3D Geomodelling for Europe
Project number: GeoE.171.005

Deliverable 2.4

WP-2: Final Report Including Lessons Learned

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Version: 31-10-2021

This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 731166. Scientific work is co-funded by the Geological Surveys and national funds allocated for science within the period 2018-2021.

Deliverable Data		
Deliverable number	D2.4	
Dissemination level	Public	
Deliverable name	Final Report Including Lessons Learned	
Work package	WP2	
Lead WP/Deliverable beneficiary	LUNG/LBGR/PGI	
Deliverable status		
Submitted (Author(s))	29/10/2021	Jahnke (LUNG, LBGR), Obst (LUNG) Szynkaruk, Żuk (PGI-NRI)
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1 AIMS AND AMBITION

Developing 3D geologic models in pilot areas across national borders is a crucial step on the way to harmonization of geologic data and interpretations across Europe and rendering them in a consistent and comparable way in order to resolve common challenges and take advantage of opportunities associated with the subsurface. Drawing on that, the 3DGEO-EU WP 2 aimed at constructing a single, harmonized geological model across the northern part of the Polish-German border region, testing and optimizing methods and workflows in order to gain experience and in the future apply it in future transnational harmonization projects. In this report we summarize the results of this work and conclusions drawn.

2 GEOLOGIC FRAMEWORK

The project area covers the northern part of the German-Polish border region (Figure 1). This area is geologically characterized as the transitions zone between the North German Basin and the Polish Trough, both sub-basins of the Central European Basin System (also named Southern Permian Basin). This zone developed as a result of post-Variscan destabilisation of the lithosphere followed by its gradual subsidence (Ziegler 1989).

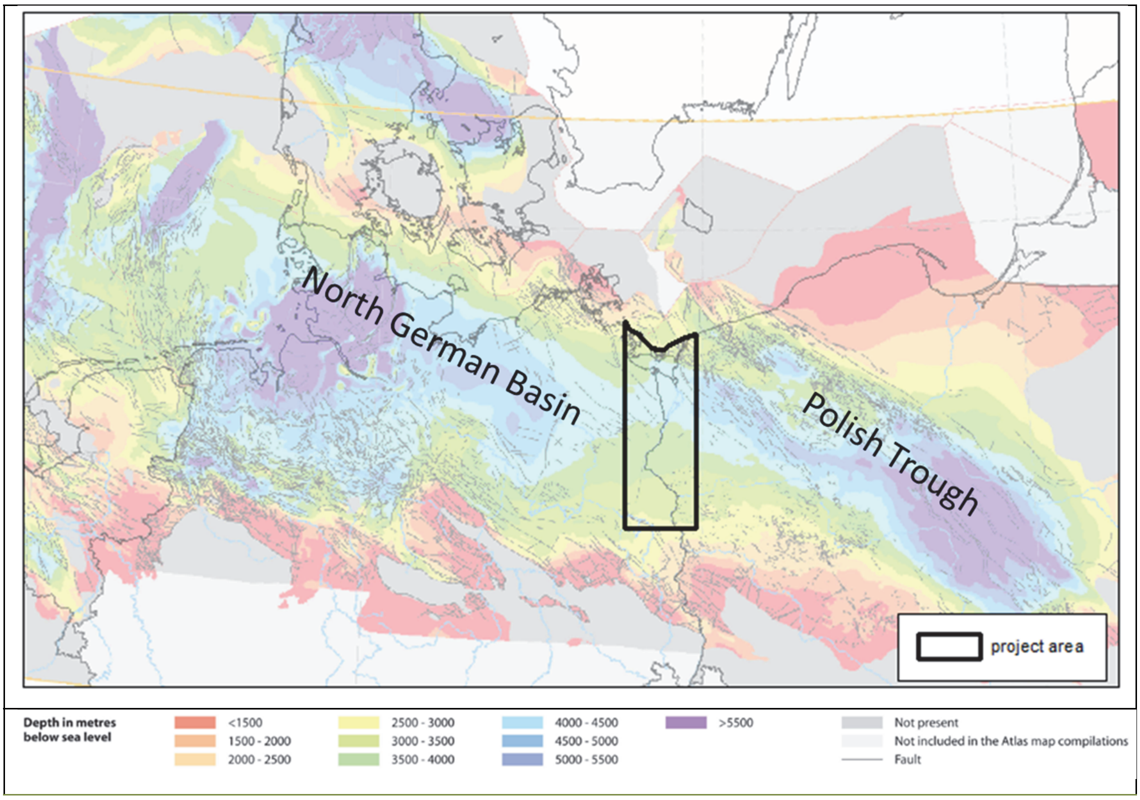

Figure 1: Location of the project area in transition between the North German Basin and the Polish Trough, both major sub-basins of the Central European Basin System. Background: Detail of the map Base of the Zechstein from the Southern Permian Basin Atlas [Doornenbal & Stevenson (Eds.), 2010].

The basement of this basin is poorly known within the study area due to scarce data – that is because exploration wells in most cases reached only target reservoirs in the Zechstein and Sedimentary Rotliegend (Upper Permian). Only at the northern margin of the basin (especially off-shore in the Baltic Sea) deeper strata is reached.

Seismic imaging below the thick Zechstein salts is usually extremely noisy and inconclusive. A few boreholes recorded sedimentary strata of Devonian and Carboniferous age underneath. In the southern, larger part of the study area, these strongly deformed strata belongs to the Variscan Externides (Rheno-Hercynian Zone), while the Variscan Foreland Basin resting over the Cadomian crust of Avalonia underlies the Permian strata in the north. Only in the northernmost part, crystalline basement rocks of Baltica form the deeper crust. This is mainly indicated by field methods (deep seismic profiles and magnetotelluric measurements), but it is also proved by cores from a few very deep boreholes drilled in northern Poland and adjacent Baltic Sea area.

Subsidence started in the Permian after a phase of widespread rift magmatism in Central and NW Europe. Deposition of clastic Rotliegend sediments under arid conditions was followed by precipitation of Zechstein evaporites. Cyclic precipitation from highly saline water resulted in accumulation of thick evaporite sequences, initially dominated by gypsum/anhydrite and subordinately limestone and clay followed by rock salt and clay-dominated clastics on top. The salt-dominated facies reached up to 2,500 in the basin centre (Kiersnowski et al., 2017), while later salt deformation changed the strata thicknesses. Today, the Zechstein sequence reaches in the study area 4,000 meters in the Goleniów salt diapir with an amplitude between the roof and surrounding depressions of up to 3,300 meters. Several salt pillows, salt domes and salt withdrawal zones form the most prominent structures in the study area.

The Triassic follows sedimentary pattern typical for the wider basin. According to the tripartite German lithostratigraphic scheme (Werner 1786), it starts with mostly continental Buntsandstein Group, followed by the marine Muschelkalk and then the continental, brackish and saline Keuper Group. Although the Jurassic is typically represented mostly by marine deposits, in the south-east of the study area continental deposits are more frequent, while in its southernmost edge the middle Jurassic strata are not present at all. Similarly, in Brandenburg the Middle Jurassic is present only locally. In turn, the Upper Jurassic can only be found in the northern part of the Polish section of the study area and northernmost edges of the German area (north of the Stettiner Haff and near the border). The Lower Cretaceous saw continental conditions and erosion that removed part of the Jurassic strata. Only a thin layer of the uppermost part of the Lower Cretaceous is present on the study site – a result of the Late Createceous marine transgression which also left a significant thickness of carbonate deposits.

The Pyrenean orogeny in the south-west resulted in latest Cretaceous/early Paleogene transpression (Kley & Voigt, 2008), and inversion of basins in the study area followed by yet another marine transgression represented by deep marine muds of Late Palaeocene to Early Oligocene age. These are covered by shallow-marine, paralic and continental mud- and sand-dominated sediments of Late Oligocene to Miocene age (German side) and Early Pliocene age (Polish side). The Paleogene and Neogene sequences though are lacking in the north due to the Quaternary erosion.

The inversion tectonics led to formation of uplifted areas as the Mid-Polish Swell or the Grimmen High. Thus, near the Baltic coast, also the Cretaceous succession was locally removed resulting in the Jurassic strata directly underlying Quaternary sediments, locally of insignificant thickness (such as near Kłęby and Czarnogłowy quarries of Upper Jurassic limestone). This unique geological situation resulted from strike-slip faulting reaching below the base of the Mesozoic along the locations of older Palaeozoic fault zones (Bobek et al. 2021). Transtensional movements during the Mesozoic also led to creation of series of northwest and north-trending systems of grabens and half-grabens in the area of the Trans-European Suture Zone (Krauss & Mayer, 2004; Seidel et al., 2018). Later in the Pleistocene, these fault zones were once again influenced by the weight of the ice sheet and its removal, and they most likely still remain active until today.

3 CROSS-BORDER HARMONIZATION OF GEOLOGICAL 3D MODELS

3.1 Prerequisites and approach

In the beginning the available database in the project area were investigated and documented and the possibilities and restriction of data sharing were analyzed. The results were documented and described in deliverable D2.1, State of the Art Report of WP2 (Jahnke et al. 2019). The major conclusions of the data study were:

Data coverage and data availability

Extended national databases of geological and geophysical data exist and are available in digital form at all partner institutes. The most regions of the project area are covered with exploration data from several decades with a high or at least sufficient density. Nonetheless at both sides of the border larger data gaps also exists in well exploration and modern digital seismics (the major sources for subsurface information) and also for gravimetrical and petrophysical data. Reasons are:

- no exploration interests in some regions
- no or reduced information in the immediate cross-border region (in a stripe of 1-2 km at both sides exploration activities were usually not allowed ore hampered)
- also within the territories of the partners the exploration was partially hampered in the past (before 1990 e.g. at military properties)
- water and swamp areas

In addition several vintage datasets are available (vintage seismics, vintage gravimetrical data) and can partially be used to close these data gaps, but this requires additional effort for digitizing, compilation and reprocessing.

Especially regarding cross-border harmonization is to be mentioned that no joint geological or geophysical cross-border investigations exist – even some harmonization projects were running in the past basing on vintage data (seismics in the 1970s, gravimetrics and magnetics in the 1970s and 1980s).

Regulations on data sharing

The largest part of the primary geological and geophysical data (e.g. well data and logs, seismic sections, gravimetrical measurements) can’t be exchanged between the Polish and German partners because of legal restrictions on both sides. Only a minor amount of data (a few scientific drillings in Germany, regional gravimetrical data and published data) could be directly shared and provided.

Conclusions and approach

A harmonized cross-border model in the Polish-German border region could not be developed as one joint model based on a joint primary geological and geophysical database. Substantial information and prerequisites (stratigraphic well logs, seismic interpretations and seismic velocity data, petrophysical and gravimetrical data) have to be compared and harmonized based on anonymized or interpreted/interpolated data. The model development based on (original) primary data had to be done in an own compilation and workflow at every partner institution.

After that the results of these specific compilations and workflows – separate and independent subsurface models - had to be joined and harmonized.

In detail WP2 developed the following workflow to construct and optimize a cross-border subsurface model:

1. Comparison and verification of primary data, when required harmonization of geological and geophysical data and interpretation
2. Development of separate and independent models at all partner institutions, aided by interpretations provided by partners
3. Cross-border comparison of the models and cross-border harmonization of the models
4. Estimation of uncertainties – definition of problems that can't be solved in context of steps 1. to 3.
5. Gravimetric modelling as a case study to verify and optimize subsurface models
    - Development of a joint Bouguer anomaly grid
    - Development of a joint petrophysical model
    - 3D gravimetrical modelling

3.2 Comparison and verification of primary data

Following the approach outlined in 3.1 in a first step the primary data were compared and verified in order to decide whether a reliable base of data and information exists for the further modelling steps at the partner institutes and whether it is possible to follow the workflow. In detail the following data were compared

- stratigraphic division and correlation
- seismostratigraphic correlation and reflector picking
- seismic velocities
- gravimetrical data base and gravimetrical processing
- petrophysical data (stratigraphic correlation, depth trends and regional distribution of rock densities)

Results are only highlighted in this final report. For details see deliverables D2.2 of WP2, Documentation of harmonization methods, workflows and results (Jahnke et al. 2021a) and D6.3 of WP6, Harmonization procedure in the Polish-German border using gravimetric data (Ayala et al. 2021).

The stratigraphic subdivision and correlation (see also chapter 2) in Western Poland and Eastern Germany show a direct litho-stratigraphic correspondence especially in the Zechstein and the Triassic succession. This is due to a rather uniform basin-wide evolution caused by large-scale subsidence. During the Jurassic and Cretaceous the basin differentiation and the halokinesis led to development of local depressions and troughs with own deposition patterns at both sides of the border. But the principle stratigraphic limits (used here: base of Jurassic and base of Upper Cretaceous) can be correlated as well as for the modelled horizons Cenozoic. So the stratigraphic information in wells and maps can be directly correlated cross-border and an additional stratigraphic fitting was not necessary.

Similar results were obtained for the seismostratigraphic correlation and the reflector picking. Several anonymized seismic 2D sections (without coordinates and metadata) in the Polish-German border region and their interpretation were compared in time domain. Table 1 lists the major seismic reflectors that are identified at both sides, their names, the stratigraphic position and the phase picking. At both sides the same major reflectors were correlated in the same stratigraphic positions and seismic phases – even if different level of detail exists depending on the local conditions and exploration targets.

Table 1: major seismic reflectors in the Polish-German border region, stratigraphic position and phase

Stratigraphic position of seismic reflectors	Short name of seismic reflectors		Phase picking
	Eastern Germany	Western Poland, (Gorzów Block)	
unconformity of Cenozoic transgression	T1		maximum
base of Turonian / Cenomanian-Turonian boundary	B1	base of Turonian	maximum
base of Cenomanian / unconformity of Upper Cretaceous transgression	B2/T2		minimum
unconformities of Lower Cretaceous transgressions	T4/T3	base of K1	
base of Upper Jurassic	-	base of J3	
base of Lias group (base Lower Jurassic)	L4	base of J1	minimum
base of Exter Formation (Rhätian, base of Upper Keuper)	K1		maximum
top of Upper Gypsum Beds - top of Weser Formation (Middle Keuper)	K2	Tk	maximum
top of Lower Gypsum Beds / base Reed sandstone – top of Grabfeld Formation / base of Stuttgart Formation (Middle Keuper)	K3		maximum
top of limestones Upper Muschelkalk	M1		maximum
top of Middle Muschelkalk (top high velocity layer)	M2’	Tm	maximum
base of Muschelkalk	M3		minimum
top of evaporates of Röt Formation (Upper Bunter Buntsandstein)	S1	Tp2	maximum
base of evaporates of Röt Formation (base of Upper Buntsandstein)	S2		minimum
top of Zechstein salt	X1	Zstr	minimum
top of Main Anhydrite, Leine-Formation (Zechstein)	X2	Z3	maximum
top of Basal Anhydrite, Staßfurt Formation (Zechstein)	Z1	Z2	maximum
top of Werra Salt (Zechstein)	Z2	Na1	minimum
base of Werra salt / top of Lower Werra anhydrite (Zechstein)	Z3’	Z1	maximum
base of Werra-Anhydrite (Zechstein)	Z3	Zsp	minimum
base of Sedimentary Lower Permian (Rotliegend)	H6	P1	

The exact correlation of the reflectors especially in Permian and Triassic at both sides is related to the equivalent lithostratigraphic succession. Differences exist in the Jurassic and the Cretaceous related to local developments (see above). In this strata the seismic correlations have to be carried out carefully and precisely fit to well marker.

In a next step anonymized velocity data (interval velocities from checkshots and VSP, velocity models, time-depth-functions) were compared. Here also a general accordance (in the range of variability seismic velocity data) were determined.

Stratigraphic well marker and depth migrated seismic reflectors are usually the major sources of data for 3D subsurface models. Thus, if well stratigraphy, seismostratigraphy and seismic velocity data are equivalent at both sides, so depth interpretation of these data and construction of 3D-models in depth-domain based on these data would give in principle similar results that depend more on the technical framework (techniques of migration and depth conversion, 3D modelling techniques). These results support the decision to develop separate models at all partner institutions and harmonize these models afterwards instead of building one joint model based on a joint data base (which could not be compiled cause of the legal restrictions). Nonetheless an exchange of shareable data (especially modelled surfaces) were done to provide modelling constrains at the border of data gaps to avoid unconstrained extrapolation that would be very difficult to harmonize.

The harmonization of gravimetrical and petrophysical data (that were used for the verification and optimization of the 3D models) will be discussed in section 3.6.1 and 0.

3.3 Development of subsurface models at the partner institutions

3.3.1 Overview

Parallel to the GeoERA framework national modelling projects were running at all institutions with the goal of the development of subsurface models with different extend, structure and scale, primary only in a national context (Figure 2). The models are (1) at the German side regional models covering the entire territory and (2) at the Polish side regional models related to large geotectonic structures/basins.

These models were used as a starting point for joint harmonized cross-border model with regard to the legal situation described in 3.1.

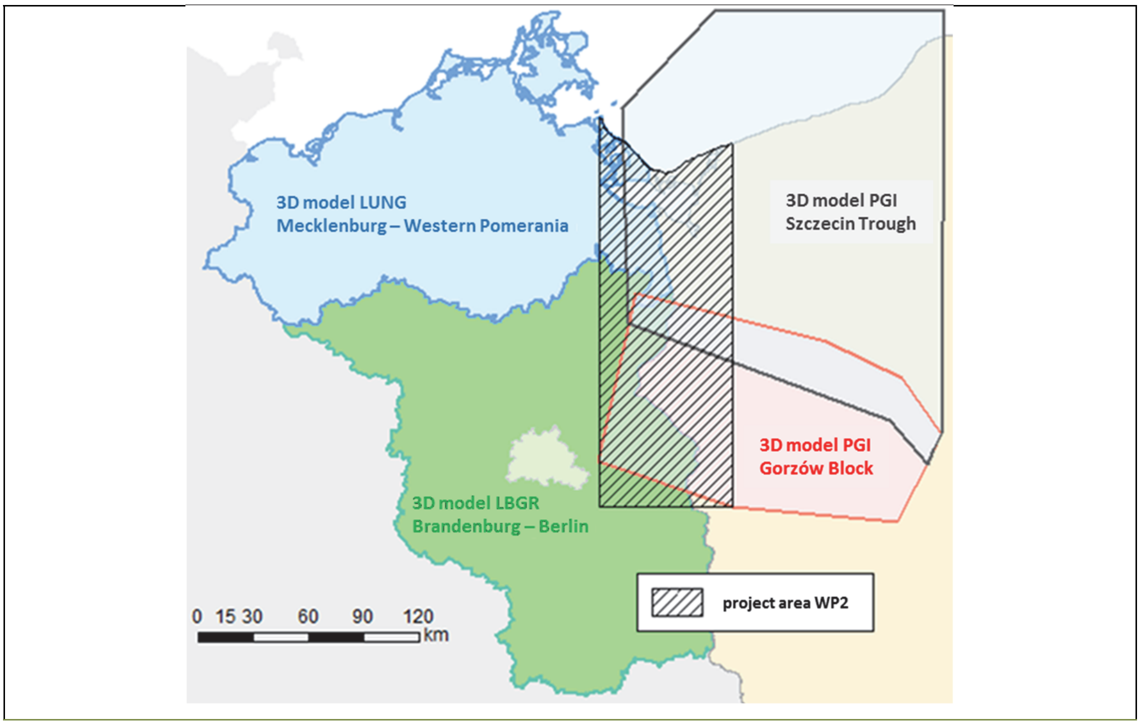

Figure 2: GeoERA-project Geomodeling for Europe (3DGEO-EU): Project area WP2, 3D-model Polish-German border region. National modelling projects in Poland and Northeastern Germany relevant for the harmonization area

3.3.2 Input models – Germany

Subsurface models of the LBGR in Brandenburg (including the area of Berlin) were developed in the following contexts:

- 2013/14: 3D model including 12 major seismic reflectors from base Cenozoic to down base Sedimentary Rotliegend, salt structures and regional fault systems (Schilling et al. 2018, available at http://www.geo.brandenburg.de/Brandenburg_3D). Regional Model without cross-border harmonization mainly based on regional reflector maps.
- 2014-2020: model including 14 stratigraphic boundaries from base of Tertiary down to base of Zechstein, salt structures and the fault network in the context of the TUNB-project (Jahnke et al. 2020). Regional Model with Inner-German harmonization. In Brandenburg based on more than 800 wells, more than 1900 seismic 2D sections, several geological maps and local reflector maps from seismic surveys.

The modelling was done in several tiles which were finally merged to one model with an area of app. 30,400 km². Cause of the harmonized and consistent primary data this merging was usually without problems and only a question of modelling techniques. The neighbouring Federal States Mecklenburg/Western-Pommerania and Saxony-Anhalt used also mainly these harmonized and consistent primary data so also the Inner-German harmonisation were possible. The models were developed with the GOCAD/SKUA software.

The model of Mecklenburg-Western Pomerania, which was finished in 2020/21 as result of the TUNB project (3D model of the North German Basin), covers an area of about 25,000 km². It is based on data from about 700 deep wells and more than 700 2D seismic lines (Obst et al., 2021). Besides interpreted seismic profiles, depth maps of major seismic reflectors were also available. Prominent lithostratigraphic horizons were modelled using SKUA-GOCAD workflows, e.g. "Structure and Stratigraphy". The GOCAD workflow "Structural Modelling" allowed to model the rather complex salt diapirs and fault systems. For the latter, fault sticks and fault polygons were incorporated. Due to the large model area, modelling was done stepwise. 11 tiles were modelled and harmonized afterwards.

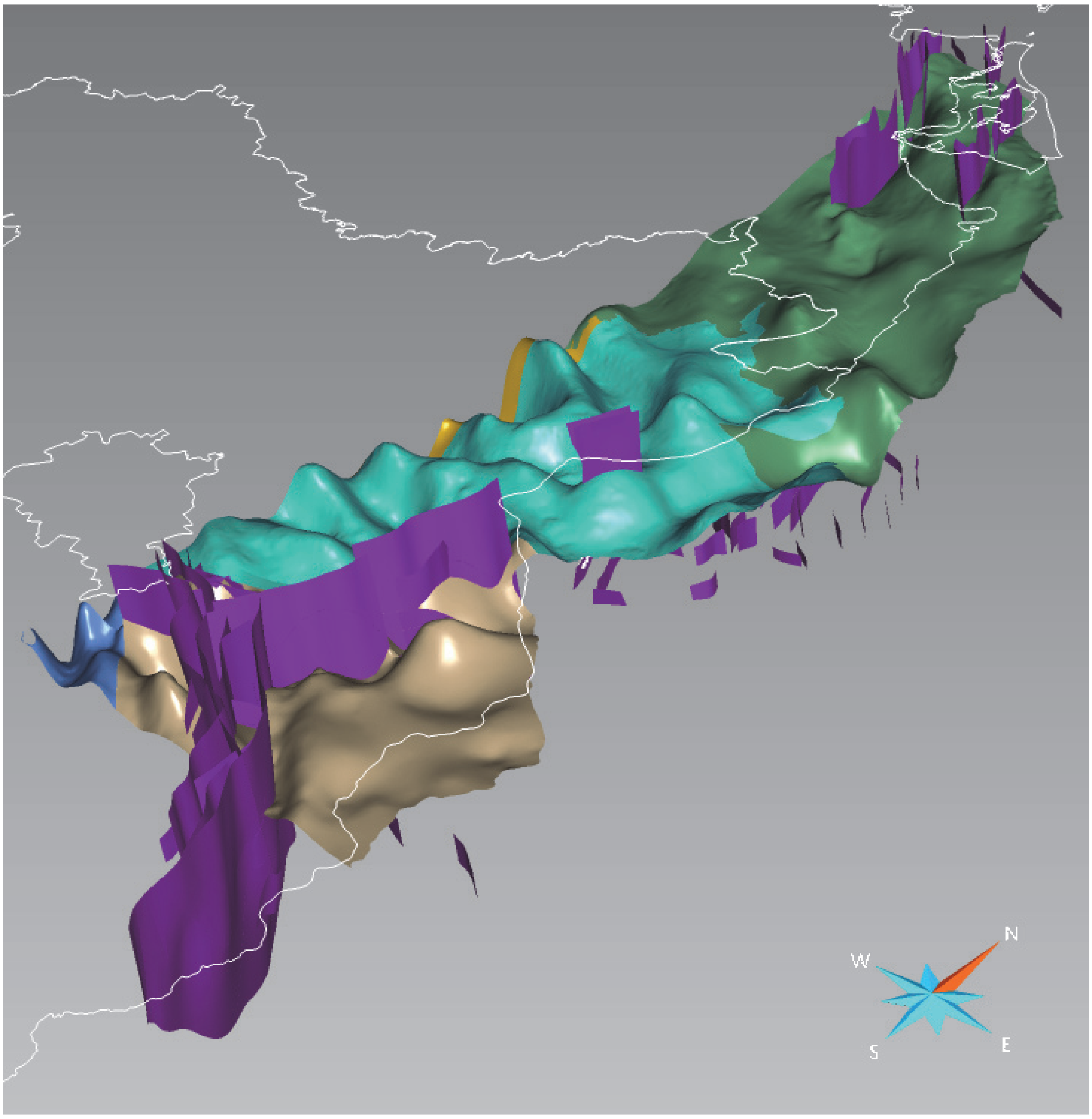

Figure 3: 3D models of Brandenburg (LBGR) and Mecklenburg – Western Pomerania (LUNG) – View of the base of Upper Triassic and the fault network showing the different models and model tiles.

The models of the TUNB-project "Deep subsurface of the North German basin including the North Sea", are available at https://gst.bgr.de/?viewHash=tunb_grenzen.

The TUNB models of the Brandenburg and Mecklenburg - Western Pomerania comprises 13 lithostratigraphic horizons of which 6 base horizons (Zechstein, Buntsandstein, Keuper, Jurassic, Upper Cretaceous and Tertiary) were used for the harmonized Polish-German border region model. The modelling was carried out in depth domain (based on wells, depth migrated seismics, geological and geophysical maps). Primary data in time domain and velocity data were not used. For Eastern Germany a harmonized and consistent large scale velocity models were developed and systematically updated from the 1970s to 1990 which were the base for a consistent depth migration (overview given in Reinhardt 1993).

Three additional horizons (top of Basal Zechstein, base of Muschelkalk base of Quaternary) were modelled on the German side to fit the existing 3D model on the Polish side of the pilot area 1. These additional horizons were chosen cause of their geological and structural importance:

- Top of Basal Zechstein: Top of the oil/gas exploration horizons in the Lower Zechstein. Prominent density contrast to Upper and Lower strata. Important boundary for the gravimetrical modelling.
- Base of Middle Triassic: Base of the high velocity layer in Middle Triassic.
- Base of Quaternary: Base of the Quaternary erosion. Quaternary erosion channels affects the Tertiary and partially also the Upper Mesozoic

3.3.3 Input models – Poland

Modelling of the Gorzów Block followed standard modelling procedures, it was based on a substantial amount of well and seismic data in a digital format. Logs from almost 200 wells, stratigraphic markers from further 100 wells as well as large number of 2D and 3D seismic datasets were compiled. These datasets included interpretations of horizons and faults, and were further interpreted, particularly in the case of the Mesozoic where surveys were focused resource exploration targets and lacked interpretation of other horizons. All of the data was integrated and used for modelling in a single workflow in Petrel. We thus obtained a structural model comprising 13 key horizons in Permo-Mesozoic, 4 horizons in Cenozoic (those were constructed in GOCAD from mainly shallow wells and mapping data) and corresponding parametric grid representing structural architecture of the area and accompanied by numerous reservoir parameters, such as density, porosity, facies associations etc. (Szynkaruk et al., 2019). Although substantial amount of data was available, there is a gap in data in the northwestern part of the Gorzów Block. It is thus important to note that reliable interpretation of surfaces in this part of the Gorzów block could be carried on thanks to interpretations and data provided by LBGR. Without these data, extrapolation of surfaces towards the western edges of the model would produce uncontrolled results.

Parametric 3D geological model for the Szczecin Trough is currently in its early stage of preparation within the national framework that produced model of the Gorzów block. Therefore for the cross-border harmonization of horizons in the Pilot area 2 we had to use already existing data. Results of previous modelling projects (Becker et al. 2017, Piotrowski et al. 2008) were compiled and digital surfaces for the horizons chosen for harmonization were verified using boreholes and more recently reprocessed seismic data. Where discrepancies were found, the horizons were gradually modified. In locations where no other information was available, old analogue seismic profiles from 1960s were scanned and interpretations digitised. This was the case in the border zone located west of the Oder river – between Szczecin and Nowe Warpno. Here, however, seismic profiles could be calibrated using only one deep borehole (Trzebież-1) penetrating all of the horizons modelled, while three other boreholes terminated in the Mesozoic. Immediately to the east and north of this area, i.e. in the northernmost section of the Oder Valley and the Szczecin Lagoon (Stettiner Haff), there are no deep boreholes and no geophysical data of any sort is available. Here, the surfaces had to be extrapolated to fit the data delivered by the Geological Survey of Mecklenburg-Western Pomerania and some surfaces appear not concordant, leaving space for equally possible geometric scenarios. Similarly, locations of fault surfaces in Germany were used to verify published information on tectonic deformations and aid interpretations of faults near the border.

Experience gained when preparing the Gorzów block model helped in data compilation and reinterpretation over the Szczecin Trough area, for example faults were modelled separately for Zechstein base and for the Mesozoic layers, given that faults do not continue across thick and weak Zechstein salts (Fig. 5). The same approach has also been used in Germany (see below).

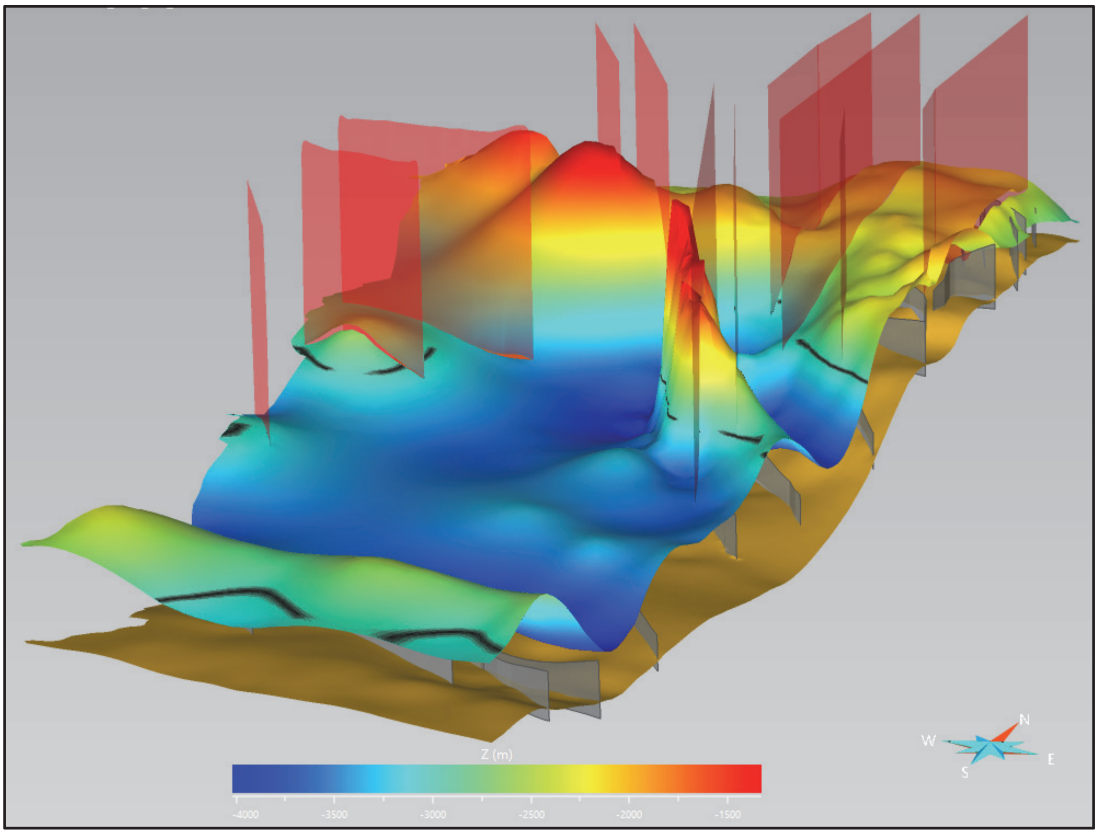

Figure 4: Perspective view showing compiled base of Zechstein (ochre colour) and top salt surfaces in Szczecin area, cut by numerous faults displacing base of Zechstein (transparent grey) and faults displacing Mesozoic sequence (transparent red)

3.4 Joining and harmonizing the models

Four different models – partially developed in other contexts - were used to produce a final, harmonized model of the northern sector of the Polish-German border region (Figure 2, see also deliverable D2.2 for details), each of them following somewhat different construction procedure. The harmonization was carried out in 3 steps:

(1) Pilot area 1 model was constructed in the southern part of the study area comprising eastern part of part of the horizons-and-faults model of Brandenburg, Germany and the 3D grid parametric model of Gorzów block in Poland. The 3D-model of pilot area 1 was finalized and uploaded in January 2020 (deliverable 2.3a).

(2) The model of pilot area 1 was extended to the north over Pilot area 2, which involved harmonizing surfaces and faults from the Mecklenburg- Western Pomerania model in Germany with horizons from a few pre-existing projects in the north on Polish side, which were reinterpreted, extended and reconstructed. The 3D-model of pilot area 2 (deliverable 2.3b) was finalized in July 2021, uploaded in October 2021 (deliverable 2.3b).

(3) Finally all models were joined in one seamless cross-border model that was the base for the further work (development of the joint petrophysical model and the gravimetrical 3D modelling). The final joint model (deliverable 2.3) was finalized in July 2021 and uploaded in October 2021 (deliverable 2.3).

The final joint model of the Polish-German cross border region has the following structure (Table 1):

Table 1: Model horizons (modelled surfaces) and model layers that were selected to constitute the final harmonized model, with major lithologies.

Model horizon	Model layer	Major lithologies
Base of Cenozoic	Cenozoic (Quaternary and Tertiary)	Clastics and marls, unconsolidated
Base of Upper Cretaceous	Upper Cretaceous	Limestones and minor marls
Base of Jurassic	Jurassic	Siliciclastics and marls/limestones in the Upper Jurassic
Base of Upper Triassic	Upper Triassic	Siliciclastics and marls
Base of Middle Triassic	Middle Triassic	Limestones
Base of Lower Triassic	Lower Triassic	Siliciclastics
Top of Basal Zechstein	Zechstein Salt	Salt with interlayers of anhydrite and clay
Base of Basal Zechstein	Basal Zechstein	Anyhdrites and dolostones with interlayers of clay and salt

Different approaches to produce consistent results from such disparate data were tested and were of key importance in this task. First the horizons which would constitute our harmonized model were agreed on what required to find a balance between existing models and the need to adequately depict major structural variations. As a consequence we e.g. added an intra-Zechstein horizon Top of Basal Zechstein (see Table 1), which was not initially present in Brandenburg model, as we had to differentiate between anhydrite-rich (dense) and salt-rich (low density and weak) layers in accordance with the development of the petrophysical model and the gravimetrical modelling.

In the near-borders zones the horizon geometries were preliminarily adjusted to interpretations from the side of the border which was better constrained with seismic and borehole data. For example, edges of the horizon surfaces from the Polish side near Szczecin, i.e. on the western side of the Oder river where the gap in digital data existed, were adjusted to the surfaces from the model of Mecklenburg-Western Pomerania delivered by LUNG.

Afterwards, the modelled horizon geometries were shared and horizons remodelled adjusting them near the border to the interpretation from the side where more data was available. This proved indispensable, given that unconstrained (thus in fact extrapolated) model edges always produce artefacts that would be very difficult to control in the final harmonization steps. Even if we model the same horizons in the same tectonic setting (Permian basin in this case), input models' edges cannot be allowed to "float" independently if we are to obtain consistent results.

Finally all pre-adjusted models (horizon surfaces and fault planes) were joined with GOCAD/SKUA software in the SKUA-workflow "Structure and Stratigraphy" to one harmonized and seamless model.

The workflow was carried out in two separate model runs:

- Mesozoic and Cenozoic succession (base of Triassic to base of Quaternary)
- Top and Base of Basal Zechstein

The reason for the two model runs was that the strong geometrical changes from the Basal Zechstein to the base of Triassic due to the halokinesis often produce difficulties in "Structure and Stratigraphy" workflow. The time- and resource-consuming step of modelling salt structures over the entire area had to be skipped because of the model dimension. The complex structures of the Goleniów salt diapir and the surrounding were not modelled in the workflow. The diapir was modelled separately by PGI and mounted into the final surfaces. The fault network was used in both model runs (Mesozoic-Cenozoic and Basal Zechstein).

The modelled horizons and faults were exported and are provided as GOCAD-ts-files. According to the national spatial reference systems the modelling was carried out in the system ETRS 1989, UTM Zone 33N (EPSG 25833). According to the requirements of the GeoERA framework the modelled horizons are provided in the system ETRS 1989, Lambert Conformal Conic (EPSG 3034).

The modelled surfaces and the fault network were are shown in Figure 5 (horizons) and Figure 6 (fault network).

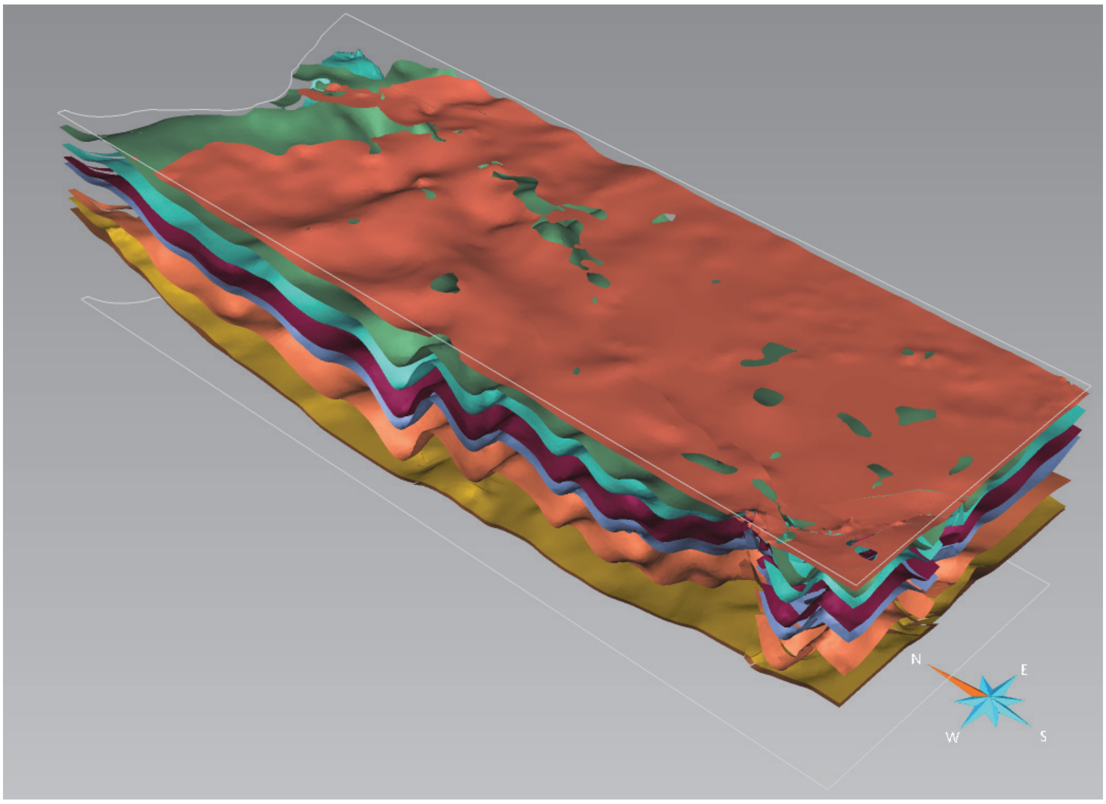

Figure 5: Horizons of the harmonized 3D-model (base Cenozoic to base of Zechstein, faults not shown). View from southwest. Vertical exaggeration 1:10

Various fault planes are included in the model (Figure 6). Those of them that cross entire modelled stratigraphic column are few and are most notable in the south-west of the model, in Germany. These faults belong to the Guben-Fürstenwalde and Buckow fault zones, the largest ones in the study area and related to the Middle Oder zone reactivated in several tectonic phases. Most other faults are conspicuously divided into two groups:

- faults displacing the basal Zechstein and
- faults displacing the Mesozoic and the Cainozoic sequences.

Faults belonging to these two groups become untraceable in thick upper Zechstein salt layer between the basal Zechstein and the Mesozoic and display differing trends and sometimes opposite dips and throws. This is due to halokinesis and decoupling of deformation across Zechstein salts.

Faults displacing the basal Zechstein sequence are numerous, but have relatively minor throws except in the NE part of the model, where this sequence is uplifted. They mostly strike NW-SE to NNW-SSE, occasionally in other directions. Faults cutting predominantly the Mesozoic sequence are the NW- to NNW-oriented faults of the West Pomeranian Fault System, with border graben structures in the northern part of the model.

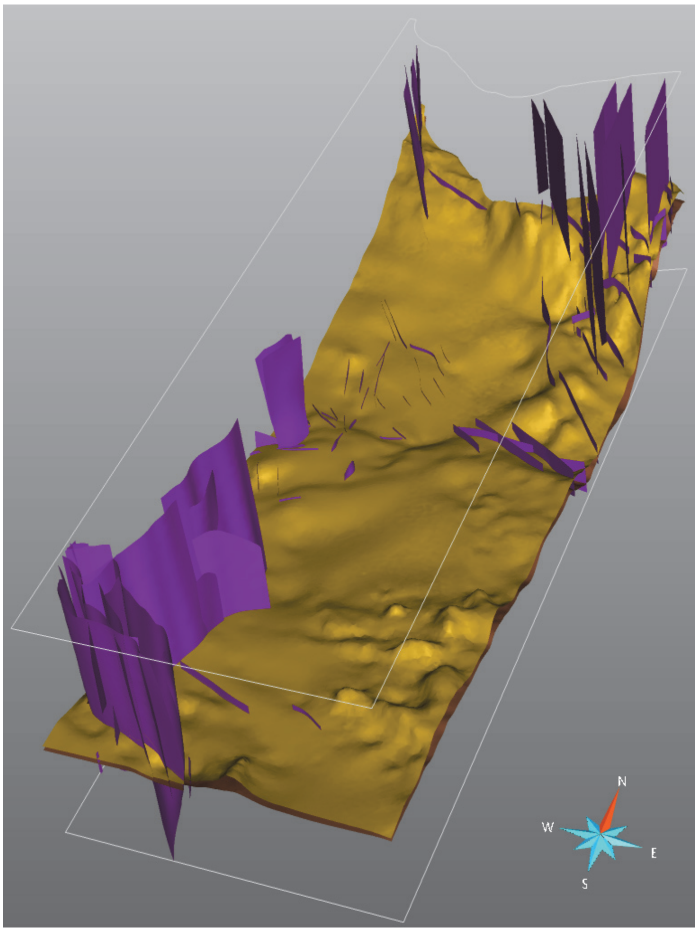

Figure 6: Fault network (violet planes) in the model area and the surfaces Top and Base of Basal Zechstein (ochre and brown). View from southeast. Vertical exaggeration 1:10

3.5 Uncertainties of the model

Figure 7 shows the current state of exploration on-shore (seismics and wells that reach Pre-Cenozoic strata - for more detailed information to the exploration state see deliverable 2.1 of the project 3DGEO-EU, Jahnke et al. 2019). On the right side of Figure 7 the distance to the closest seismic line is mapped to visualize the exploration gaps. Off-shore seismics was not included.

As outlined in chapter 3.1 the modelling in the border zone has been hampered by lack of data which stems from restricted access in the cross-border region. Seismic information, which is the major source for subsurface data is significantly reduced here:

- no cross-border profiles and surveys exist at the time,
- seismic profiles usually end at a distance of at least 100 meters from the border at both sides
- seismic coverage and information is reduced at the end of profiles (range of some 100m to km, depending on the technical configuration).

Thus a stripe of 1-2 km at both sides of the border has no or reduced seismic information even in areas where there are seismic profiles close to the border.

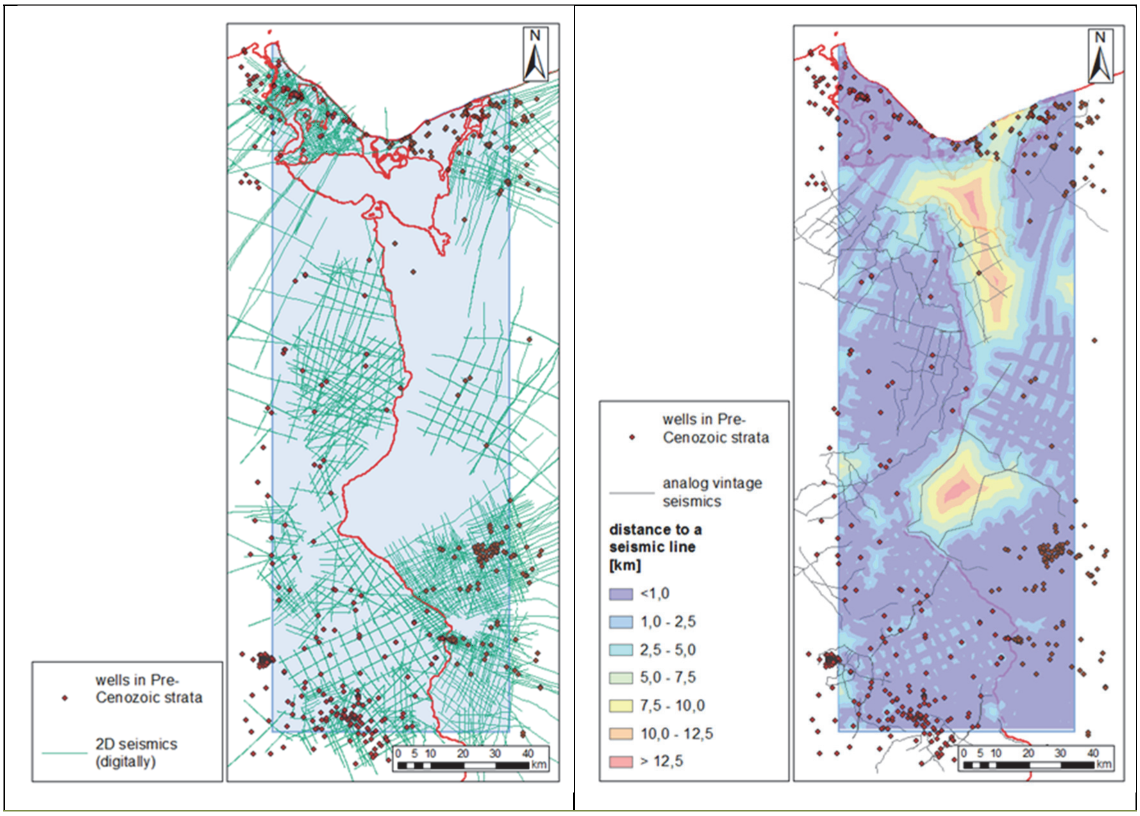

Figure 7: Left: digital 2D seismics and wells reaching the Pre-Cenozoic in the model area. Right: distance to the closest seismic digital 2D line (colored areas) and analog vintage 2D seismics.

In addition to the problems in the near-border zone two large exploration gaps with areas > 400 km² exist along the border region at the Polish side. Only in the south of the investigation area a more ore less closed and very dense data coverage exist (pilot area 1: models of LBGR and Gorzów Block).

The distance to seismic lines as well as to boreholes can be used as a simple proxy for the uncertainty of a geological 3D model that was developed based on these data. The uncertainty of the model increases with an increasing distance from wells and seismic lines depending on the local geology – in areas with a simple uniform layering less - in highly structured and disturbed areas more. When plotting the data coverage with wells and seismics over the depth map of the base of Triassic (Figure 8) it becomes obvious, that (following the geometries of the developed model) the northern gap is situated in a region with intense halokinesis (depth of base of Triassic ranging from -1000 m b.s.l. in the Szczecin lagoon down to -3750m b.s.l. in the south of this gap) but in contrast the southern gap show less salt dynamics (depth of base of Triassic ranging from -2500 to -3000 m b.s.l.). So it has to be assumed that the developed model shows especially in the Northern gap large uncertainties.

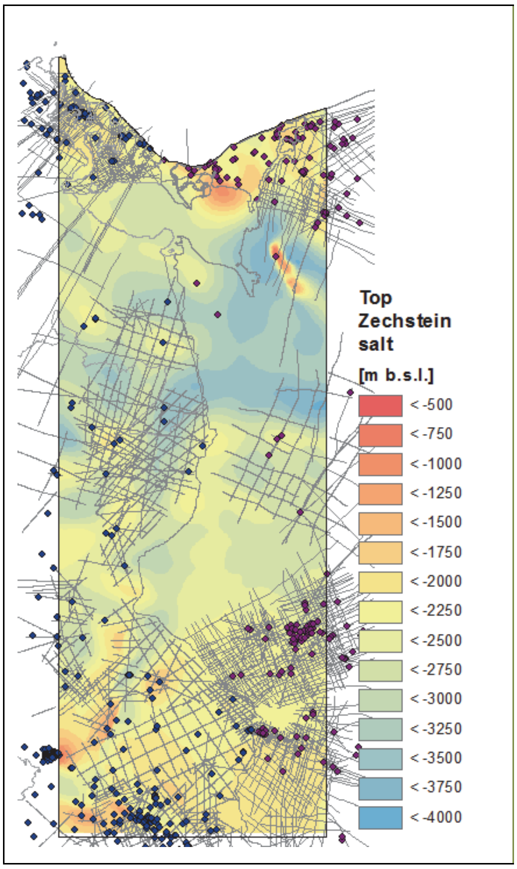

Figure 8: wells and digital seismic 2D sections in relation to the depth of Triassic (= Top Zechstein salt)

To close the exploration gaps vintage 2D seismic sections from the 60s and beginning of the 70s were researched and compiled (Figure 7, right). It was found that the northern gap is partially covered by analog vintage seismics from the 1960s, which was incorporated as an additional (but relatively uncertain) information. The exploration gap in the center of the model is nearly free of seismic investigations and drillings.

3.6 Gravimetric modelling and model verification

As an additional approach in cooperation with WP6 IGME-CSIC gravimetrical modelling was used to verify the developed model geometries. This requires beside the geometries of the subsurface model the gravimetrical signals (Bouguer anomaly) and a model of the rock densities, which have to be developed in additional workflows.

3.6.1 Harmonized Bouguer grid

For the project area and an extended surrounding a map of the Bouguer anomaly were developed based on a harmonization of the primary gravimetrical data. These include in a first step an extension of the gravimetrical database at the German side (digitizing of app. 30000 vintage stations from the 1960s to 80s). All data were reprocessed to modern standards (for details see D2.2 of WP2, Jahnke et al. 2021a and D6.3 of WP6, Ayala et al. 2021). The data distribution (stations locations and station density [km²/station]) is shown in Figure 9.

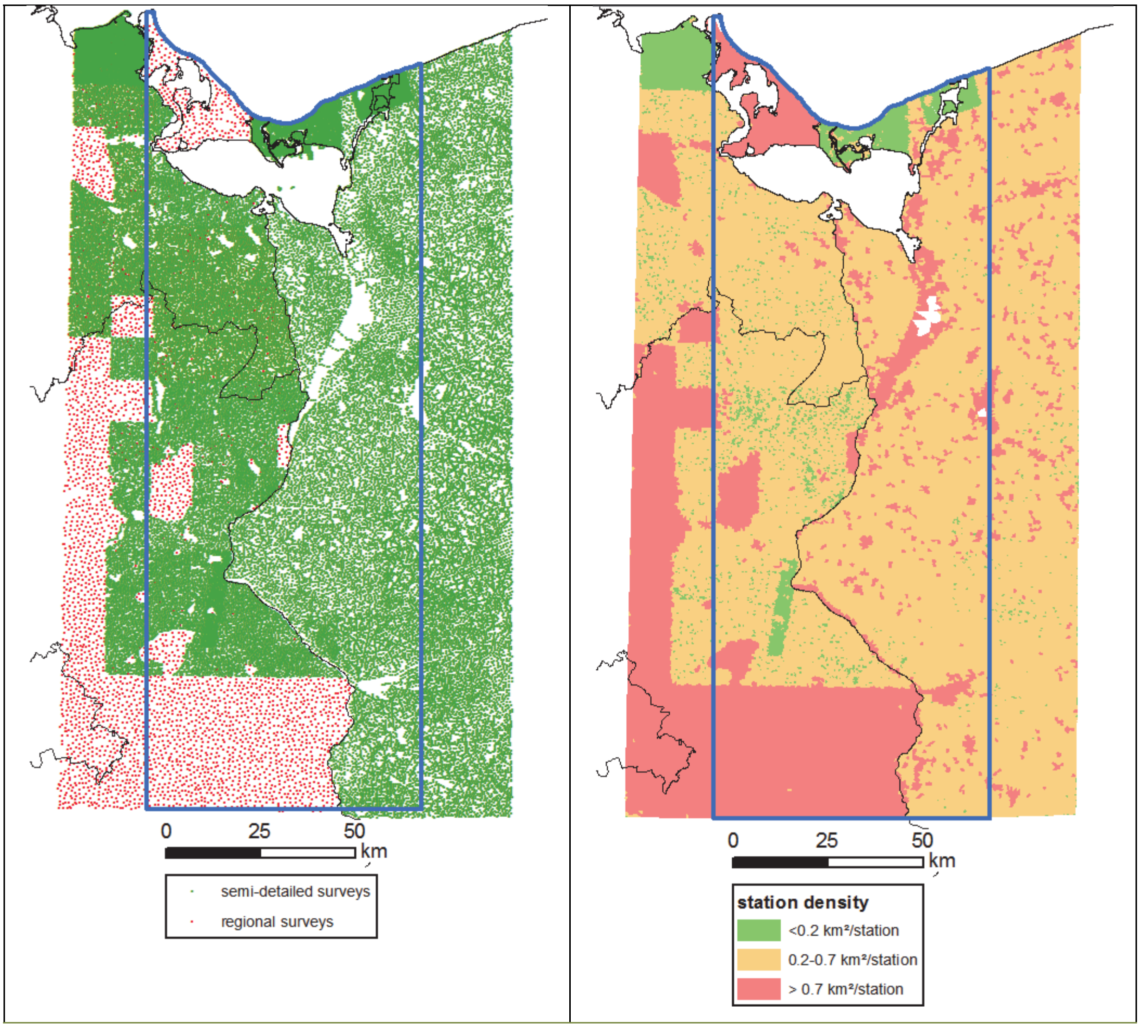

Figure 9: distribution (left) and density (right) of the used gravimetrical stations in the project area. Semi-detailed surveys (left: green dots, right: station density <0,2 km²/station up to 0,7 km²/station) and regional surveys (left: red dots, right: 0,7-2 km²/station).

The coverage with gravimetrical stations is quite dense also in the areas with data gaps in seismics and well bore exploration. Off-shore data are in principle available (Szczecin lagoon, Baltic Sea) but partially still analog (German side) and not used in this case study.

The compiled Bouguer map is shown in Figure 10. The final joining was done in a workflow combining primary and interpolated (gridded) data (for more details see D2.2 of WP2, Jahnke et al. 2021a and D6.3 of WP6, Ayala et al. 2021). The gravimetrical data are well defined in measuring and processing and therefore could be harmonized and connected cross-border without any problems. The map is more comprehensive and detailed comparing to former works, e.g. analog isoline maps based on semi-detailed data (Jamrozik et al. 1978, 1984, 1987) and digital map based on regional data (Skiba et al. 2010) and the constructed grid has relatively high-resolution to adequately depict structures.

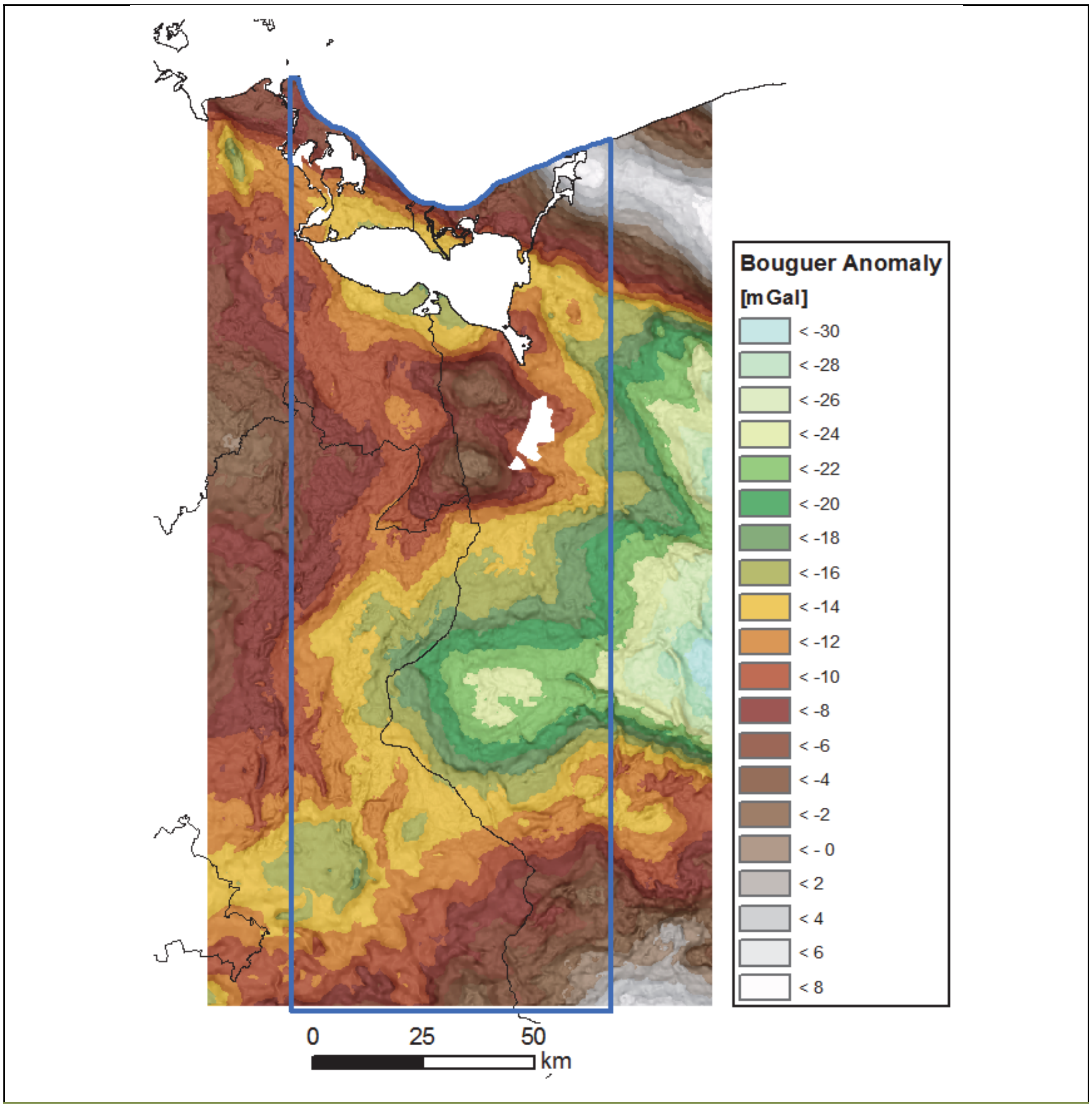

Figure 10: Final harmonized cross-border map of Bouguer anomaly.

3.6.2 Joint density model

The results of the joint cross-border density model (density averages for each model layer defined in Table 1) are shown in Figure 11 (spatial distribution) and Figure 12 (histograms).

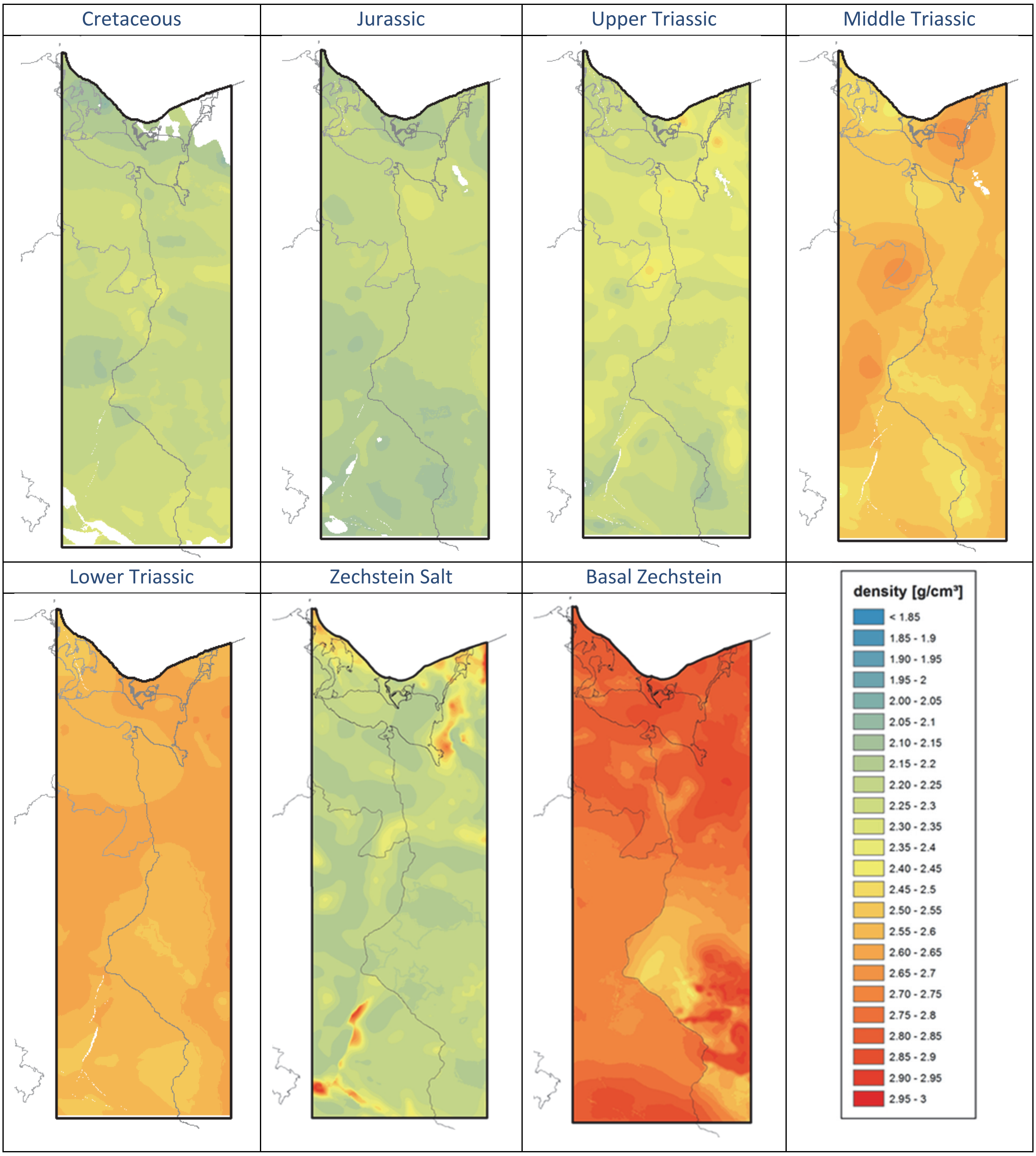

Figure 11: Final density model: spatial distribution of rock densities for the layers Cretaceous to Basal Zechstein

The harmonized data show characteristic density ranges for the litho-stratigraphic model layers, with a general increase of the density from the Cenozoic to the Triassic, a typical decrease for the light salt of the Zechstein and a further increase at the anhydrites and dolostones of the Basal Zechstein.

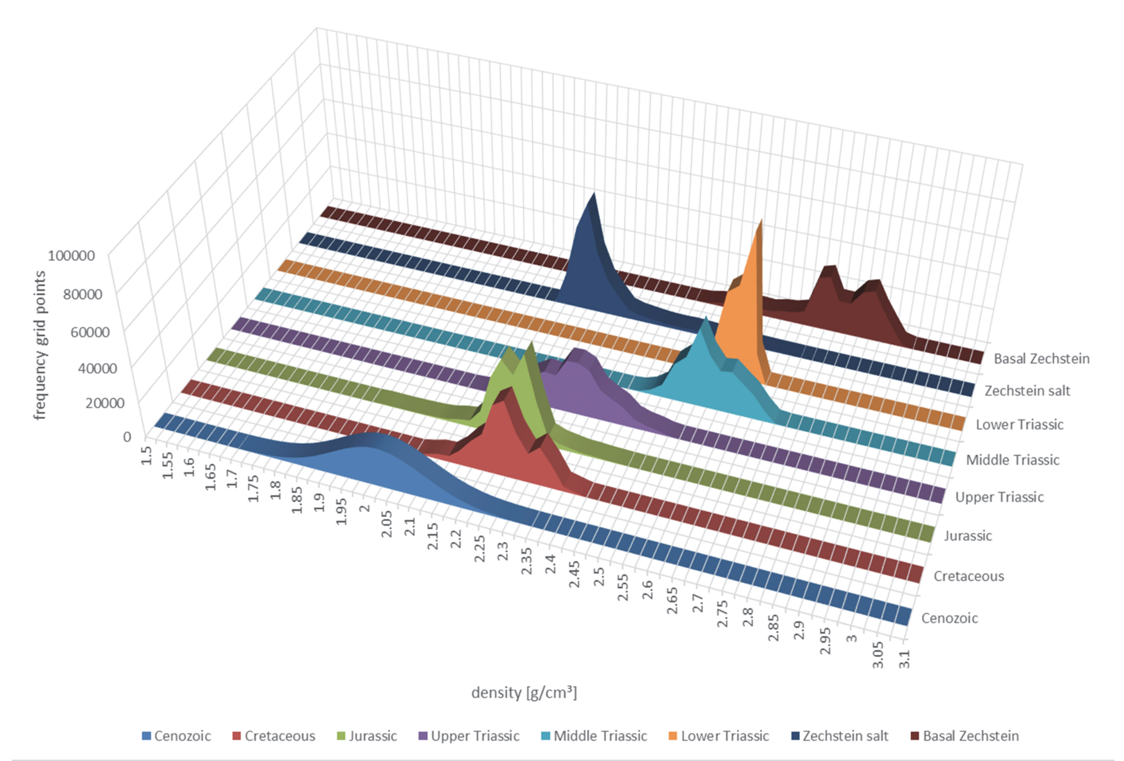

Figure 12: Histograms of the interpolated densities for the model layers

Despite the successful development of a harmonized and seamless cross-border model of the entire project area, the harmonization of the density data is considered problematic. The data show strong deviations at both sides (absolute values, density-depth trends, interpolated density grid files). The major problem was that two different kind of data exist that could not be directly compared:

- modern log data in high depth resolution from the 1990s and younger and averages based on these (Polish side, Gorzów Block model)
- vintage core data from the 1960s to the 1980s and averages based on these (German side and northern part of Polish side)

At one hand no logs are available for the wells with vintage core data. At the other hand especially for the logged Polish wells core data were mostly taken only in horizons of special interest (Lower Zechstein, Upper Rotliegend) and not for the whole succession. Therefore both kind of data cannot be directly compared. To overcome the problems it was decided to correct the core based data (stratigraphic averages and empirical density depth trends) and to fit them to the density-depth trends that were obtained for the gamma-gamma-data of the Gorzów Block, because the wire-line data were regarded to be more reliable (for more details see D2.2 of WP2, Jahnke et al. 2021a and D6.3 of WP6, Ayala et al. 2021). The final density model is in the litho-stratigraphic averages, their variations and trends reliable, but in the spatial resolution and certainty much less robust. Thus, the petrophysical information are - besides the uncertain model geometries in exploration gaps - the most critical parameters in 3D modelling in the Polish-German border region.

3.6.3 *3D gravimetric modeling – results and new insights*

Gravimetric modeling was meant to compare the model geometries and ranges of layers' densities to gravimetric signal, thus reducing uncertainty and permitting to review model geometries, constricting the range of available solutions and defining problematic areas. Additionally, gravimetric modelling permitted to identify potential basement discontinuities underneath modelled surfaces.

The gravimetrical modelling includes forward modelling (calculation of the gravimetrical signal of a given geometry and it's density distribution) and the inversion of model layers (varying geometry and density of a given layer to minimize the misfit to the measured gravimetrical signal). The input data for the gravimetrical approach were the joint model geometries (chapter 3.4), the joint density model (chapter 0) and the Bouguer map (3.6.1). All data were provided as grid-files with an identical extend and resolution to the project partner IGME/CSIC. The gravimetrical modelling was carried out at IGME with the software OASIS Montaj. The most important findings are summarized below, for full discussion please see deliverable no. D6.3 of the 3DGEO-EU project (Ayala et al. 2021).

3.6.3.1 Short-wavelength anomalies as indicators of either unpicked density variations or under- or overestimated lateral salt flow or interpretation uncertainty in data-poor regions.

The power spectra analyses of the Bouguer signal indicates that the depth of the causative bodies is located up to c. 20 km depth. This depth suggests that the Bouguer anomaly in this area does not have the contribution of the lower crust-mantle boundary (the Moho). First forward modelling and inversion runs of the Paleozoic and Proterozoic layer (with estimated averaged depth of 6km and 20km) show characteristic misfits and anomalies (Figure 13) with short wavelength especially in the Northeast (in the regions less constraint by seismics and wells - northern data gap, compare Figure 7 and Figure 8). In the southern data gap (compare Figure 7 and Figure 8) the misfits are low. Here the modelled geometries and densities fit the gravimetric signal. The extrapolation of the horizon geometries lead to correct results because the region shows a relatively flat layering without intense halokinesis. The misfits in the northern data gap can be correlated with halokinetic structures (diapirs, salt pillows and marginal sinks) that could at the time not correctly described in geometry and/or in density with the available data base. Because of the ambiguity of the gravimetrical signal these anomalies can't be attributed to an explicit horizon. It only gives an information that there is overestimation (positive misfits) or an underestimation (negative misfits) of mass in the model – what can be related to the density but also to the geometry of the layers.

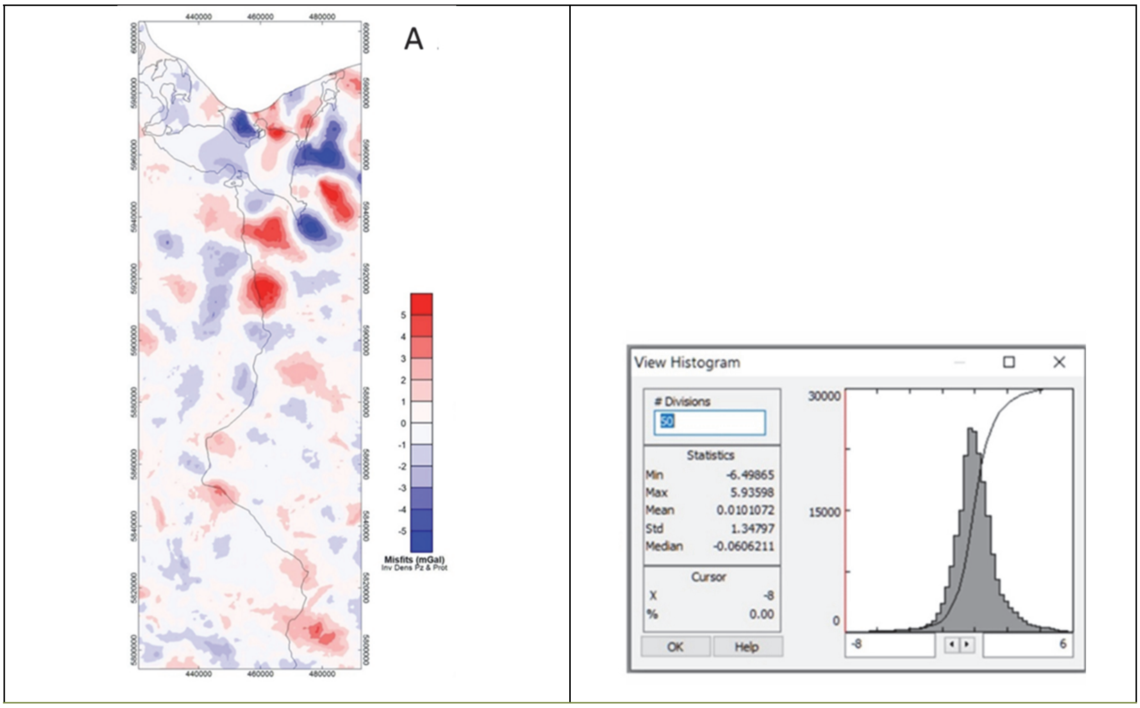

Figure 13: A) Misfits (difference between observed and calculated anomaly, in mGal) from the inversion of Paleozoic and Proterozoic densities. B) Histogram of the misfits

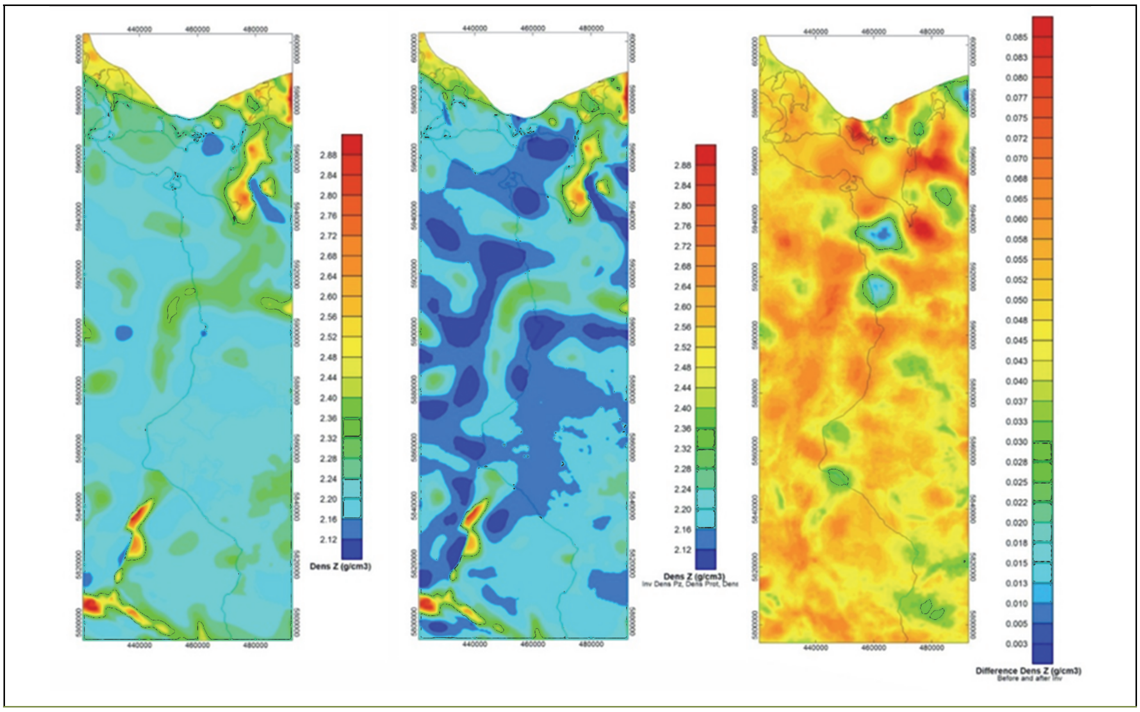

Figure 14: Left: Initial Zechstein salt layer density. Middle: Zechstein salt layer density after four steps inversion (1 - Density Paleozoic, 2 - Density Proterozoic, 3 – Density Zechstein salt, 4 - Geometry Top Basal Zechstein). Right: Differences between initial and inverted Zechstein salt layer density.

The results of a further inversion (Paleozoic, Proterozoic, Zechstein salt) give some hints for the optimization of the model. Figure 14 shows the results of an inversion of the Zechstein density that lead to a considerable decrease of the misfits. The changes of density from initial to modelled state are low (reduction in arrange of 0-0.1 g/cm³ with an average of 0,05 g/cm³) what is in the range of the uncertainty of the petrophysical data. This decrease of density is especially related to salt accumulation structures (salt pillows and diapirs). Regarding that the Zechstein salt layer has the greatest variation in thickness (<500 m up to 4000 m in the Goleniów diaper) and density (densitiy range from ≈ 2.2 g/cm³ for pure salt up to >2.7 g/cm³ for residuals in salt depletion areas), the influence of the Zechstein salt on the gravimetrical signal is very high especially in regions with intense halokinesis.

The verification and optimization procedure of the gravimetrical modelling could not be finalized to a completely verified and optimized model in the frame of this case study, but the approach at this state can at least define reliable regions of the model, where the geometrical and petrophysical models fit the gravimetrical signal (more than 80% of the project area, see Figure 13) – and regions where the models are less reliable at the time (what is related to complex structures and low data coverage). These findings will support further activities and work to inprove the existing model in the area both on national level and as well as in further cooperation.

3.6.3.2 Long-wavelength anomalies and/or density variations: hints about basement structure

Gravimetric modeling also allowed to draw conclusions about the structure of the basement below the deepest surface of our model, the base of Zechstein. Very few wells reach beyond this depth, because most of them were focused on oil and gas exploration targets in the Zechstein and the Rotliegend. Also, seismic imaging is extremely noisy at those depths due to seismic signal attenuation in thick Zechstein salt layers.

We therefore hoped for gravimetric modelling to provide insights about basement structure – what it did. Figure 15 shows the modelled density variation in the Paleozoic and Proterozoic. In the regions with a larger misfit of the model (compare Figure 14) these densities are not reliable. In the other (reliable) areas the density model shows characteristic directions that can be related to known fault directions (striking NW-SE and NE-SW) and can probably be attributed to crustal structures with different densities (even the absolute values might also be influenced by the – still not optimal - density distribution in the upper strata).

A further - in depth - interpretation in the context of the Variscan and Caledonian geology is out of the scope and the timeframe of this case study, which is focused in optimizing 3D reconstruction workflows based on gravimetric, structural and petrophysical data. But the results will encourage again further work in the area both on national level and as well as in further international collaboration and joint publications.

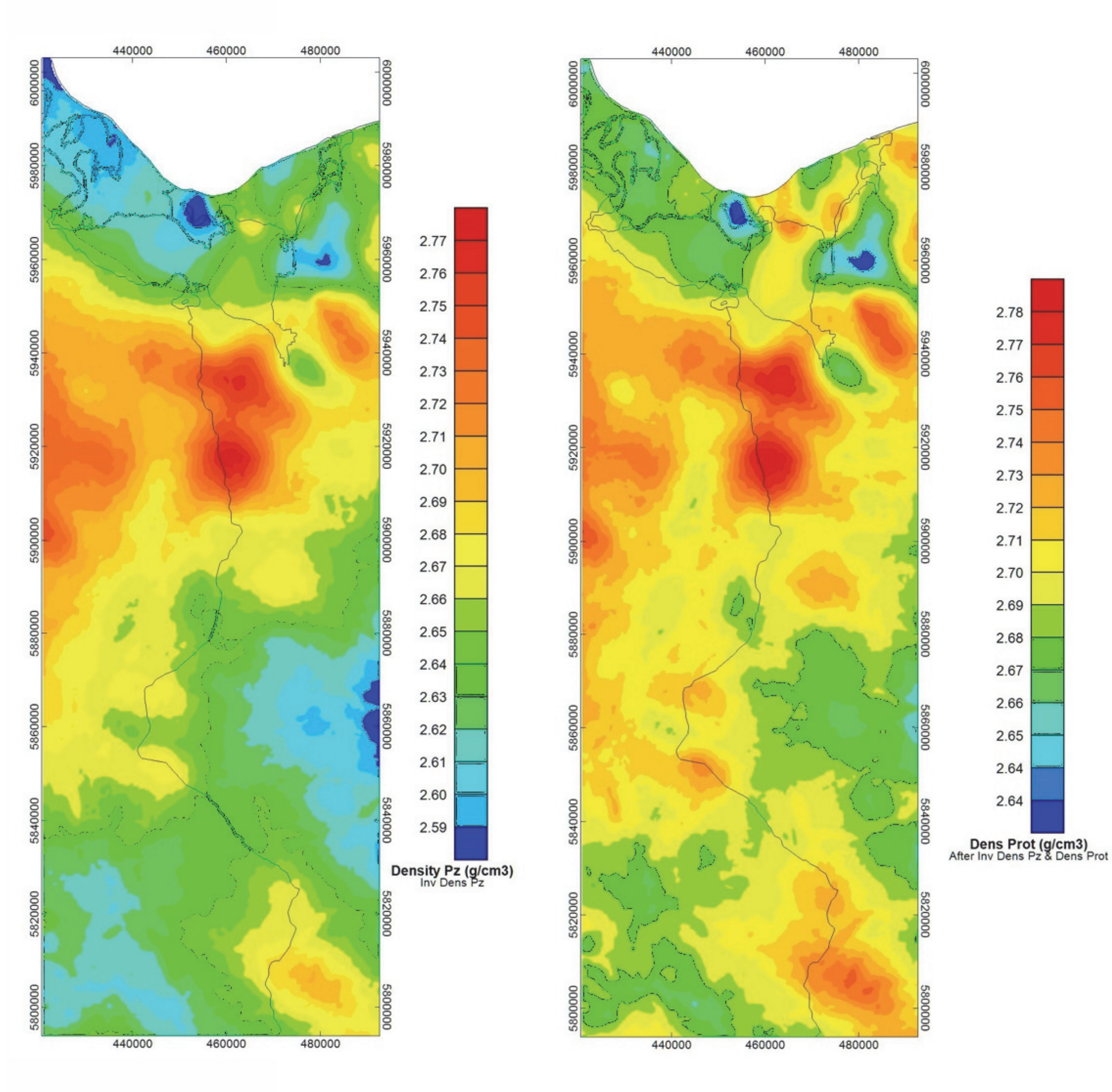

Figure 15: Calculated density variations in Paleozoic (left) and Proterozoic (right) crust after two-steps inversion. Note that most pronounced short-wavelength density variations in the northern region correspond to data gaps (compare Figure 7 and Figure 13 A) and are most probably due to misfits of densities and/or geometries in upper Permian and Mesozoic layers.

4 LESSONS LEARNED

The experience gained throughout the project permits to formulate the following conclusions and recommend further actions needed to provide efficient Geological Service for Europe. Such service would allow access to consistent and manageable data which could support decision making at the pan-European level:

4.1 Communication and discussion across border

Successful modelling in cross-border regions mainly depends on coordinated work with contineous exchange of findings, ideas and cross-validation. Making harmonized models from completely independent inputs is, in our opinion, unrealistic and unattainable. For example, although raw data could not be exchanged across border in this project, at least a comparison and discussion of anonymized data was possible (Fig. 11, anonymized seismic 2D sections in time domain with reflector interpretation at both sides of the border) and was crucial to make sure that the same geologic facts and features are described and that identical or at least comparable definitions exist. Comparable processing of data was equally indispensable and could only be achieved through consultations, and often trial-and-error exercises that can only be conducted by direct engagement of interested parties.

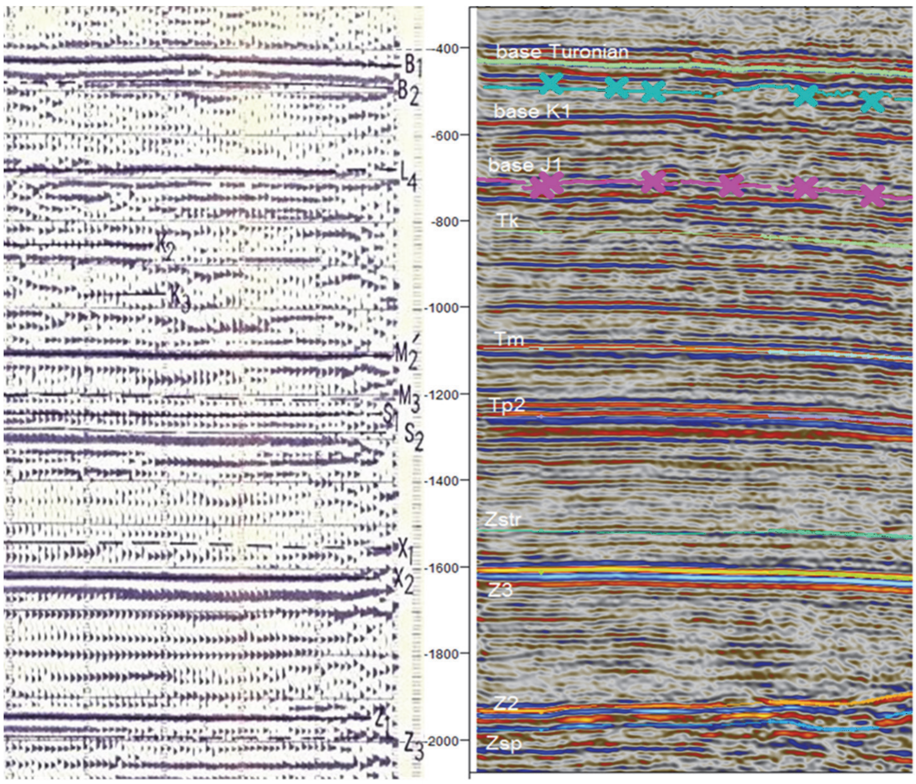

Figure 16: Comparison of anonymized seismic profiles to harmonize interpretations of horizons.

Recommendation: strengthening links, cooperation and discussion between the European Geological Surveys is a need, as well as adopting common experience, know how, methods and workflows.

4.2 Strengthen the exchange of primary and interpreted data

To apply modern workflows in cooperation projects, all relevant data must be shared or at least data must be compared and interpretations have to be shared, to enable any reliable harmonization. No seamless and consistent model can be made when individual model edges are allowed to remain unconstrained. Also interpreted and interpolated data (e.g. geological models) are useful and helpful in addition (or at least instead) of primary data. An example is an attempt to join the model of the Gorzów block with the Brandenburg model before reassessing the horizon surfaces in the Gorzów block with data supplied by LBGR as is shown in Figure 17.

Most of the work in WP2 was done on the base of an exchange of interpreted data. This was possible because the interpreted data were intensively discussed and the data handling and data processing was harmonized (see 4.1).

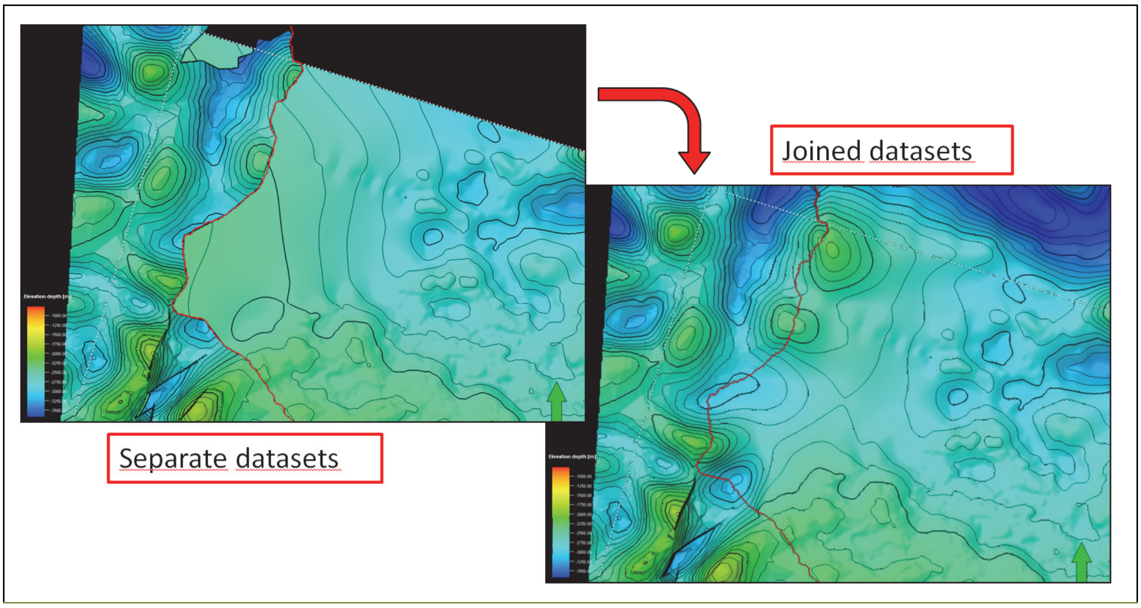

Figure 17: Joint Gorzów block and Brandenburg models. Left: surface base of Triassic / top of Zechstein salt (see Table 1), extrapolated in data-poor region on Polish side, before cross-border interpretation was taken into account. Right: the same surface remodeled with interpretations provided by LBGR.

Recommendation: Efficient Geological Service for Europe will need employment of open data standards across European national states (selected primary data, geological models, maps and interpretations, metadata).

4.3 Closing of data gaps

Lack of data in border regions can substantially multiply the uncertainty of interpretations, thus also model uncertainty, and produce modelling artefacts. A number of interpretations is often possible in such areas. But such data gaps are a common reality (see chapter 0).

Figure 18: common reality – a data/information gap

Recommendation: Collection of at least a few new high-quality cross-border investigations (joint geophysical/geological studies e.g. cross-border seismic profiles or joint drilling campaigns) would be essential to efficiently harmonize geological/geophysical interpretations in neighbouring countries, e.g. in the Polish-German border region – and probably elsewhere in Europe. Projects at a European level would be necessary in order to obtain such data.

4.4 Using of alternative methods

Potential field geophysical methods (gravimetrics in our case) is one example for a powerful (but less used) tool for verifying and improving overall model quality, reducing or locating most prominent uncertainties and gaining insights in inaccessible areas (such as due to poor seismic coverage or poor seismic signal). In our study area this method permitted to define areas that need to be revisited as well as revealed structures below the model base that help our understanding of geodynamics of the area (Figure 19).

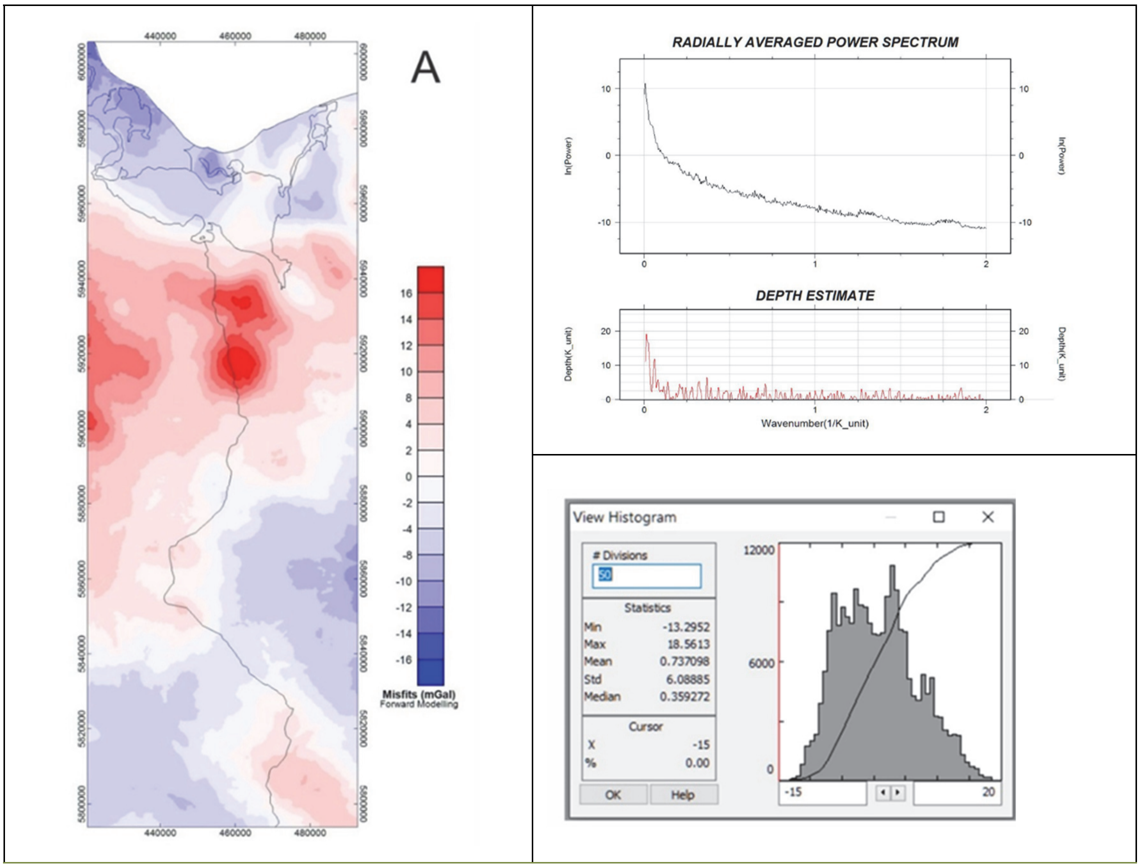

Figure 19: Left: Misfits from the Forward Modelling [mGal] (difference between observed and calculated anomaly). Right (above): Radially averaged power spectrum of the misfits from the forward modelling. Right (below): Histograms of the misfits after forward modelling [mGal]

Recommendation: applying potential field methods (gravimetric and/or magnetic susceptibility modelling) should become standard practice wherever such data are available especially in underexplored areas that tend to be present near-border. Facilitating gravimetric/magnetic data exchange in border areas and defining common data processing rules are the key to achieve that.

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