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1 INTRODUCTION

1.1 Background and ambition

In Germany and Poland various efforts have been made to develop 3-dimensional geological models in the last years. In Germany a model of the North German Basin was created for 13 selected stratigraphic horizons from the base of Zechstein to the base of Rupelian in the framework of the project "Subsurface potentials for storage and economic use in the North German Basin" (TUNB, duration 2014-2021, https://gst.bgr.de/shortlink/tunb). This project based on a cooperation of the Geological Surveys of the north German Federal States and the Federal Institute for Geosciences and Natural Resources (BGR). The Polish Geological Institute (PGI-NRI) is developing models for two structure regions in Poland at the time (Gorzów Block completed during the GeoERA lifetime) and the Szczecin Trough (ongoing) for similar strata.

The goal of the WP2 in the GeoERA project "3D Geomodeling for Europe (3DGEO-EU)" was to harmonize the data inventory and its interpretation and to develop a transnational 3D geological model for selected horizons and structures in the Polish-German cross-border region.

For this purpose a project area was defined to include the border regions of the different national projects (project area 3DGEO-EU WP2, see Figure 1). This area has an extension on ≈210 km in N-S direction and ≈70 km in E-W direction and covers an area of about 14000 km².

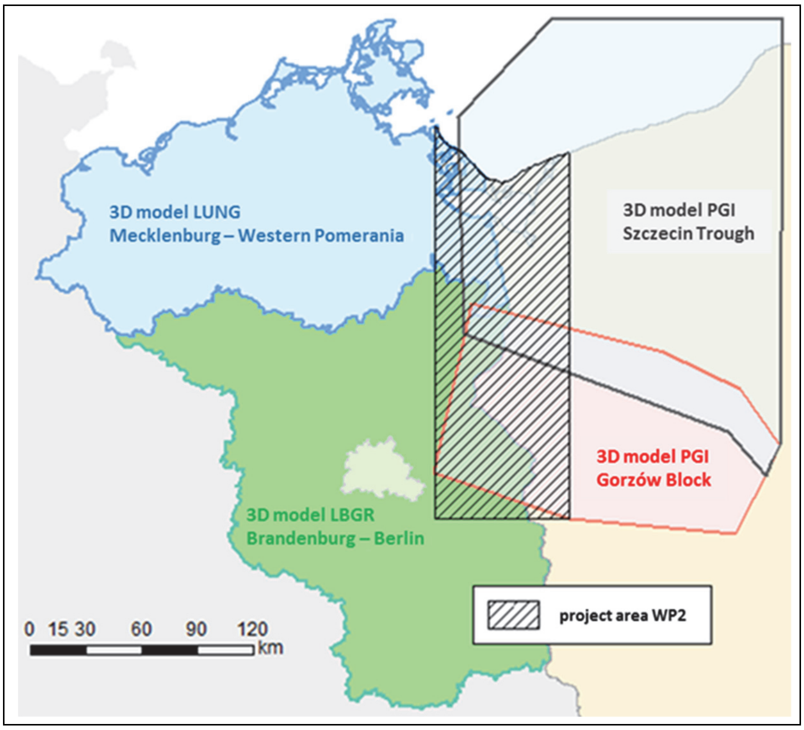


Figure 1: GeoERA-project Geomodeling for Europe (3DGEO-EU): Project area WP2, 3D-model of the Polish-German border region

2 HARMONIZATION METHODS, WORKFLOWS AND RESULTS

2.1 Cross-border stratigraphic/seismostratigraphic correlation

2.1.1 Stratigraphic correlation

The cross-border stratigraphy in the Central European Basin System (including the North German Basin and the Polish Trough) was correlated at the Pan-European scale in former projects (e.g. compilation in the frame of the SPBA (Doornenbal & Stevenson (eds.) 2010). The following stratigraphic correlation charts (Figure 2 to Figure 5) show the situation in Germany and Poland from the Upper Permian (Zechstein) to the Cretaceous.

The lithostratigraphic succession during the major subsidence phases of the Central European Basin System (Upper Permian to Upper Triassic) is very similar in the northeast Germany and northwest Poland. The lithostratigraphic units can be directly correlated and compared. The Zechstein succession (Upper Permian, chronostratigraphic series: Lopingian, see Figure 2) consists in both countries of sequences of evaporites including pelite, limestone/dolomite, gypsum/anhydrite, rock salt and potash salts (Figure 2). The lower cycles of the Wuchiapingian (Germany: Z1 – Z3, Poland PZ1 – PZ3) are identical. However the younger cycles of the Changhsingian show some differentiation (Germany Z4 – Z7/8, Poland PZ4a – PZ4d). The geological model of 3DGEO-EU, WP2 includes the base of the Zechstein (base of Z1/PZ1) and the top of the Basal Anhydrite in the Staßfurt formation (Germany: Z2, Poland PZ2, see Figure 2).

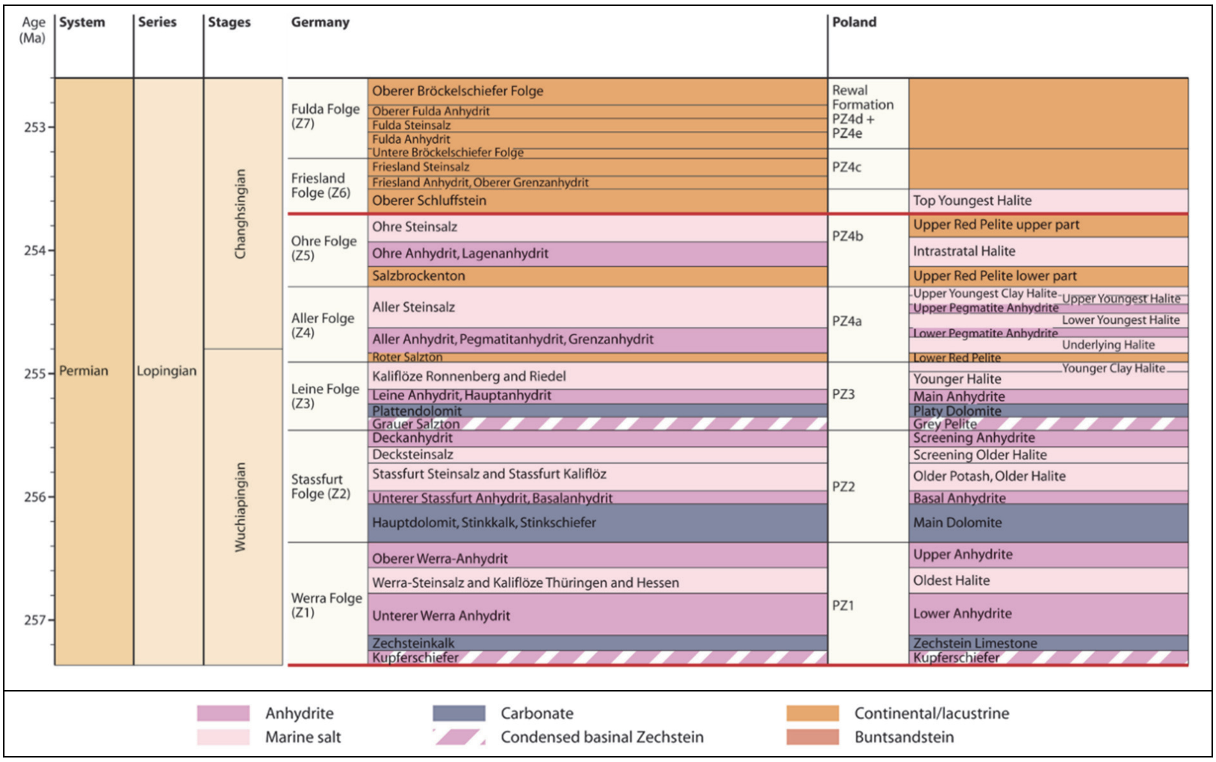


Figure 2: Stratigraphic correlation chart of the Upper Permian for Germany and Poland (Lopingian, Zechstein) (from Doornenbal and Stevenson (eds.) 2010 , Chapter 8, Figure 8.1)

The Triassic succession in the North German Basin and the Polish Trough is also very similar and can be directly correlated (Figure 3). In both regions the lithostratigraphic units of the Germanic Triassic

(Buntsandstein group, Muschelkalk group, Keuper group) are used. The model includes the base of Triassic (Base of Buntsandstein, Bunter sandstone), the base of Muschelkalk and the base of Keuper. The bases of the chronostratigraphic series of Middle and Upper Triassic slightly differ from the lithostratigraphic units (see Figure 3).

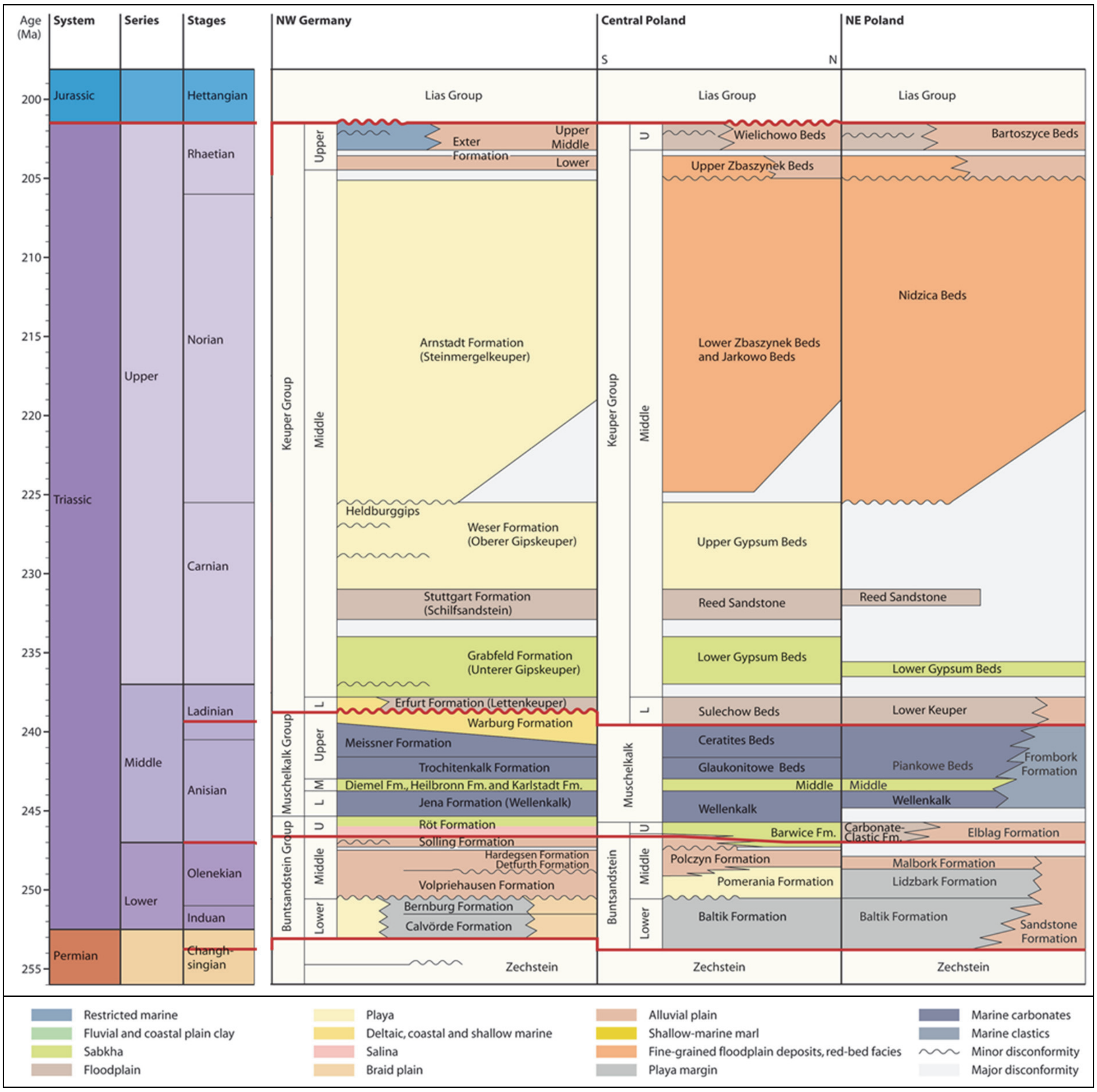


Figure 3: Stratigraphic correlation chart: Triassic for Germany and Poland (from Doornenbal and Stevenson (eds.) 2010, Chapter 9 Triassic, Figure 9.1)

Mainly from the Jurassic to the Cretaceous the area of Central European Basin System differentiated in local sub-basins (differentiation phase) with varying facies (Figure 4 and Figure 5). In addition, halokinetic movements modified the sedimentation areas and the local structural framework. Compressional stress during the Late Cretaceous and early Paleogen led to an uplift of discrete structures, e.g. the Mid-Polish Swell or the Grimmen High (inversion phase). The sedimentary succession in eastern Germany (northeastern part of the North German Basin) and western Poland (Polish Trough) shows an increasing facies differentiation (Figure 4 and Figure 5).

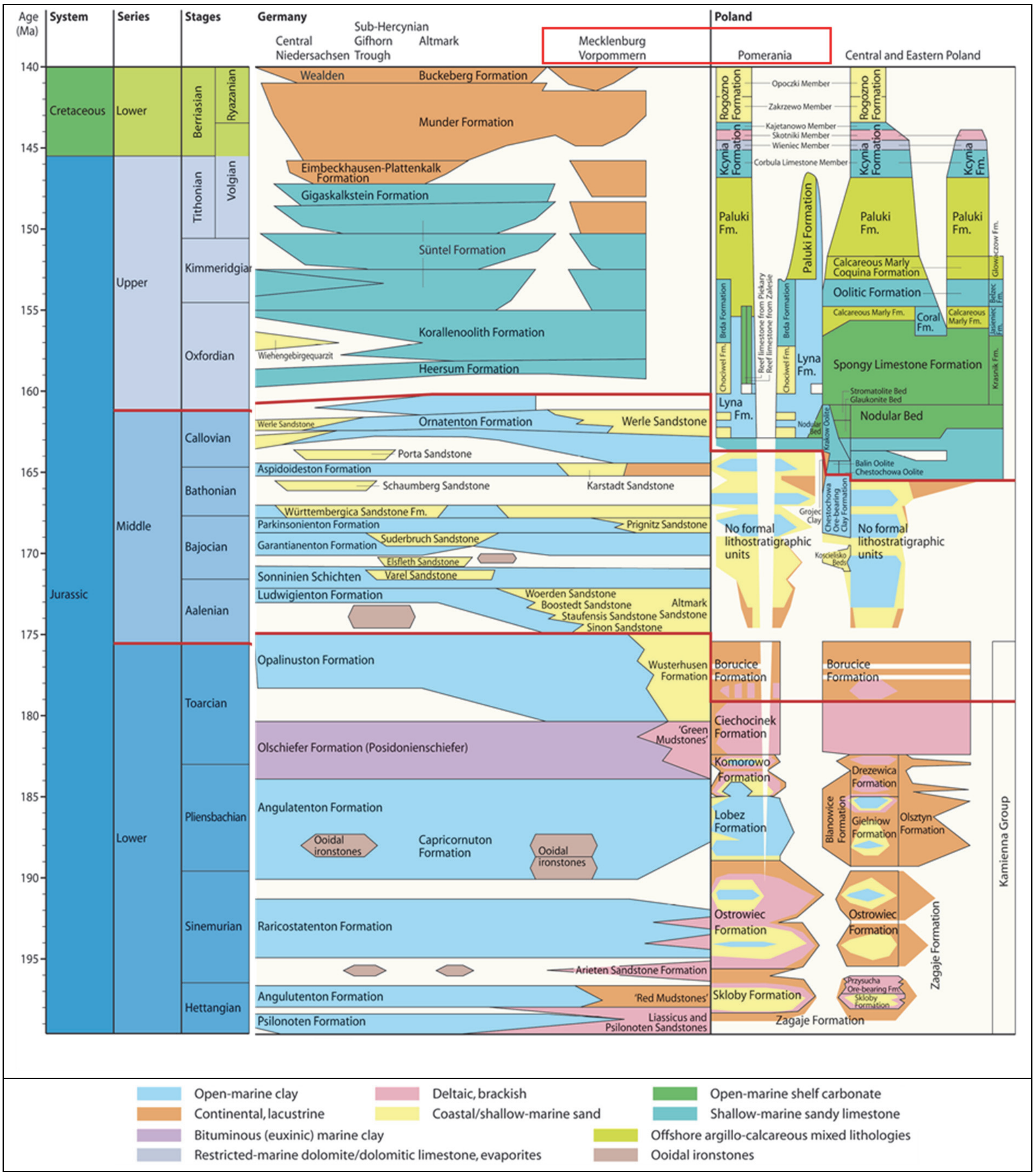


Figure 4: Stratigraphic correlation chart Jurassic for Germany and Poland (Doornenbal and Stevenson (eds.) 2010, Chapter 10 Jurassic, Figure 11.1) The region of the Polish-German cross-border model is represented by the marked "Mecklenburg Vorpommern" in Germany and "Pomerania" in Poland.

The model includes the base of Jurassic and the base of Upper Cretaceous. The Lower Jurassic (Lias group) is distributed in entire project area. The Middle and especially Upper Jurassic occur only in the northern and eastern parts (no-deposition or erosion elsewhere). The Upper Cretaceous is marked by characteristic transgression horizon at the base in the entire model area (transgression of Albian–Cenomanian that produces a very prominent seismic reflector). The Lower Cretaceous successions (not shown in Figure 5) are only limited preserved in eastern Germany and western Poland (low primary thicknesses and erosion during Cretaceous and Cenozoic) and is not modelled as a separate layer.

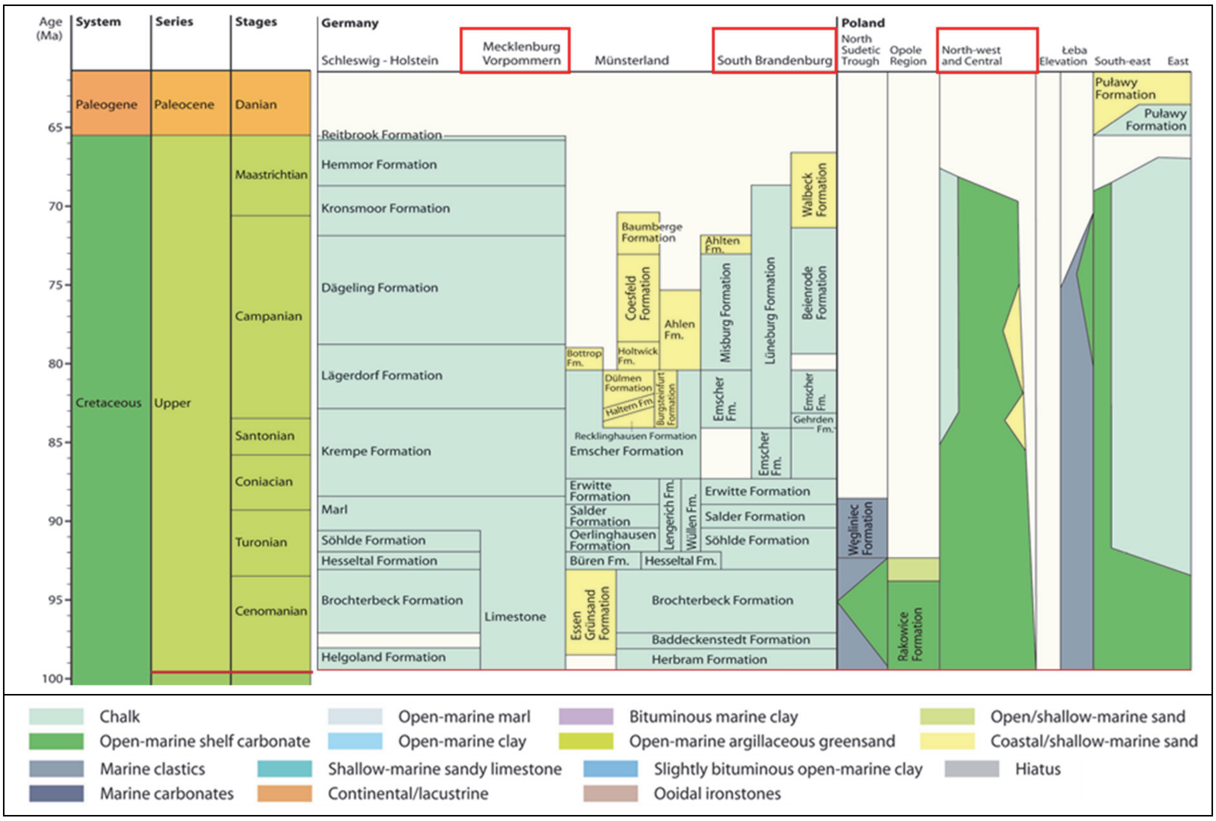


Figure 5: Stratigraphic correlation chart of the Upper Cretaceous for Germany and Poland (Doornenbal and Stevenson (eds.) 2010, Chapter 11 Cretaceous, Figure 11.1). The region of the Polish-German cross-border model is represented by the marked “Mecklenburg Vorpommern” and “South Brandenburg” in Germany and “North-west and Central” in Poland.

In the Cenozoic succession, the prominent transgressive horizons, i.e. the base of Tertiary and the base of Quaternary (ice-sheet transgression), are included in the model. Both horizons can be correlated by lithological criteria. The unconformity of the base of Tertiary is also a prominent seismic reflector (base of Quaternary only partially).

2.1.2 *Seismostratigraphic correlation*

Beside lithologic and stratigraphic information from boreholes, the seismic information is the major source for geological interpretation in the model area. So in addition to the stratigraphic correlation the seismic interpretations were compared. Primary data (seismic sections) could not be exchanged because of legal restrictions, but a comparison and discussion of interpretations and anonymized results were possible and were done. Figure 6 shows an example of the comparison of two anonymized seismic section close to the border with the picking of the reflectors and the reflector names. Although the age of the data, its processing and the resolution of the sections are different, the interpretations are generally similar, with some differences (selection of reflections and local phase picking). The comparison thus permitted to select the same reflectors and generally correlate interpretation, although with a degree of uncertainty unavoidable without cross-border seismics.

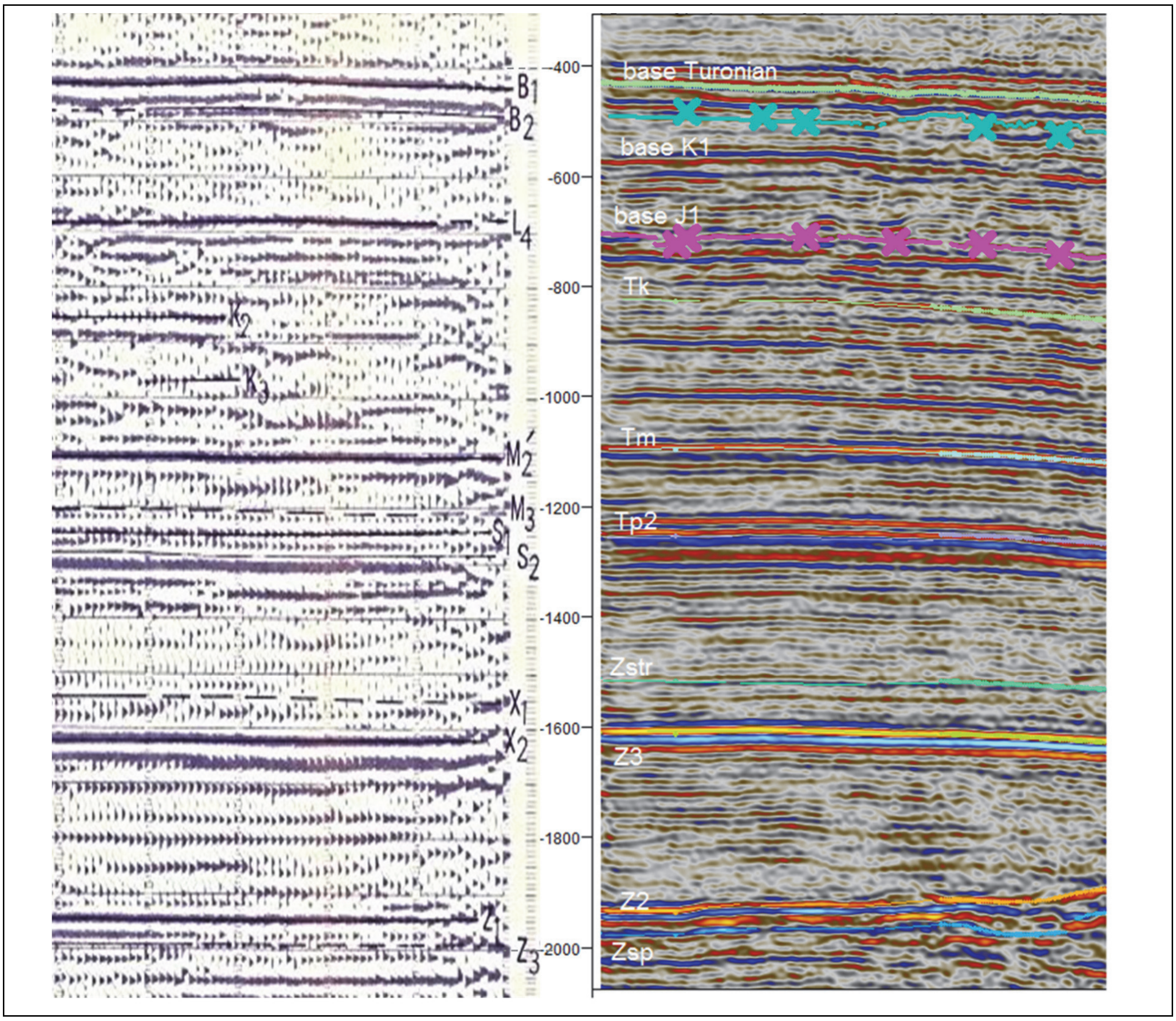


Figure 6: Seismic time sections close to the German and Polish border (vertical scale in milliseconds) with reflector picking – German side (left) Polish side (right)

Table 1 shows the correlation of the major seismic reflectors that can be identified in the Permian and Mesozoic succession across the border in western Poland and eastern Germany. The result of the comparison is the general consistence of the stratigraphic correlation and the picking of the reflectors, even if differences exist e.g. due to local facies variations. The exact correlation of the reflectors especially in Permian and Triassic at both sides is related to the equivalent lithostratigraphic succession (even some reflectors in the Triassic were not picked in Poland). Differences exist in the Jurassic and the Cretaceous related to local developments (e.g. the base of Upper Jurassic cannot be identified in seismic sections in Eastern Germany). In this strata the seismic correlations have to be carried out carefully and precisely fit to well marker.

Table 1: major seismic reflectors in the Polish-German border region, stratigraphic position and phase (see also stratigraphic correlation charts Figure 2 - Figure 5)

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 of Lower Jurassic)	L4	base of J1	minimum
base of Exter Formation (Rhätian, base of Upper Keuper)	K1		maximum
top of Upper Gypsum Beds - top 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	

In a second step velocity data were compared for selected intervals. Checkshots/VSP from a few scientific drillings from Germany could be shared. In addition existing velocity models and time-depth functions were compared. Figure 7 shows as an example time-depth curves from velocity models for the high velocity layer in the Middle Triassic (Table 1: M2’ to M3) from the Gorzów Block (southeast of the model area) and from several surveys at the German side from North to South. The data from Gorzów Block fits to the velocities in the south at the German side. The same results were obtained for other seismostratigraphic intervals. A general accordance (in the range of variability seismic velocity data) were determined.

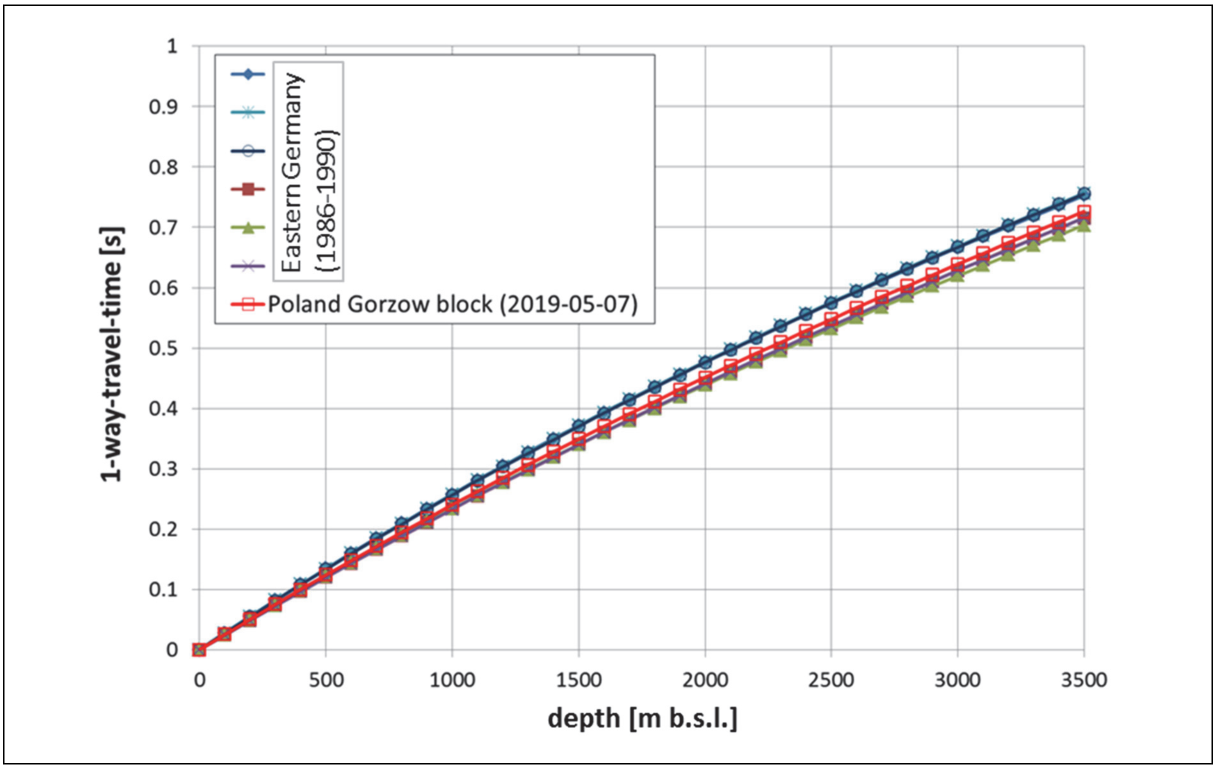


Figure 7: Time-depth curves from several velocity models in Eastern Germany and Gorzow Block in Poland – high velocity layer in the Middle Triassic (Muschelkalk) (interval M2'-M3, compare Table 1)

2.2 Harmonized structural interpretation and fault network

The Central European Basis System underwent several deformation phases since its formation in the Permian. Beginning with the evolution of the Southern Permian Basin c. 300 Myrs ago, the area underwent several deformation phases under varying stress regimes, including the contraction and inversion of sub-basins during the Late Cretaceous/Early Paleogene. A major factor in the structural evolution was deposition of thick layer of Late Permian (Zechstein) evaporites; dominanted by salts with a thicknesses of up to 2500 m in the centre of the basin (Kiersnowski et al., 2017). Due to enhanced halokinesis, today, the Zechstein sequence within the highest salt diapir in the study area is up to 4000 m thick and the amplitude between the diapir roof and the surrounding salt-withdrawal depressions reaches 3300 m.

These thick Zechstein salts commonly decouple deformation beneath and above salt layers leading to different shape and pattern of faults in the Mesozoic cover and the Palaeozoic basement. Hence, faults were modelled separately for the base of Zechstein and for the Mesozoic to Cenozoic cover. The reason for that is that tracing faults across several hundreds of meters (or more) of salt layer would be both impossible and counter-productive given that few of these fault zones show spatial correlations. Therefore individual fault planes usually cannot be traced from one structural level to another across the salt-bearing formations or are clearly shifted and may easily display opposite throw and dippping.

Figure 8 (left) shows the modelled fault traces detected by seismics in the model area in the Mesozoic and at the base of the Zechsteins. Additionally the top of the Zechstein salt and the (estimated) trace of the Variscan front after several authors is drawn. Figure 8 (right) shows the current status of exploration onshore by wells and 2D-seismics.

The harmonization of the faults was constrained by the following aspects:

1. Fault/fault zones parallel/subparallel to the border

The major fault directions are NW-SE to NNW-SSE in the northern part of the model (mainly related to the Trans-European Suture Zone and the border of the East European Craton) and NNE-SSW and NW-SE in the south. The German-Polish border follows the river Oder/Odra and show similar directions (NW-SE, NE-SW) and seems to be crossed by no or only a few individual faults. The Oder/Odra river valley is supposed to follow deep tectonic structures (inferred Oder/Odra fault-zone). Most faults here are arranged parallel to these major deep faults with strikes roughly coinciding with the Oder river and so fault lineaments are often subparallel or parallel to the border and do not cross it. This becomes obvious, e.g. in the northern part (islands of Usedom and Wolin, Szczecin lagoon) or in the southern part of the model where the Buckow fault zone (striking NE-SW in the Subsalinar and Suprasalinar) ends right before the German-Polish border. An extension of this fault zone to the northeast (parallel to the border) is presumed in deeper crustal levels but could not be observed in the available data (which is sparse in this part of the model Figure 9 right).

2. (Lack of) exploration activity in the border zone

Modeling of faults in the border zone has also 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).

So a narrow strip 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. Even less favorable are areas (especially on Polish side of the border) where no digital seismic data exists at all within a 10-20 km wide zone.

Other aspects that affect the detection, interpretation and modelling of faults in the study area are the following:

- a lot of seismic profiles run parallel/subparallel to fault directions or cross them at small angles – the detection of fault is difficult or not possible in this cases,
- only vintage seismics exists in large areas (analog seismics from the 1960s and 1970s), because there were no exploration interests since the 80s in these areas (especially southwest of Szczecin Trough, compare Figure 8, right)
- vintage seismic is particularly ill-equipped to detect faults below Zechstein salt sequence.

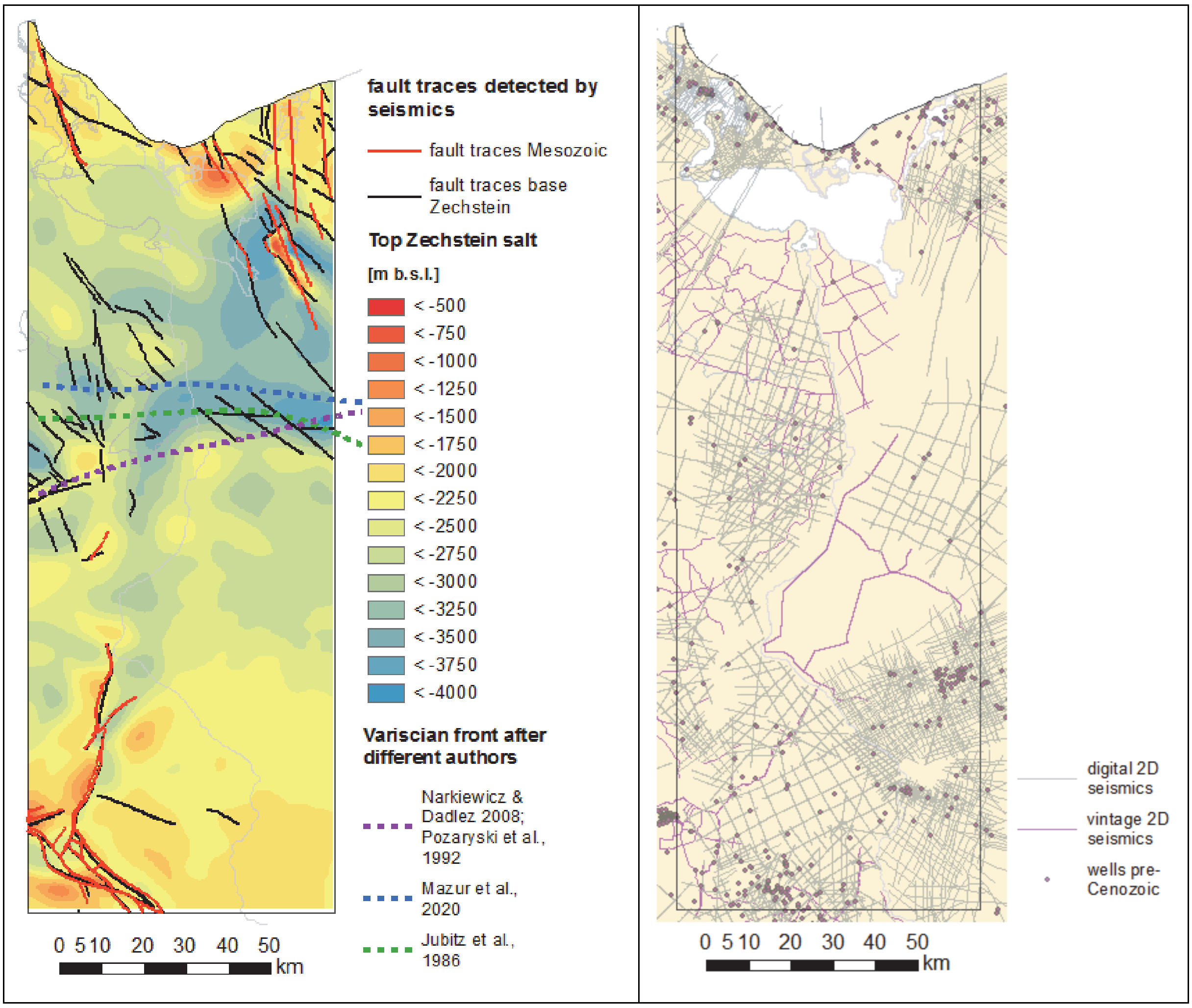


Figure 8: Left: fault traces of sub-salt faults (base of Zechstein) and supra-salt faults (Mesozoic) in the Polish-German border region. Top of Zechstein salt and (estimated) traces for the Variscan front after several authors. Right: current status of exploration onshore by wells and 2D-seismics (digital and vintage seismics)

For the modelling of horizons the information gap along the border is usually not so important because the horizons follow regional trends, but the modelling of discontinuities like faults or also diapirs needs a more detailed resolution. An example is the fault system in the middle of the project area developed in the sub-salt sequence, striking NW-SE at both sides of the border. Some individual faults of this systems end close to the border according to the current database. However, they could probably be prolonged and connected to traces at the opposite side of the border if information needed to connect them were not missing because of lack of investigations in this region.

3. Large scale faults in the deeper Pre-Permian strata

The most important fault zones crossing the border occur in the Pre-Permian succession (e.g. the Variscan front or fault zones sub-parallel to the southwestern edge of the East European Craton). Nevertheless, these deep faults are not analyzed in the scope of our modelling project (based on well data and seismics). Locating and harmonizing these deep faults would require further investigation in future project possibly including some cross-border seismic experiments focused on deeper strata.

2.3 Development of the harmonized cross-border 3D-model

2.3.1 Modelling workflow at LBGR and LUNG

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 1). The models at the German side are regional models covering the entire territory of the states Brandenburg, Berlin (Schilling et al., 2018; Jahnke et al. 2021) and Mecklenburg – Western Pomerania (Obst et al., 2021). They were used as a starting point for joint harmonized cross-border model. They comprise 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. 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

The modelling was carried out in depth domain. Primary data in time domain and velocity data were not used. For Eastern Germany 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).

LBGR and LUNG used a harmonized data base of primary and interpreted data (wells, seismic sections, regional depth maps of reflectors). The 3D modelling was done with the software GOCAD/SKUA usually with the workflow “Structure & Stratigraphy”).

The workflow “Structure and Stratigraphy” follows the usual steps:

- definition of the stratigraphic sequences and the stratigraphic contacts
    - the following horizons were defined as erosive in modelling (transgressive horizons): base of Quaternary, base o Tertiary, base of Upper Cretaceous)
    - the other horizons were defined as concordant
- data verifying (checking stratigraphical and geometrical implausibilities)
- definition of the spatial resolution
- definition and building of the fault network
    - definition of the throw type, definition of the contact to other faults
    - definition of special modelling parameters (e.g. smoothing)
- definition and building of the horizons
    - definition of special modelling parameters (e.g. smoothing, degree of thickness variation between horizons, using of erosion outlines)

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 within the workflow "Structure & Stratigraphy" had to be skipped because of the large dimension of the models. The diapirs were constructed separately in the national models and mounted afterwards into the final surfaces. In the area of the Polish-German cross-border model no diapirs occur at the German side, so this step was not necessary here.

The fault network was used in both model runs (Mesozoic-Cenozoic and Basal Zechstein).

The final surfaces of the horizons and the fault planes were exported as GOCAD-ts-files and were used as a starting point for joint harmonized cross-border model. Figure 9 gives an impression of the model structure with a horizon and the fault network at the German side of the border region.

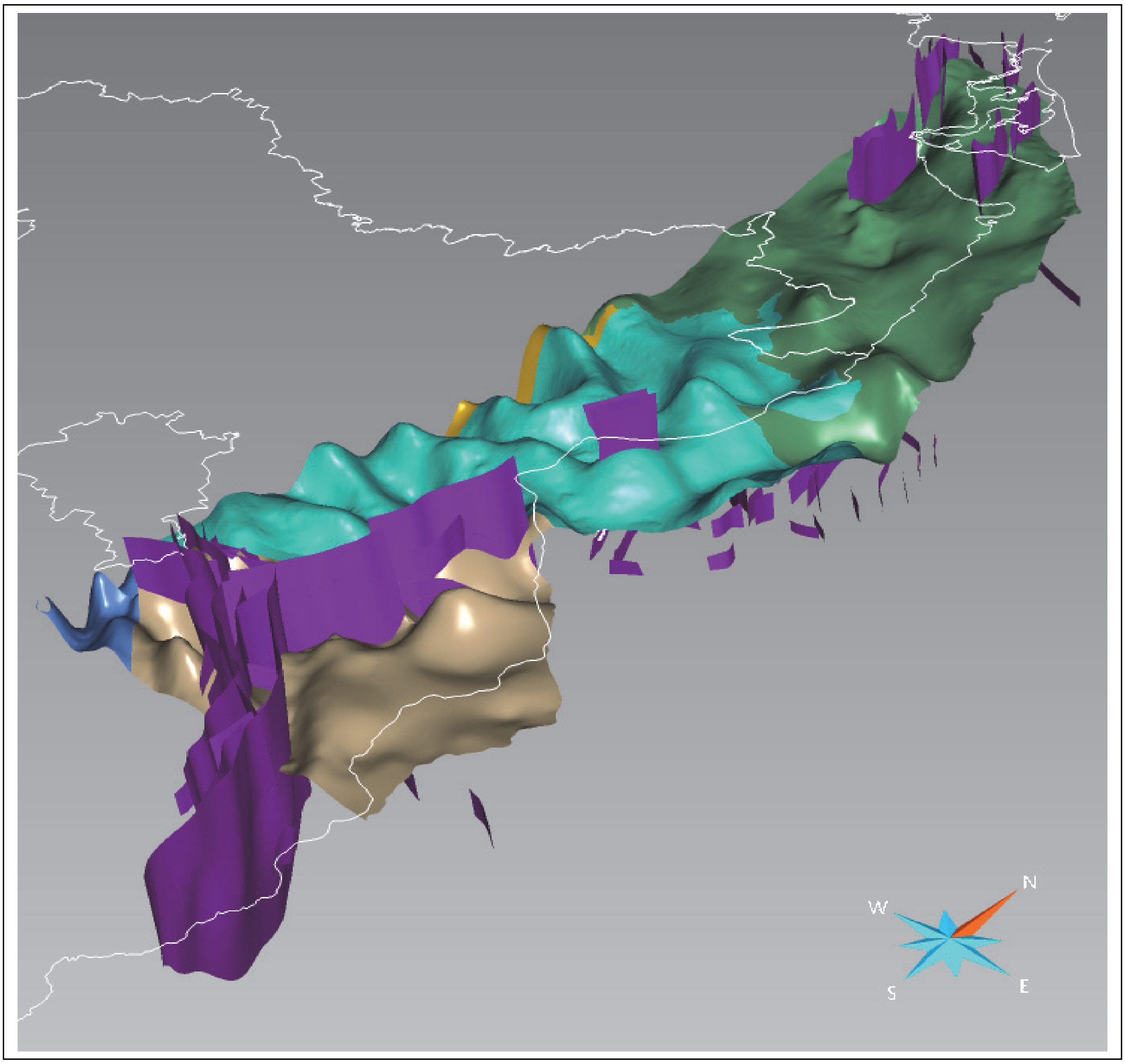


Figure 9: 3D models of Brandenburg (LBGR) and Mecklenburg – Western Pomerania (LUNG) – View of the base of Upper Triassic and the fault network showing the different models and model tiles (for the LBGR model). Vertical exaggeration 1:10.

2.3.2 Modelling workflow at PGI

Models used for harmonization on Polish side of the border differed substantially between the southern (Pilot area 1) and the northern parts (Pilot area 2). The model in the Pilot area 1 was developed based on the 3D parametric modelling of Gorzów Block, carried out as part of a larger framework aiming to gradually model all sedimentary basins in Poland. The Szczecin Trough model (Pilot area 2) used results of previous mapping projects that needed to be extended and reinterpreted with newer seismics and also augmented with vintage seismics due to large data gaps along the border. These gaps exist because in Poland exploratory boreholes and seismic surveys were mainly focused on regions where hydrocarbon exploration targets existed.

The Gorzów block model was primarily developed within the parallel national project. It is based on a substantial amount of 3D and 2D seismics and almost 300 deep wells, 200 of which had digital logs. These data were reinterpreted using well correlation profiles which allowed to correct stratigraphy and interpret facies, lithologies, sedimentary environments, densities and other parameters. Existing seismic data and horizon interpretations were used in time domain and similarly new interpretations were carried out where these were lacking (mostly to delineate shallower, Mesozoic horizons omitted in resource-focused seismic interpretations). Fault interpretations available in seismic surveys (faults sticks and fault polygons) were generalized and extended where interpretation was lacking. Due to lack of data near some parts of the Polish-German border, interpreted surfaces from the Brandenburg 3D geological model and two publicly available wells were provided by LBGR and used to control the near-border geometries. Interpretation was carried out in Petrel and final structural and parametric model was constructed with the standard modelling workflow (modelling horizons and faults together and then constructing and populating grids) in the same software. One exception was the Cenozoic layer, which due to the lack of seismic signal in the shallow zone was constructed separately in GOCAD/SKUA and then integrated with the model in Petrel. This Cenozoic part of the model is based on numerous shallow wells, mapping and partially on reinterpreted cross-sections from geological mapping projects.

Modelling of the Szczecin Trough followed a different procedure, because a full 3D model of this area was not available at the time. Modelling started with compiling the results of previous projects aiming at integration of data, including maps of chosen seismic horizons and faults. These horizons had to be reinterpreted and adjusted to borehole logs reviewed in 2008. They had to be adapted to more recently reprocessed 2D seismic data covering the southern part of the Szczecin Trough. In the central part of pilot area 2, however, near the border with Germany, only old analogue profiles were available and there was only one borehole penetrating all of the horizons modelled (Trzebież-1). These analogue seismic profiles from the beginning of 1960s showed only the geometry of three most prominent reflectors in depth domain. Thus, they had to be tied to the adjacent surfaces from Meckenburg-Western Pomerania as well as to scarce borehole data from Poland. Similarly, as in the case of horizon surfaces, fault surfaces were compared and adjusted to fault surfaces in Germany. After the horizon surfaces were modelled in Petrel, they were exported to Skua-Gocad where fault traces were constructed, separate for the base of Zechstein layers and for the Mesozoic. Horizons were then remodelled in Skua-Gocad to account for fault throws.

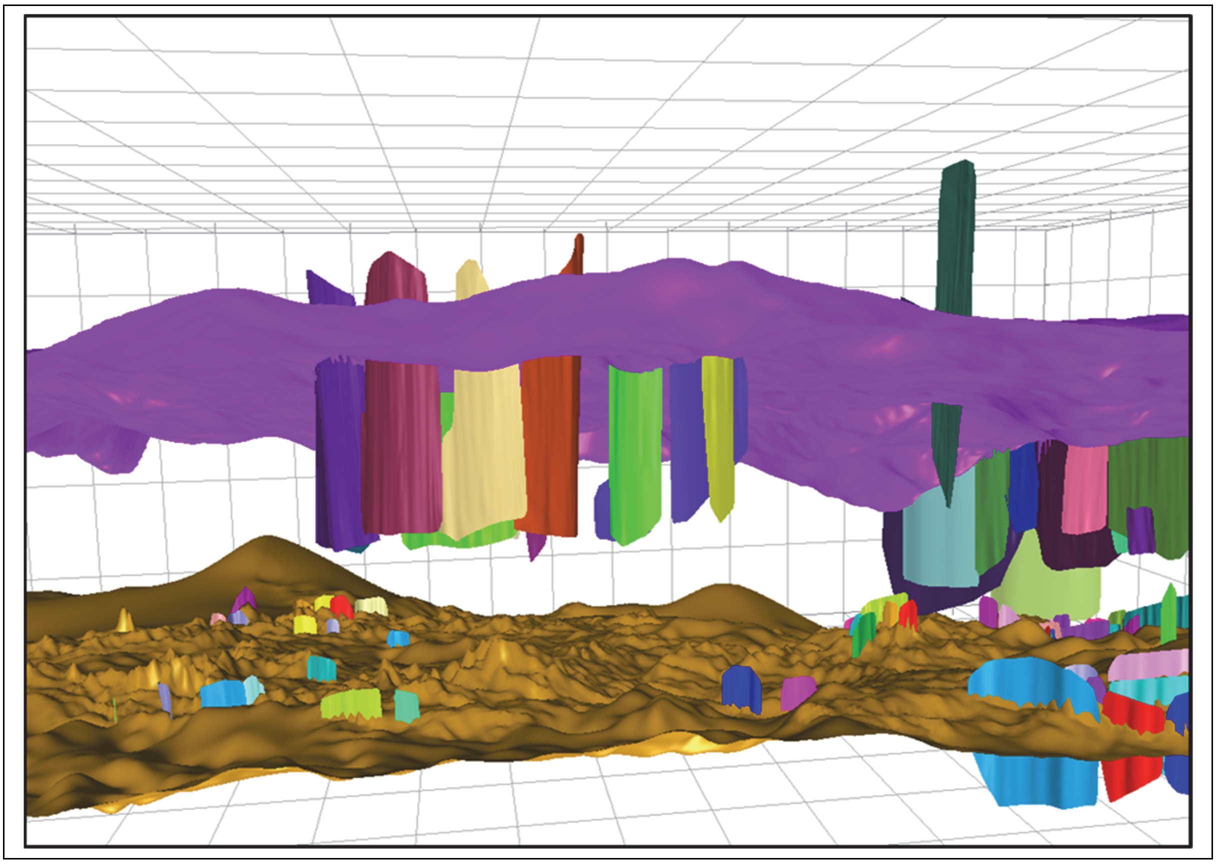


Figure 10: Visualization of the Gorzów Block model to the east of the 3DGEO-EU study area, depicting the base of Zechstein (ochre colour) and the base of Middle Triassic (violet) crossed by numerous faults (various colors). Decoupling of faults across the rock salt-dominated upper Zechstein layer (occupying ca. half of the space between the two shown horizons), is visible, given that faults crossing the base of Zechstein do not continue upwards into the Middle Triassic base and faults that cut the Middle Triassic horizon show partly different trends than the ones cutting the base of Zechstein. View from the south, vertical exaggeration 1:15.

2.3.3 Harmonization workflow for a joint cross-border horizon model

Four different models – developed in other contexts - were used to produce a final, harmonized model of the northern sector of the Polish-German border region, 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 2.3b).

(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.

(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.

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

Table 2: 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
	Cenozoic (Quaternary and Tertiary)	Clastics and marls, unconsolidated
Base of Cenozoic		
	Upper Cretaceous	Limestones and minor marls
Base of Upper Cretaceous		
	Jurassic	Siliciclastics and marls/limestones in the Upper Jurassic
Base of Jurassic		
	Upper Triassic	Siliciclastics and marls
Base of Upper Triassic		
	Middle Triassic	Limestones
Base of Middle Triassic		
	Lower Triassic	Siliciclastics
Base of Lower Triassic		
	Zechstein Salt	Salt with interlayers of anhydrite and clay
Top of Basal Zechstein		
	Basal Zechstein	Anyhdrites and dolostones with interlayers of clay and salt
Base of Basal Zechstein		

In the first step 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, 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, 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 used as input data in one joint SKUA-workflow "Structure and Stratigraphy" of the GOCAD/SKUA software at LBGR (pilot area 1) and at LUNG (pilot area 2 and final model) running with the usual steps described in chapter 2.3.1.

The workflow was again carried out in two separate model runs (see 2.3.1):

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

The time- and resource-consuming step of modelling salt structures over the entire area were 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 finally joined surfaces and the fault network were are shown in Figure 11 (horizons) and Figure 12 (fault network).

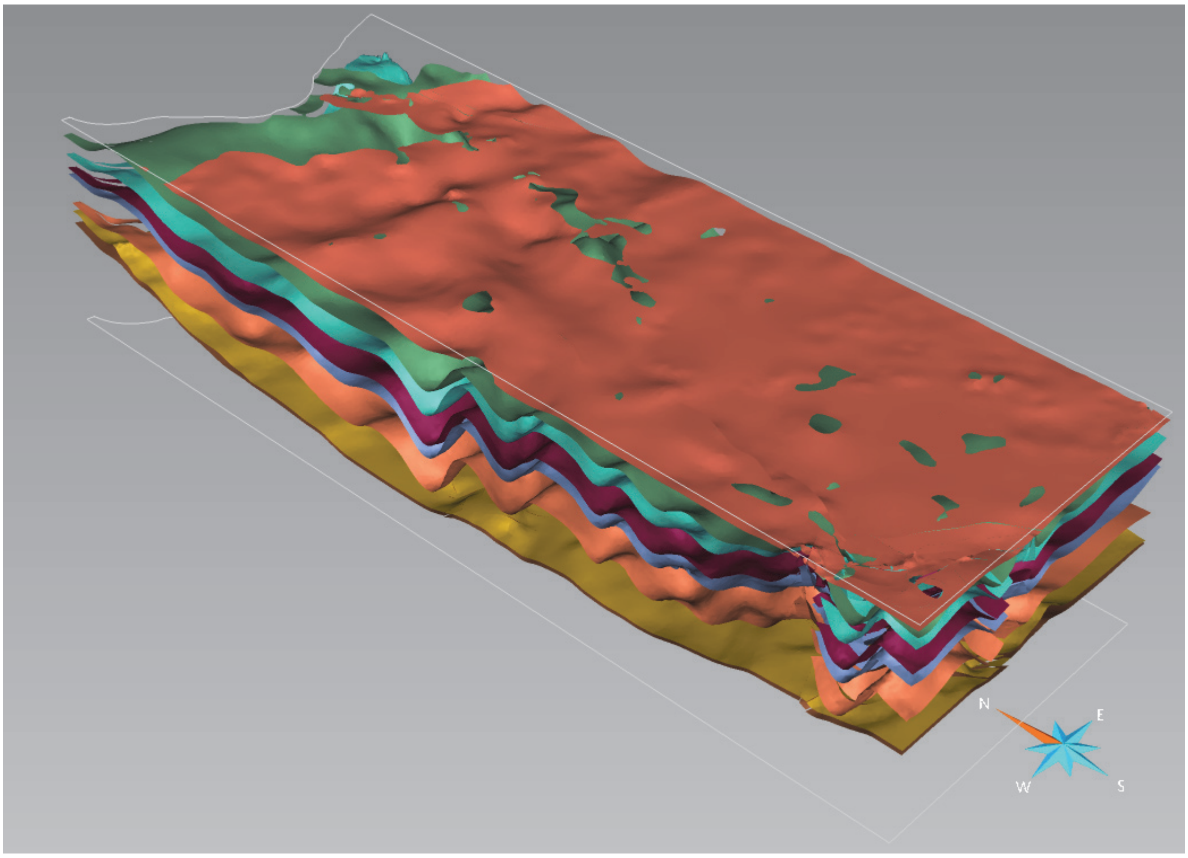


Figure 11: Horizons of the harmonized 3D-model (base of Tertiary to base of Zechstein, faults not shown). View from southwest. Vertical exaggeration 1:10.

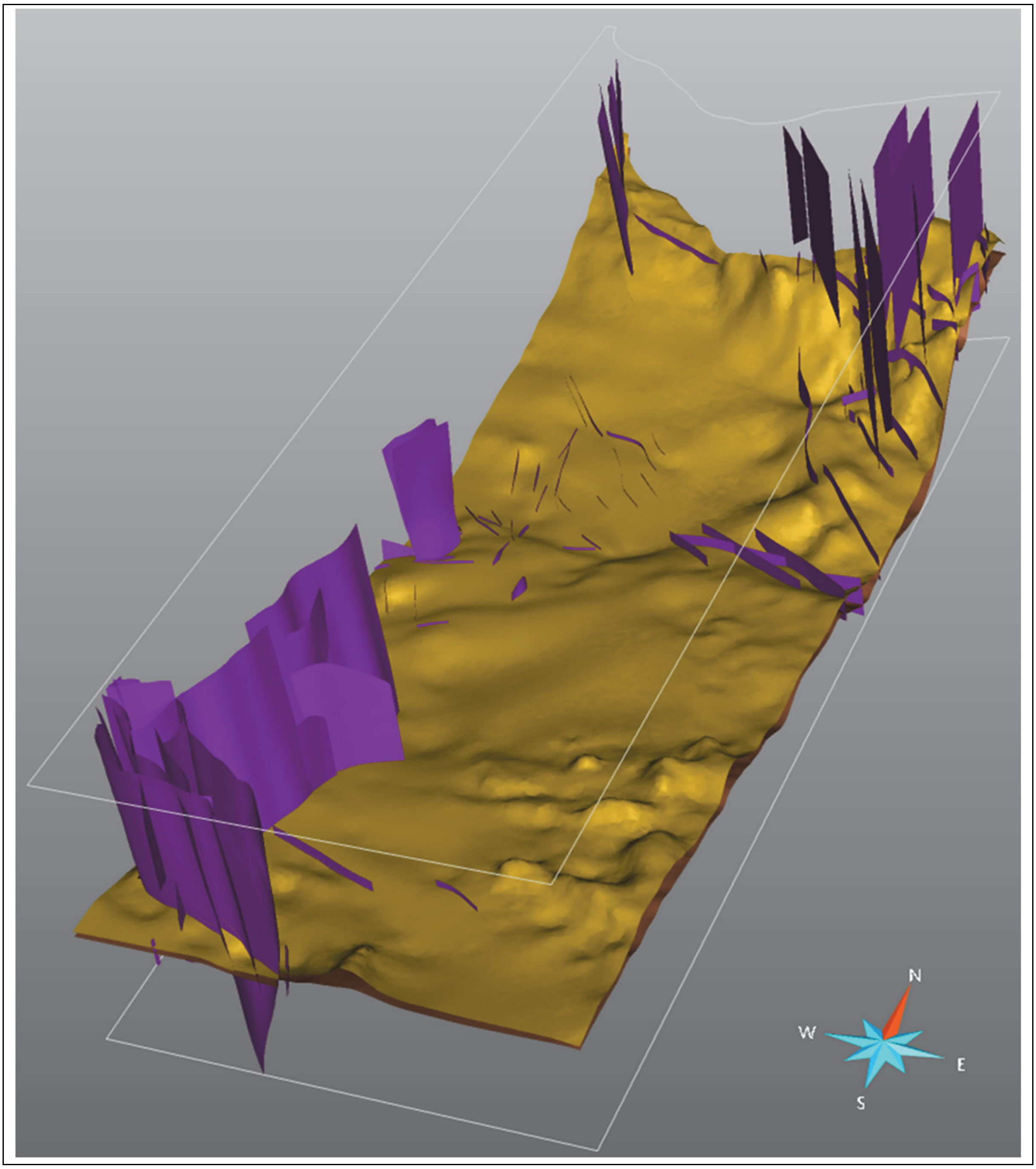


Figure 12: Fault network (violet planes) in the model area and the surfaces Top and Base of Basal Zechstein (ochre and brown). View from southeast. Vertical exaggeration 1:10

2.4 Harmonized cross-border petrophysical/geophysical models

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 a model of the (in situ) rock densities and the gravimetrical signal (Bouguer anomaly) which had to be developed in additional workflows which are only outlined in this chapter. A detailed presentation of the data processing, the workflows and the results (especially the gravimetrical modelling, what is not described here) is given in deliverable 6.3 in cooperation with WP6 (Ayala et al. 2021).

2.4.1 Petrophysics – density model

The available petrophysical data for a density model are very heterogeneous in the Polish-German border region:

Germany (LUNG & LBGR):

a) core measurements from boreholes from the 1960s to the 1980s
b) empirical density-depth relationships for lithostratigraphic units (Kopf, 1967; Krauss , 1972; Köhler & Eichner, 1973) basing on core data
c) synthetic lithostratigraphic density logs and stratigraphic averages based and a) and b) No density data based on wire-line logs (gamma-gamma, RHOB) were available.

Poland (PGI):

a) core measurements from boreholes from the 1960s to the 1980s
b) density data from gamma-gamma logs (RHOB logs) in the pilot area 1 (Gorzów Block)
c) 3D-parametric model of the Gorzów Block along with stratigraphy, lithostratigraphy, lithology, density

In addition to the different kind of data also a very heterogeneous spatial distribution exists with large data gaps on the German and Polish side (Figure 13).

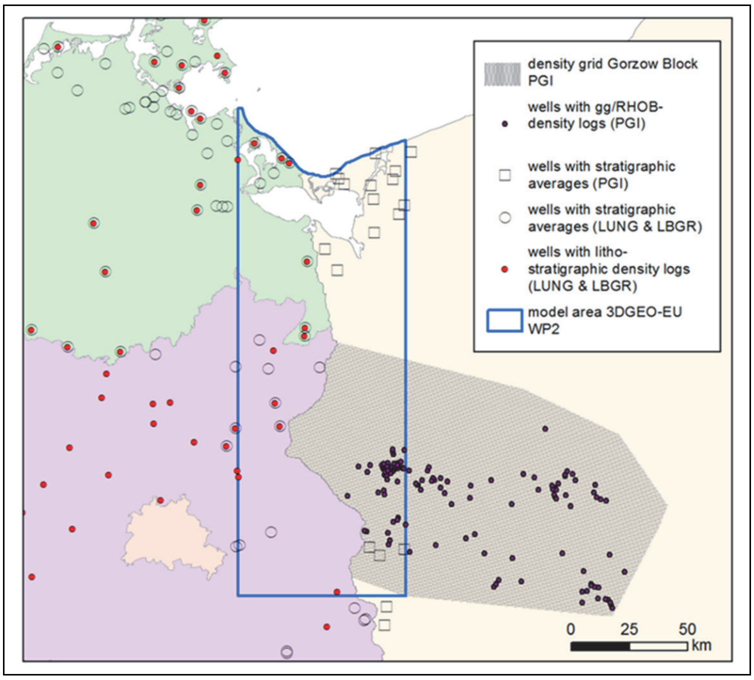
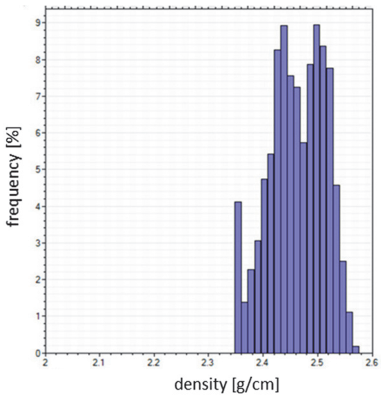
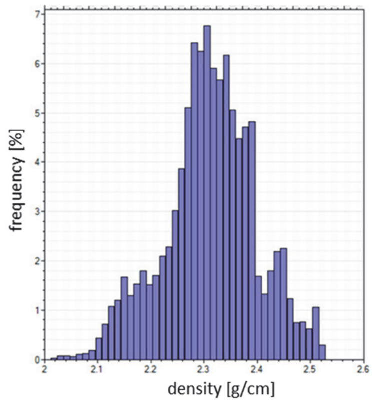


Figure 13: Petrophysical database (density) in the German-Polish border region

An exchange of primary well data between the German Geological Surveys (LUNG and LBGR) and PGI was not possible because of the legal restrictions. The data could be exchanged only in an anonymized way (averaged data without coordinates) and as interpolated data (interpolated grids). A comparison of the data was carried out in the following way:

In a first step both sides provided their spatial interpolations for the density as gridded data (Figure 14, example Upper Triassic). The histograms of the gridded data and the spatial distribution (especially the fit at the border) were compared. Large deviations were found in absolute values and the spatial distribution for several horizons.

Histogram of the density data (gridded data) Eastern Germany, Brandenburg (LBGR) – based on core measurement	*Histogram of the density data for the Upper Triassic (gridded data) from the Gorzow Block , Poland (PGI) – based on gamma-gamma-logs*
	

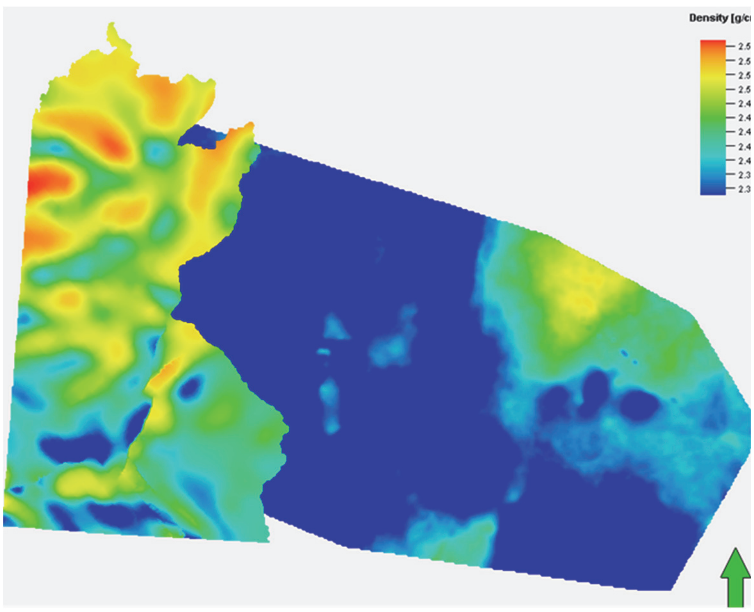


Figure 14: Above: histograms of gridded density data from LBGR and PGI. Left: Spatial distribution of the density in the Upper Triassic in eastern Brandenburg, Germany (left) and Gorzow Block, Poland (right) with an initial interpolation on both sides

In the second step anonymized well data from both sides were plotted against the depth for the stratigraphic layers in order to analyze the differences and compare density-depth-relations (Figure 15, examples for the Upper Triassic and Lower Triassic).

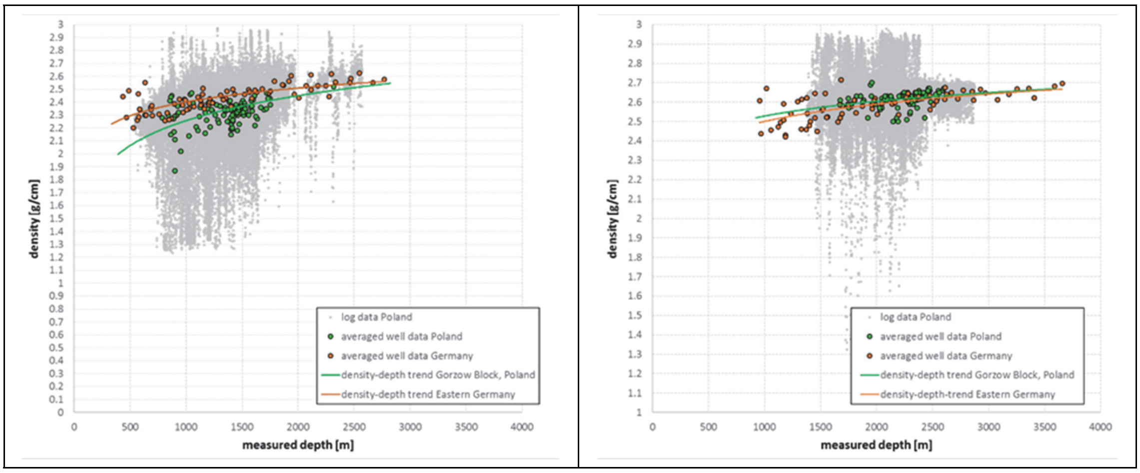


Figure 15: Density-depth data and trends for the Upper Triassic (left) and Lower Triassic (right) – anonymized log data from Gorzow Block Poland (original and averaged) and averaged well data from Germany and Poland, interpolated (logarithmic) density-depth trends basing on the averaged data

The result of the comparison was that density data in eastern Germany for the Cretaceous to Middle Triassic layers are higher than the Polish data and also the density-depth-trends differ. The German data (based on core measurements and empirical density depth functions) seem to represent only the higher range of density values compared Polish data (based on gamma-gamma-logs) (Figure 15, left). The differences in density generally decrease with the increase of the density and depth (e.g. for the Lower Triassic the German and Polish data are comparable see Figure 15, right).

These effects were interpreted as biased density-depth relations for core data especially at the German side. The problem was that in the sampling of the 1960s to 1980s only core samples were taken and investigated without any control by RHOB-logs. The core recovery was not continuous and usually focused to selected horizons (reservoirs in the Lower Zechstein, Rotliegend). Mesozoic strata were sampled mostly in the 1960s and early 1970s. Cores plugs could only be taken from stable parts of the well bore column. Weak material is disturbed or destroyed due to drilling and to relaxation of the core because of pressure reduction. So the core data are representative for the stable parts of the column and have usually higher densities in comparison to the weak parts of the strata.

According to these results the core based density data were corrected with depth-depending functions fitted to the log data for the Gorzow Block. The corrected data are comparable to the averaged gamma-gamma-data. Interpolations at the German side fit very well at the border (Figure 16 and Figure 17 example Upper Triassic, compare Figure 14 and Figure 15). The interpolation was carried out with a Co-Kriging procedure. The depth was used as additional Co-variable for the interpolation of the density (for the Zechstein salt layer the thickness was used as Co-variable). The geometries of the harmonized 3D-model were used for depth and thickness, which are available for the entire model region (see chapter 2.3.3). With this approach the density-depth trend and the spatial variation of the depth is included in the interpolation, what helps to overcome the problems of the heterogeneous data distribution and the data gaps (where the correlation between depth and density is used for interpolation). Nevertheless, the obtained density distributions are estimates in wide regions of the model area. The Co-Kriging was carried out with the ArcGIS extension Geostatistical Analyst.

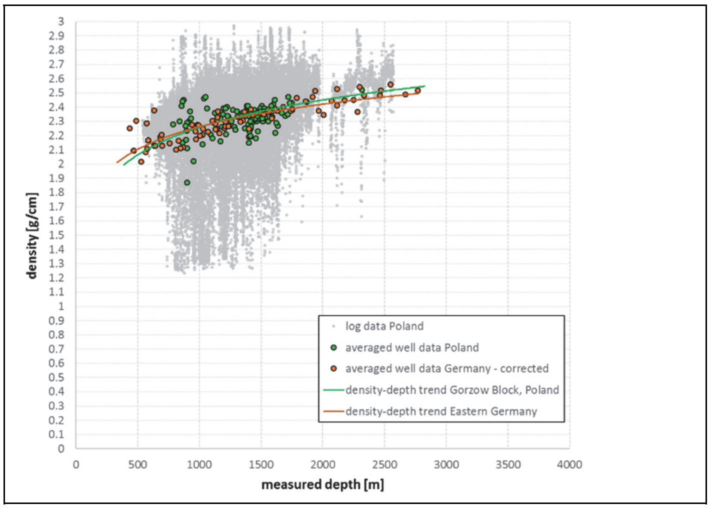


Figure 16: Density-depth data and trends for the Upper Triassic – anonymized log data from Gorzow Block Poland, corrected well data from Germany and Poland, interpolated (logarithmic) density-depth trends basing on the averaged data

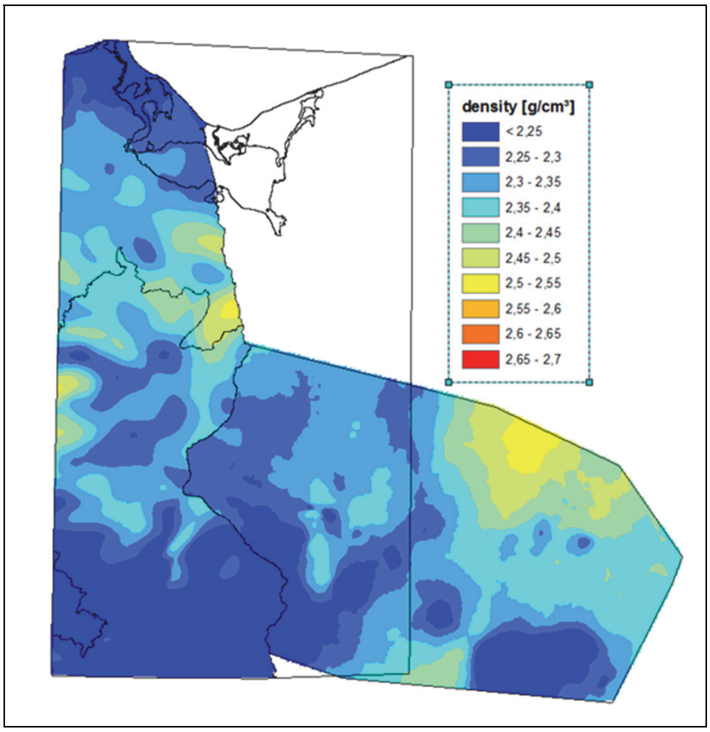


Figure 17: Spatial distribution of the density in the Upper Triassic. Separate interpolation for Eastern Germany (left, corrected density data) and Gorzow Block, Poland (right)

The interpolated harmonized densities for the model layers are shown in Figure 18. A statistical evaluation of the results is presented in Figure 19. The harmonized data show characteristic density ranges for the lithostratigraphic layers of the model (see **Table 2**), with a general increase of the density from the Cenozoic to the Triassic, a characteristic decrease for the Zechstein salt and a further increase at the Basal Zechstein (Figure 19).

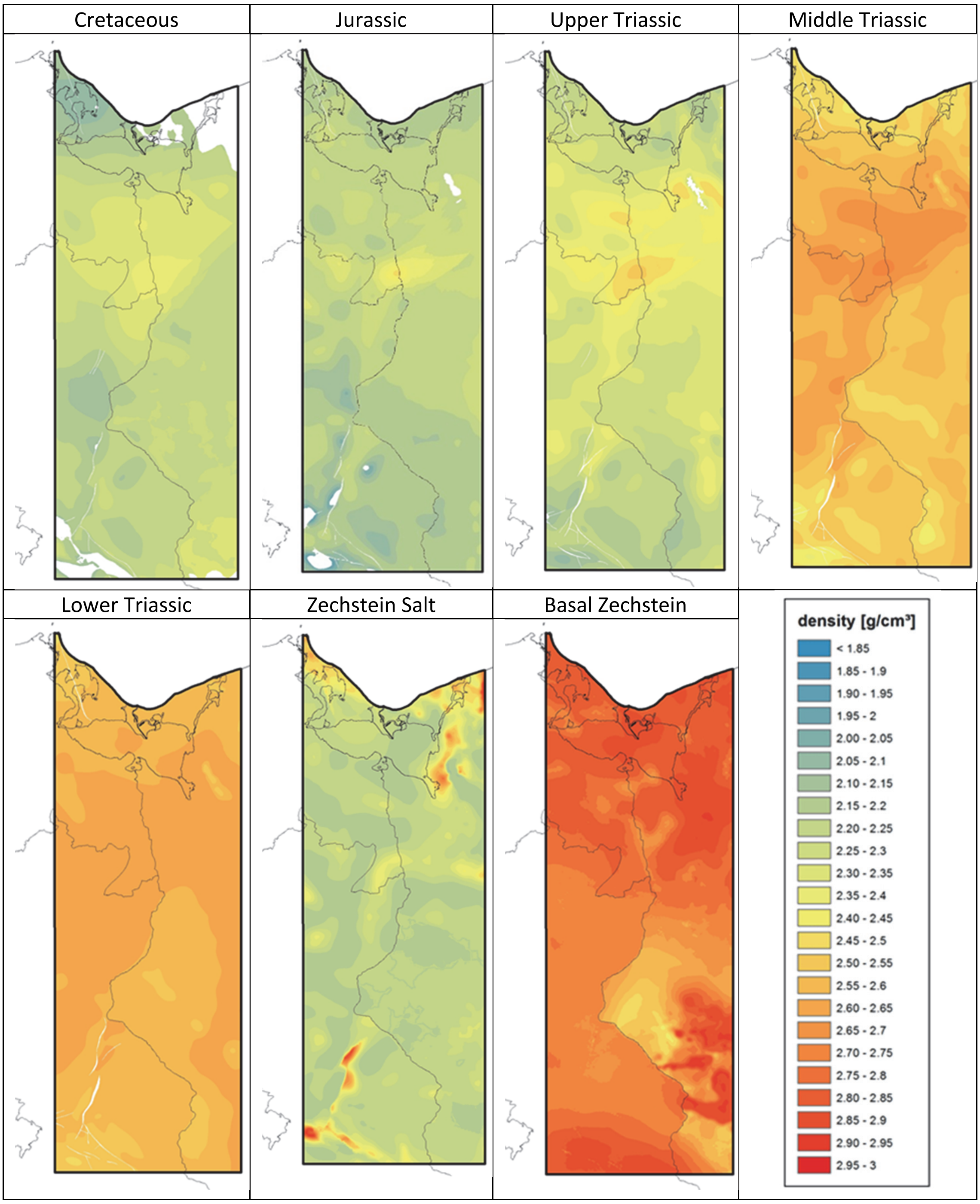


Figure 18: Final density model: spatial interpolation of densities for the layers Cretaceous to Basal Zechstein

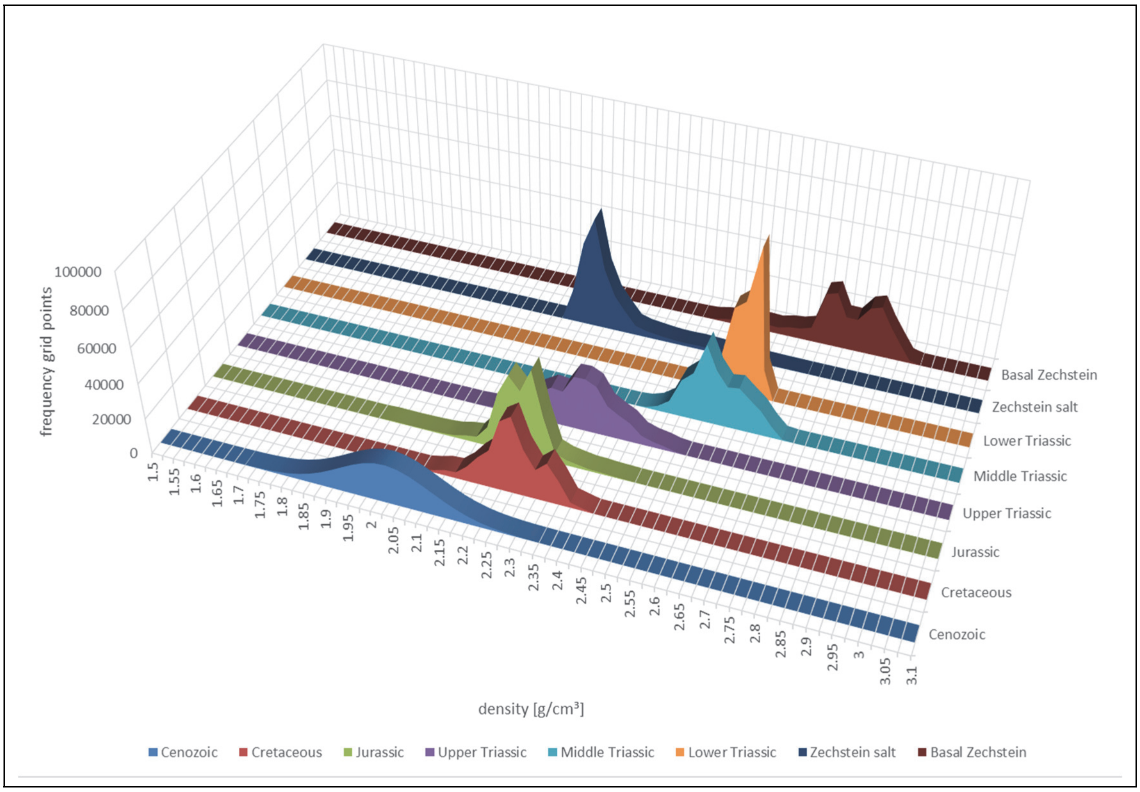


Figure 19: Histograms of the interpolated densities for the model layers

2.4.2 Gravity – cross-border map of Bouguer anomaly

Database

For the project area and 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 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 20.

The coverage with gravimetrical stations is quite dense also in the areas with data gaps in seismics and well bore exploration (compare Figure 8, right). Off-shore data are in principle available (Szczecin lagoon, Baltic Sea) but partially still analog (German side) and not used in this case study.

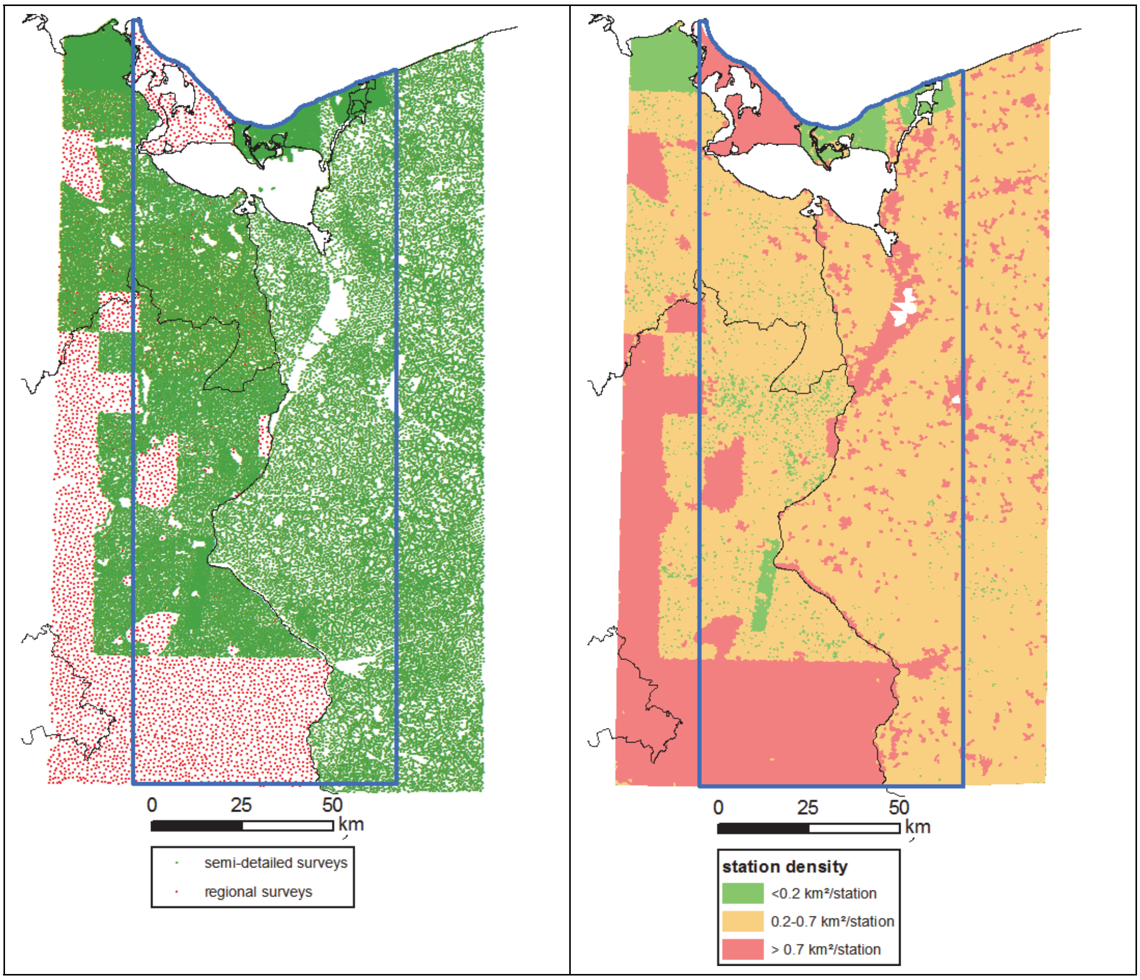


Figure 20: distribution (left) and density (right) of the used gravimetrical stations in the project area. Semi-detailed surveys (left: green dots, right: station density <0.2 km²/station up to 0.7 km²/station) and regional surveys (left: red dots, right: 0.7-2 km²/station).

Harmonized processing

All data were reprocessed to modern standards (Gravity datum ISGN71, Normal gravity after Moritz 2000) including Free-air correction, Bouguer-reduction, terrain correction based on DEM and a harmonized reduction/correction density (for details see D6.3 of WP6, Ayala et al. 2021). Because of the slightly different processing at the Polish and German side a comparison of the Free-air correction and Bouguer-reduction were carried out at several points. The differences of the parameters and the deviation of the resulting Bouguer anomaly are low (< 0.1 mGal) and could be neglected in a joint Bouguer map.

Joint map of Bouguer anomalies

The semi-detailed data at the Polish and the German side could not be exchanged cause of legal restrictions (industrial data). Only the regional data from the German side could be exchanged. In order to compile a joint and harmonized map of the Bouguer anomalies the following approach was used:

1. Providing of the German regional data of LUNG and LBGR to PGI.

2. Interpolation of a joint Bouguer map at PGI basing on the Polish semi-detailed data and the German regional data. Development of a joint grid of the Bouguer anomaly with a resolution of 250 x 250m. Providing of the joint grid to the German partners.
3. Interpolation of the final harmonized Bouguer map basing on the gridded data from PGI and the German semi-detailed and regional data from LUNG and LBGR.
4. Final review and revision of the harmonized Bouguer grid at all institutions.

The resulting harmonized cross-border Bouguer map is shown in Figure 21. The Bouguer map has a larger extend than the project area to cover structures in the surrounding. 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.

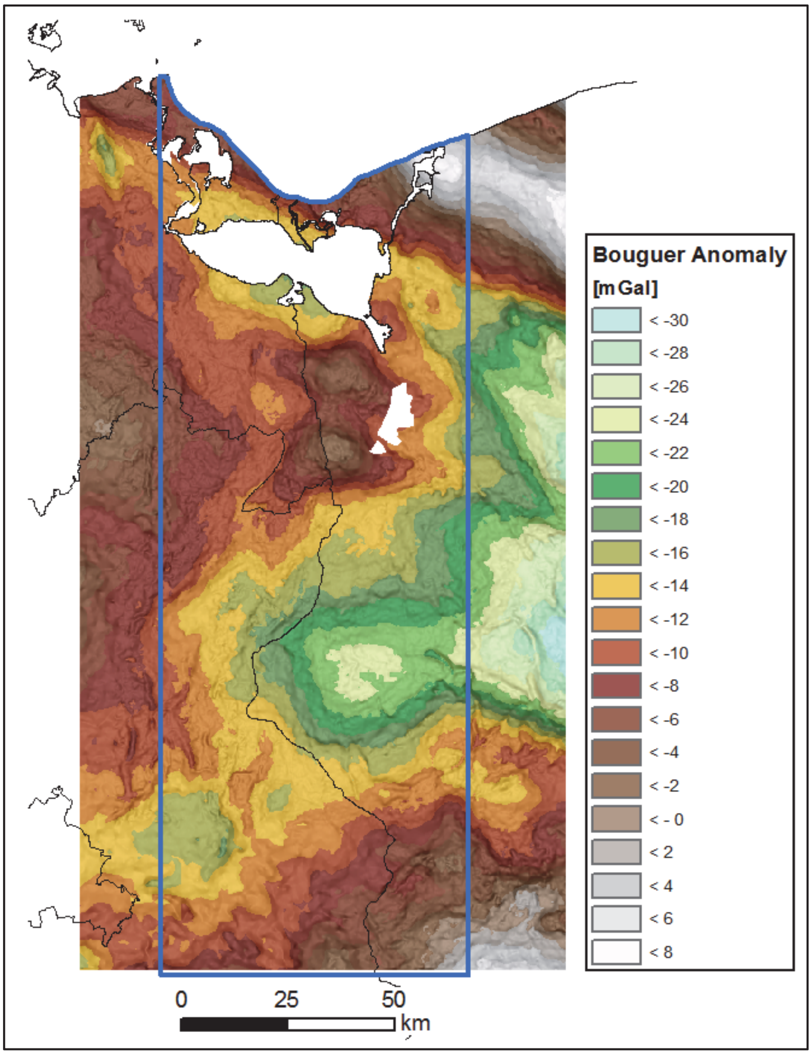


Figure 21: Final harmonized cross-border map of Bouguer anomaly

3 SUMMARY

The data evaluation (documented in D2.1 State of the Art Report, Jahnke et al.2019) shows that the national data bases at the partner institutions are comparable in quantity and quality in the field of drillings, seismic and gravity and offer good preconditions for the development of a joint and harmonized deep subsurface model, but it also shows that this project has to overcome several specific challenges:

- Because of legal restrictions only a minor amount of the data could be shared in the project and published (public research and national investigation wells, regional gravity data). Non-public data could only be used in the internal work of the partners.
- Data gaps exist in wellbore and seismic exploration (usually the major data source for deep subsurface models) in the near-border zone and also in larger parts of central study area (surround Chojna and in the region Stargard – Szczecinski - Gryfino). To close these gaps vintage data were thoroughly researched, compiled (vintage seismics) and partially reprocessed (vintage gravimetrical data). This work required additional effort for digitizing, compilation and reprocessing data in the timeframe of the GeoERA.
- The finally available data at the partner institutions have very different age and processing state from analog vintage data from the 1960s to modern digital data.
- 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).

In order to handle these problems a general approach was developed:

- 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) had 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.
- Potential field methods (gravimetry) were used in a case study in cooperation with WP6, IGME to close the data gaps in wellbore and seismic exploration. This approach required in addition to the geometries of 3D subsurface model the development of a joint density model and a joint Bouguer map.

First the horizons which would constitute the harmonized model were agreed on what required to find a balance between existing models and the need to adequately depict major structural variations. The final model contains 8 horizons (the major stratigraphic boundaries from the base of Zechstein to the base of Quaternary and – as an important contrast in the density model – the top of the Basal Zechstein, see Table 2) and the fault network. The stratigraphic and the seismostratigraphic correlation of these horizons and also additional horizons that were modelled in the national projects were compared and analysed in detail in order to obtain joint and harmonized data definitions. After that the building of the horizons in the separate national models started. 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. Finally all pre-adjusted models (horizon surfaces and fault planes) were joined in one joint modelling workflow to one harmonized and seamless model. The restrictions in data sharing hamper the modelling process partially but a harmonized cross-border subsurface model could be constructed successfully based on the developed approach.

The harmonizing of the gravimetrical and petrophysical data showed also that the restrictions in direct exchange of data hamper the data analyses and result in increased effort because anonymized and interpolated data had to be produced and to be used. The harmonization based on these kind of data can nevertheless be successful (especially if the data are of good quality and well defined as in the case of the gravimetrical data) but can be problematically and uncertain (in the case of density data). The use of vintage data (necessarily to fill data gaps) requires background knowledge of the measurement techniques and former interpretation (and additional effort in digitizing analog data) but generally does not hamper the evaluation and analysis.

As results of the harmonization a detailed and robust map of Bouguer anomalies with a (gridded) resolution of 250 m (even the primary resolution ranges between 250 m and >1000 m) and a harmonized density model could be developed. The density model is in the lithostratigraphic averages, their variations and trends reliable, but in the spatial resolution and certainty much less robust. Therefore the petrophysical information are - besides the uncertain model geometries in exploration gaps - the most critical parameters of the model. For further details and especially the gravimetrical modelling and its results see deliverable 6.3 in cooperation with WP6 (Ayala et al. 2021).

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