this workflow, main achievements are here synthetized:

<u>Pyrenean Case study</u>; Interpretation of > 2000 km of seismic sections and building an intial 3D model of six target horizons using the software Move (Basement top, Paleozoic top, Keuper top, Paleocene top [includes the Upper Cretaceous sequence], Eocene flysch top, Bartonian marls top, continental molasse top). Acquisition of > 3100 new gravimetric stations (400 of them in high mountainous areas), plus ca. 1000 stations from previous IGME studies and > 4400 from public databases (SITOPO). More than 300 new petrophysical sites (hand-samples or derived from the IGME paleomagnetic lithotheque). 2D and 3D forward modeling of the target horizons, the derived basement geometries were very useful to fill horizon gaps among seismic sections.

<u>Northern Polish-German border region;</u> Digitalization of more than 27.000 stations from old studies (analogic reports). Harmonization of almost 50,000 gravimetric stations for building a homogeneous Bouguer anomaly map (grid with a final resolution of 250m). Harmonization of the petrophysical information for the target horizons (core based data 52 boreholes, 33 from the German side and 19 from the Polish one, wireline data from 78 polish wells). Integrating all these attributes together with the 3D harmonized seismic model (main goal WP2). 3D forward modeling of all horizons. 3D joint inversion of the Zechstein salt (evaporites with very variable density) and of the Basement (poorly constraint by the seismic information).

Challenges

<u>Scientific challenges:</u>

Standard derivation <u>of residual anomaly maps</u> (Bouguer minus the regional anomaly) was not straight forward in both case studies. In the Western Pyrenees this is caused by the non-coaxial geometry of both, the lower crust subduction geometry and the Variscan basement rocks. Similarly happens in the German-Polish border regions with a strong signal from the underneath Variscan rocks. In the Pyrenees we decided to perform a 2D forward modeling including the Moho geometry (based on receiver functions data, deep seismic reflectors and magnetoteluric exploration) additionally, a standard residual anomaly map (low band pass filter 25 km) was derived for the core of the modeling area (still affected by non-coaxial geometries) and then the geometry of the basement was inverted in different sequences. In the German-Polish border we focused on that problem by means of integrated joint inversion of two single horizons (density is pseudo-fixed in the rest), the upper Zechstein level (very variable density) and in the basement (Paleozoic and Proterozoic separately).

Technical challenges and other problems:

1) Old analogic data: A significant effort had to be done during the development of D6.3 (Harmonization procedure in the East Germany/West Poland border using gravimetric data). 27000 data needed for the Bouguer anomaly map harmonization had to be digitalized and reviewed.
2) Acquisition of gravimetric data in rough terrains. About 14% of the new gravimetric data (more than 400 stations) were acquired in highly mountainous regions of the Western Pyrenees (hiking up to 2700m, cumulated height above 1500m/day) to guarantee a homogeneous data distribution. Therefore, this portion of the dataset implied a higher investment of time (x4) and budget effort (x3) comparing to regular acquisition.
3) Legal constraints and data ownership regulations preclude the sharing of information (raw gravimetric and petrophysical data) in D6.3, this issue may affect many other European regions. But we were able to overcome this problem; harmonization criteria were applied separately to the raw data and grid files (gravimetric, petrophysics) or unlocalized numeric data (petrophysics) were later on merged.
4) Other Problems: A number of reasons have hindered the normal development of this working package: a gravimeter crash in summer 2019, early snow during the 2019 autumn, the COVID pandemic (with severe mobility restrictions and accommodation difficulties during 2020-21), in addition to other personal problems (*force majeure*) of part of the IGME staff, seriously affected the data acquisition agenda (more than one-year delay) and the accomplishment of key forecasted in-person meetings (with WP2). All these reasons, not totally balanced by the four-month extension of the project deadline, were difficult to consider in the risk-mitigation plan and have precluded an optimal attainment of the project, although we still believe the efforts and results of the project have satisfactorily met the proposed objectives and the project expectations.

Results

The main results in the South Western Pyrenees are the building of a robust Bouguer anomaly map (1 station/km^2) and the construction of a 3D model for the region that integrates structural and stratigraphic elements (including boreholes) and 2000 km of seismic sections interpreted in the frame of this project (Figure 10). Besides, the forward modeling (2D and 3D) and the joint inversion of the gravimetric signal together with structural (including three new balanced sections) and petrophysical data have helped us better constraining the geometry of the basement rocks (with the highest density contrast) and finding model inconsistencies. The approach is particularly useful in areas without seismic information.

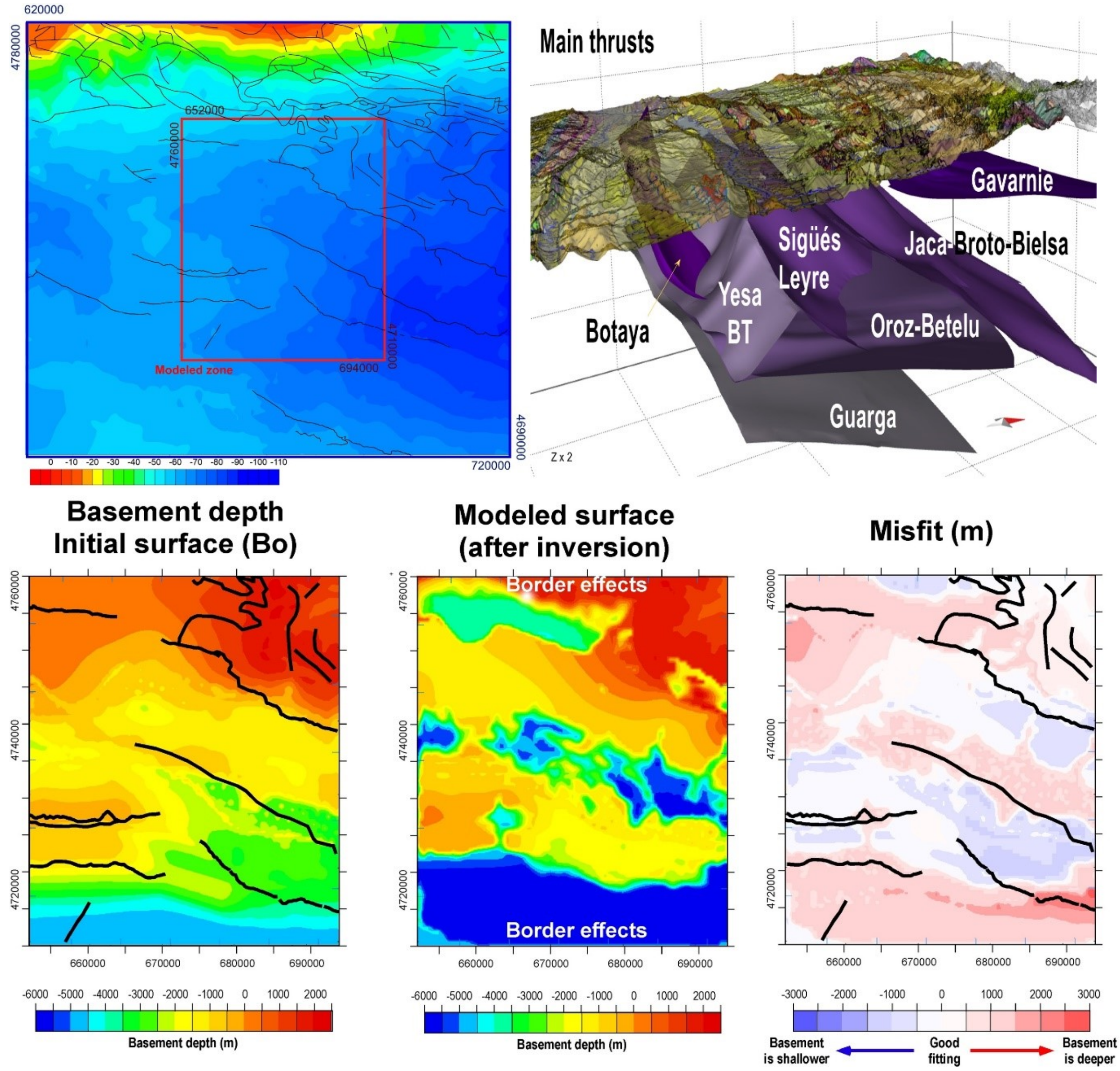

Figure 10: Main results from WP6 in the Western Pyrenees. New Bouguer anomaly map with main structural features. 3D model derived from the seismic interpretation. Comparison of the basement surface before and after the inversed modeling.

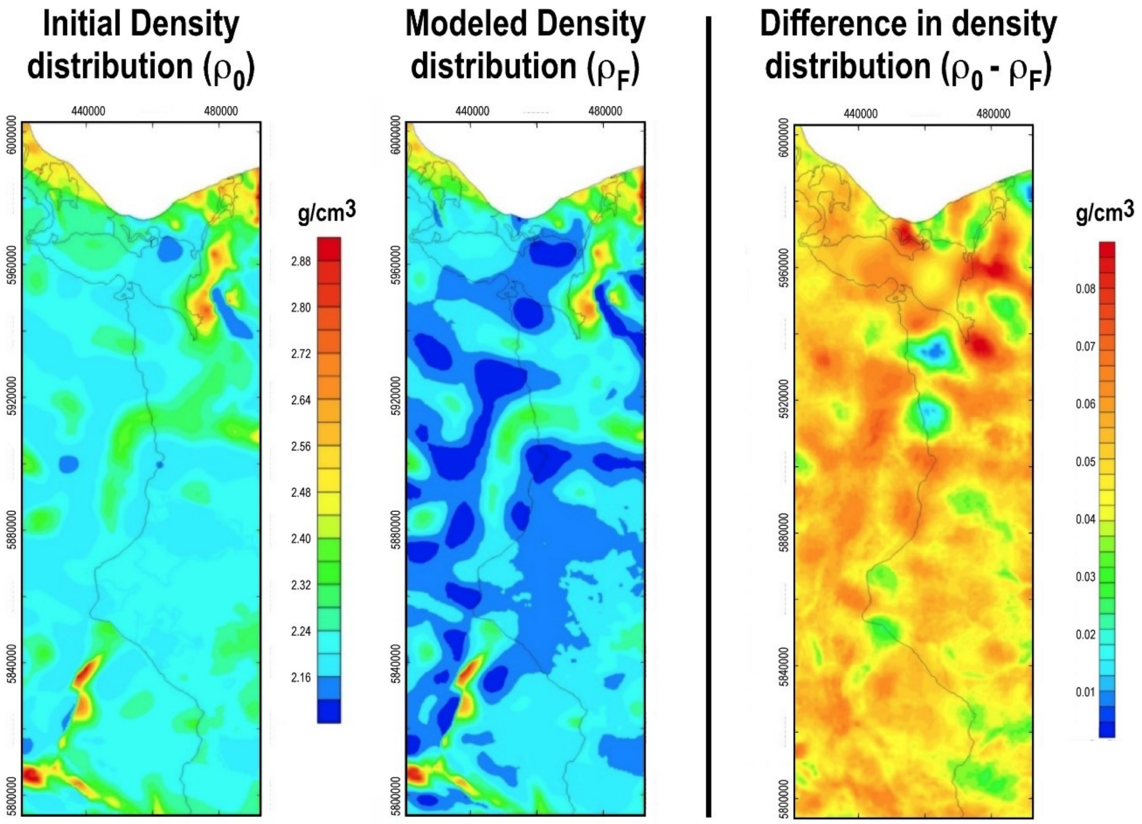

Figure 11: Main results from WP6 in the Northern Polish-German border region. Left) Initial density distribution of the Upper Zechstein Layer. Centre) Gravimetrically modeled density distribution. Right) Difference (Initial-Modeled). The larger discrepancy areas should review in the initial model. As a general rule, density was overestimated in the initial model, meaning that there is likely more salt than anhydrite in this layer.

The main results in the Northern Polish/German border are the harmonization of a cross border Bouguer anomaly map (1...5 stations/km^2) based on almost 50,000 gravimetric stations (as well as the harmonization of the vast petrophysical information derived from more than 100 borehole logs for the target horizons). Besides, the forward modeling (3D) and the joint inversion (3D) of the gravimetric signal together with the petrophysical data and the 3D model of the stratigraphic horizons (derived from the seismic data in the WP2) have allowed us to get insights of both, the geometry/density of the Zechstein evaporitic layer (including the distribution of potential less known or unknown structures) and the geometry of the basement rocks underneath the Permian-Mesozoic basin, usually obscure to the seismic signal that we have related with Variscan structural features (Figure 11).

Lessons to be learned:

The joint gravimetric, structural and petrophysical modeling is a very suitable and powerful approach for harmonizing 3D models in areas with scarce, uneven or non-accessible subsurface. However:

- Gravimetric data acquisition (rough terrains) or harmonization (cross border areas) maybe long-lasting (e.g. digitalization of old analogic data, etc.). In any case, it is most cost-efficient than other geophysical approaches (seismic).

- Harmonization of gravimetric and petrophysical data can be affected by copyright and sharing regulations. In the frame of this project we find a way to overcome these problems but also implied additional time investments.
- Uncertainty along standard reconstruction workflows (geological + potential fields data) is known to a certain extent, but its propagation is almost unknown.

Other Challenges:

- FAIR principles do not apply to many gravimetric databases (national and international level).
- Petrophysical data models for potential fields geophysics are not fully developed and existent databases are very limited.
- Major efforts should be done in the future to mitigate these problems (EDGI, EPOS).

Table 9: Overview of deliverables in work package 6

Deliverable	D6.1 Harmonization procedure of the western Pyrenees using geological, gravimetric, petrophysical, seismic and data
Short description, remarks	Comprehensive report on the new and previously available data (geologic, seismic, gravimetric, structural and petrophysical), methods and procedures used to build the 3D model of the South western Pyrenees.
Link	Report on harmonization in western Pyrenees
Deliverable	D6.2 Report and digital files of the South western Pyrenees model
Short description, remarks	**Digital files** of the Pyrenean model include (UTM 30N ETRS89): Digital elevation model in GRD format, Geological map (geoTIFF), balanced cross sections (TIFF image and navigation file in SHP format), some sample seismic sections (with and without interpretation, HR TIFF and navigation file in SHP format), gravimetric synthetic data (Bouguer anomaly map in GRD format), boreholes location and synthetic stratigraphic column (TXT format) as well as 3D model data; modeled stratigraphic horizons and main thrusts (all in GRD format). A brief accompanying **report** is also available as a user manual.
Link	3D model of the South western Pyrenees - digital files and report
Deliverable	D6.3 Harmonization procedure in the Polish-German border region using gravimetric data
Short description, remarks	Comprehensive report on the harmonization of the gravimetric and petrophysical data. Description of methods, results and discussion on the outcomes derived from the 3D forward modeling and the 3D joint inversion of specific horizons (evaporitic Zechstein and Basement rocks).
Link	Harmonization procedure with gravmag in POL-GER border region (Report)
Deliverable	D6.4 Report. Optimized 3D reconstruction workflow based on gravimetric, structural and petrophysical data

Short description, remarks	Review of data acquisition and processing procedures of the three main variables considered (gravimetrics, balanced sections and petrophysics) for the 3D reconstruction workflow in areas with poor or heterogeneous subsurface information. It does not pretend to be a complete and systematic review of all aforementioned topics, but a comprehensive and practical instruction's manual on common procedures used by some European Geological Surveys (and some universities). It also include a concise analysis on sources of uncertainty.
Link	Optimized 3D reconstruction workflow (Report)

3.7 WP7

Work Package title:

Information Platform Interface

Objectives

The main objective of the work package Information Platform Interface is to govern the interactions with the GeoERA-IP project and to manage all kinds of communication and data exchange between the 3DGEO-EU project and other GeoERA projects, especially IP. Therefore WP7 has developed and evaluated all requirements of 3DGEO-EU WPs in dense accordance with the parts of the Project Data Management Plan relating to IP and EDGI to enable an efficient and consistent uptake and embedding of project results into the GeoERA-IP project. This also includes uploading 2D and 3D data to EGDI as well as editing the corresponding metadata (MicKA).

Results

The requirements for the technical implementation substantially comprise three main topics, which evolved from the different needs of the two different partners (GIP & 3DGEO-EU):

- spatial reference,
- data exchange formats,
- EGDI functionalities

Since GeoERA is a pan-European project dealing with transnational projects the necessity of using proper spatial reference systems becomes evident. However, only ETRS89-LCC is supported by the EGDI-platform. Using this reference system within the 3DGEO-EU project was heavily discussed and criticized as it turns out that ETRS89-LAEA is more suitable because true area projection is required: WP1 analyzed the result of the projection of a 3D-model from ETRS89-LAEA into ETRS89-LCC in an early project stage. The distortion of the resulting data led to the decision that it is not recommendable to use ETRS89-LCC. Despite this result the EGDI-platform insisted on the usage of this spatial reference system.

As mentioned in the previous chapters, this project has produced harmonized cross-border three- as well as two-dimensional data, which mainly consist of derived information based on existing primary data (e.g. well data) and national or regional 3D models. The criteria for the data formats highly depend on the data type itself. Two and 2.5-dimensional raster data was exchanged in three data formats: ESRI ASCII grid, CPS-3 and GeoTiff depending if the data should be visualized as 3D model or in a 2D map (GeoTiff). Since the project members usually used one of the most common GIS (e.g. ArcGIS, QGIS) the exchange format of vector data is limited to constraints given by the mentioned software. As a result of technical limitations and outdated data formats the exchange format for all kind of vector data was the OGC GeoPackage v1.2.1. Most of the three-dimensional data (3D-models) has been developed with the SKUA-Gocad Software Suite which generates the Gocad ASCII format (*.ts) by default. But there was also 2.5D data which was exchanged in raster formats. In most cases the data conversation and preparation were done by this work package. There was also an intensive data testing phase at the end of the project runtime which revealed a few problems within the data import capabilities of the EGDI-platform. Until the date of this report the import routine of EGDI is not able to read Gocad ASCII files properly. The routine does not recognize the spatial reference system of the model and does not check the direction of the z-axis.

A very interesting part of the work done was the discussion about the different EGDI functionalities. These included searching, data access and different visualization methods for 2D, 2.5D as well as 3D. However most of these functionalities were also desired by other projects but the following ones are special 3DGEO-EU related:

- Uncertainty visualization,
- Glyphs or 3D primitives,
- additional (textured) objects

Unfortunately due to different adverse conditions in the development of the 3D viewer, a lot of the desired functionalities could not be implemented until the date of this report or are still under development.

Although 3DGEO-EU and its different work packages are very ambitious and highly sophisticated projects, most of the produced data follows the state of the art in 2D and 3D geological data processing. And so are the used data formats and the special needs of the WPs. Communicating these needs and discussing them with the GIP was often not that easy. Sometimes it took very long to get an answer to a certain question. In contrast to the active development and discussion of the visualization and the data exchange, the metadata system (MicKA) was developed to such an extent that the creation and editing was very easy. Only the documentation and explanation of some of the metadata fields is sometimes a little bit confusing and needs some user friendly revision.

Table 10: Overview of deliverables in work package 7

Deliverable	D7.1 Technical requirements for project data and results
Short description, remarks	Overview of the project goals and results, which will be transfered and published via the GeoERA-Information Platform (GIP)
Link	Technical requirements for project data and results (Report)
Deliverable	D 7.2 Data exchange report
Short description, remarks	Overview of the technical details of the data and the metadata transfered and published via the GeoERA-Information Platform (GIP).
Link	Data exchange report

4 LESSONS LEARNED AND CONCLUSIONS

The conducted work and efforts of the partners resulted in many products, i.e. technical reports and digital data sets (3D geomodels) for various work areas. But in addition, the partners gained experience and increased their knowledge level on the tackled research issues, which enables the project partners to share some valuable general lessons learned with readers.

Reflecting the project structure, the partners worked on three main themes: (a) cross-border harmonization (of 3D geomodels), (b) improved workflow for an optimized subsurface reconstruction (i.e. harmonization using potential field geophysical methods) and (c) the visualization of uncertainties of 3D geomodels. Thus, lessons learned and resulting recommendations are presented separately below.

Cross-border harmonization

Cross-border harmonization is a very difficult task, as inconsistent data, variable processing techniques and different interpretational and regional geological concepts on both sides of a border provide challenging issues. As lessons learned, we present the following key topics that hamper cross-border harmonization:

Legal restrictions

One of the most limiting factors for an efficient cross-border harmonization is caused by legal restrictions which effects data sharing opportunities.

The disparity of national laws and their consequences for sharing subsurface data should be considered right from the beginning of project planning. Data sharing opportunities should be addressed in advance, exploring the possibilities of transnational data agreements.

Variable data density

In addition to the aforementioned topic, variable data density and quality in a cross-border region cause special challenges in the interpretation and consistent modelling there. As one of the first steps in a harmonization process, the present differences in data density or data type should be investigated. Data availability defines, at what level a cross-border modelling can be done.

Different interpretations/concepts

The intensive harmonization work of cross-border partners proved a very significant influence of different interpretations and interpretation concepts that were applied in the past decades by the partners on both sides of a border. For example, the cross-border 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. Another example are different interpretation concepts for seismic horizons, as e.g. differences in seismic picking concepts cause discrepancies along borders. Observed discrepancies could be removed by seismic re-interpretation, but that requires a tremendous amount of time.

It is important to have knowledge of differences in national nomenclatures and classifications, stratigraphic and structural interpretations, and used concepts. Such information should be compiled and stored in a comprehensible manner, that former interpretations in the respective countries can be followed and reproduced by other geoscientists (e.g. from other surveys) as well.

Inconsistent definition of structural regions

Cross-border discrepancies do not only arise from national differences in lithostratigraphic, seismic stratigraphic and interpretational concepts, but they may also depend on the structural complexity of an analyzed area. Thus, cross-border partners need to find agreement on a structural concept, i.e. a consistent cross-border definition of structural regions. A consistent structural interpretation and modeling require thus an intensive study of the structural genesis in the region of interest.

Technical limitations

Furthermore, technical limitations hamper harmonization efforts as well. For example, 3D models may be available in various proprietary data formats, which makes it difficult to exchange models across borders or does not allow for manipulation of the models by all involved partners. Cross-border harmonization is challenging if highly variable models (structural models with triangularly meshed surfaces vs. 3D volume or grid models) exists on both sides of a border.

Considering the aforementioned general problematic topics and other observed issues occurred during the specific work in the WPs, some general recommendations can be given:

General recommendation for an integrated and corporate modelling approach

For the creation of a harmonized cross-border 3D geomodel, an exchange of previously finalized geomodels and a subsequent simple technical merging of these models along the border is not enough at all. In case that only interpreted data (e.g. preliminary models) can be shared, then an intense communication (which should include frequent work meetings) and a comprehensive knowledge transfer between partners must be ensured, thereby allowing partners to discuss and evaluate the validity of model parts and available data and to define interpretation and modelling concepts, thus preventing misinterpretations and contradictory modelling among partners.

The most efficient way to create consistent, harmonized cross-border geomodels is to apply a harmonized modelling approach, where partners do not “only” share data, model parts, knowledge and concepts, but do modelling work together instead of separately. One of the partners or a working team with geomodelers from the involved partners might be assigned to execute the modelling work in a border region. Another option could be to assign an independent contractor for this task. If such an integrated and corporate modelling approach is chosen, the created geomodels are harmonized from the beginning and a subsequent harmonization is not needed anymore.

General recommendation to EU/GSOs to promote cross-border harmonization

In Europe we are still at a starting point for generation of pan-European 3D-models. National geological services mainly take care of national issues, where border harmonization may not have a high priority, or resources (e.g. staff) are not sufficient. The experiences from the project 3DGEO-EU show, that cross-border harmonization faces many challenges and is a very difficult task. Thus the EU should promote the topic of cross-border harmonization in order to ultimately achieve the goal of a harmonized geological database across Europe. National Geological Surveys need to promote and set-up cross-border harmonization projects and to integrate these activities into a European framework.

Also, when further knowledge is gained in cross-border regions (additional data, more detailed interpretations, etc.), it is also necessary to continuously promote cross-border exchange between national services and research institutions and to consider capacities on both sides of a border for model update and maintenance.

Harmonization using potential field geophysical methods

For a number of reasons (shallow or highly subsident basins, mountainous regions, cross border areas, etc.), there is a lack of seismic information in many European regions. Besides and very often, legal restrictions limit the access to this information and, thus, the building of consistent 3D models. Especially WP6 of this project has focused on potential field geophysics (particularly gravimetrics) and classic structural geology techniques (like balanced cross sections) as quick, cost-effective and efficient methods for 3D modeling, especially useful for the harmonization of cross-borders regions (Northern German/Polish border) or regions with scarce and heterogeneous subsurface information or areas where the access to the subsurface information is restricted (SW Pyrenees).

Visualization of uncertainties of 3D geomodels

WP4 has provided a structured and documented overview on the role that uncertainty plays in the geological modeling process following the overall value chain. It first sheds light on where the uncertainty is coming from in our input data, the sources of uncertainty. It then summarized what is already available for the treatment and assessment of the uncertainty during the modeling process and finally showed methods and software that are available for the visualization of uncertainty in order to communicate our working results. As lessons learned can also be summarized along this value chain, we present the following key topics.

Sources of uncertainty

This assessment requires a quantitative estimation of the uncertainty coming from the input data (e.g. well logs, seismics and drilling reports). The corresponding uncertainties are due to the technical imprecision of the tools and to ambiguities in interpreting these data. However, often Geological Surveys don't have the necessary information to determine the uncertainty quantitatively, resulting in the use of rough estimates. Further research and literature studies are needed here. For example it would be of benefit to establish and provide some kind of rules of thumb that estimate the uncertainty from the type of data, the vintage/age of the data, principal method of data acquisition and so on.

Uncertainty assessment regarding 3D modeling and conceptual uncertainty

One option to assess the potential variability of the geological model, and so of its uncertainty, is the use of the Monte Carlo approach (see Deliverable 4.2). While this approach is conceptually simple, it is technically demanding. The approach to generate multiple models from input data that have been slightly varied requires a high degree of automation. Several international groups and consortia are working on suitable software environments (e.g. Loop, GemPy) but their use is often demanding as these environments are not commercially supported software tools with established user interface. However, GSOs should team up to keep track of these developments.

Software for visualization of uncertain geological models

The basic and most important methods that are needed to visualize structural uncertainty of 3D geomodels already exist and can be used within open source software that is publicly available. This software needs to be integrated into the overall modeling workflow which is dependent on the surrounding software architecture of the different GSOs, for example by implementing the necessary data converters from the geoscientific modeling software to the visualization software. However, if the more advanced visualization methods are needed which are not readily available in open source software, a quick implementation will be challenging and would likely be expected too much for individual Geological Surveys. For this reason the European GSOs should collaborate on a long term instance to make these methods available.

We consider all three of the aforementioned key tasks, such as software implementation, method development and provision of quantitative uncertainty description as challenging tasks that should be tackled and solved in a collective action by the community of Geological Survey Organizations in Europe.

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