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Harmonization procedure in the Polish-German border region using gravimetric data

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Abstract for stakeholders

Cross-border harmonization of subsurface models is one of the main goals of GeoERA Energy projects, and specifically of the 3DGeoEU one. Very often, legal constraints at different levels preclude the sharing of information and the building of consistent 3D models and prevent tackling key challenges of the European Green Agenda (CO_2 and Hydrogen storages, deep geothermal reservoirs, etc.). In this sense, WP6 of the 3DGeoEU project, among other goals, focuses on potential field geophysics (gravimetrics and magnetics) as a quick, cost-effective and efficient method for 3D modelling, especially useful for the harmonization of cross-borders regions or regions with scarce and heterogeneous subsurface information. Beyond the main efforts done in the frame of WP2 (a 3D model of the Polish-German border region based on seismic and well interpretation), in this particular activity we have performed the harmonization of the gravimetric and petrophysical data and the joint modelling together with the initial 3D geological model (seismic one) aiming to improve the 3D reconstruction of this cross-border region. The methodological approach follows the 3D modelling workflow proposed in (D6.4).

The main results attained during the project life are the accomplishment of a new harmonized Bouguer Anomaly grid based on more than 50,000 stations (from vintage campaigns from the 1960s to the 1980s) and a new harmonized petrophysical dataset (averaged density distributions of model layers). This harmonization was previously precluded by strict sharing regulations of information that were overcome in the frame of GeoERA, although represented a time-consuming activity.

The 3D gravimetric signal modelling using the software Oasis Montaj allowed to compare gravimetric response of the model with model (initial) geometries and helped consequently to locate discrepancies. These discrepancies, visible as short-wavelength anomalies (mostly located in data-poor areas), will allow verification of model geometries, depths and density distribution within model layers. Another important result is the observed long-wavelength anomalies translating to density variation within the Paleozoic and Proterozoic crust below the modelled geological structures, where seismic and drilling data is all but unavailable. Here the gravimetric modelling permits to draw conclusions about location of prominent basement structures such as major faults and deformation fronts.

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1 INTRODUCTION – BACKGROUND, AIMS AND GOALS

Cross border harmonization of subsurface models is one of the main goals of GeoERA Energy projects, and specifically of the 3DGeoEU one. Very often, legal constraints at different levels preclude the sharing of information and the building of consistent 3D models and prevent tackling key challenges of the European Green Agenda as the evaluation of potential structures for CO_2 and Hydrogen storage, deep geothermal reservoirs, etc. Besides, this problem also represents a major drawback for building a unified and harmonized 3D geological model for whole Europe, one of the midterm goals of EuroGeoSurveys. The WP6 of the 3DGeoEU project, among other goals, focuses on potential field geophysics (gravimetrics and magnetics) as a quick, cost-effective and efficient method for 3D modelling, especially useful for the harmonization of cross-borders regions or regions with scarce and heterogeneous subsurface information.

In this report, we specifically focus on the harmonization efforts along of the northern part of the border region between Germany and Poland. In this region, the lack in continuity of 2D seismic surveys across the border is a major drawback for the construction of a unique 3D geological model in the region. WP2 (and related deliverables) have done big efforts to unify and harmonize interpretations of stratigraphic sequences, structural features, geophysical data etc. and, under these criteria, have correlated the seismic stratigraphy at both sides and to be able to interpolate seismic reflectors, etc. in the border region. The relevant results from the harmonized model are described in deliverables D2.2 ("Documentation of harmonization methods, workflows and results for different geological/geophysical datasets and levels of investigation"), D2.3 ("Improved and harmonized geological 3D model at the Polish-German border region") and in D2.4 ("Final report"; Jahnke et al. 2021a, b, c) that includes a synthetic overview of this case study as well as some final suggestion on best practices, lessons learned and recommendations for future similar case-studies.

Complementarily to this work, the main goal of this report D6.3 ("Report on Harmonization procedure in the Polish-German border region using gravimetric data") is **to aid in the harmonization of a consistent 3D model in this region as a case study** integrating the abundant gravimetric information existent at both sides of the border together with the unified 3D model based on seismic data. To do so, we also consider some secondary goals:

A) Harmonizing the **gravimetric data** in the region. Data from several campaigns, performed in different periods, with different instruments, different datum, etc. Many of them had to be digitalized on the German side of the border. This vast dataset entirely covers the target region with a much better and even density of information than the seismic sections (usually stopped some hundreds of meter away from the border and in some near-border settings simply inexistent).

B) Harmonizing the abundant **petrophysical information** derived from core data and borehole logging (formation density logs) in the frame of the unified stratigraphy.

C) Performing a joint 3D forward and inversion modelling of all data together to get insights on the quality and consistency of the initial 3D reconstruction across the border.

The project area covers the northern part of the Polish-German border region (Figure 1). From the geological perspective this is the transitions zone between the North German Basin and the Polish Trough (sub-basins of the Central European Basin System/Southern Permian Basin).

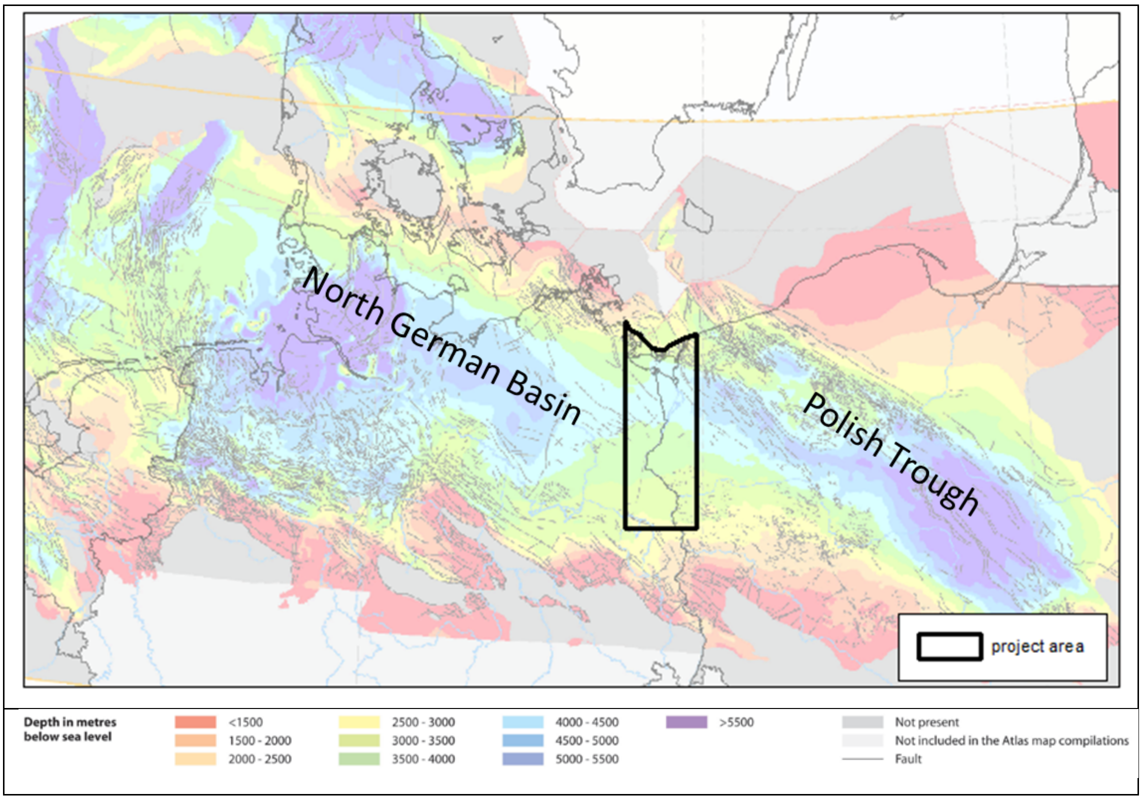


Figure 1: : Position of the project area in the Central European Basin System (Map after Doornenbal & Stevenson 2010, Fig. 8.2 depth of the base of the Zechstein)

Figure 2 shows the current state of exploration (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 2 the distance to the closest seismic line is mapped to visualize exploration gaps and the uncertainty of the geological 3D model that was developed on the base of well data and seismics. Depending on the local geology the uncertainty of the model increases with an increasing distance from wells and seismic lines. Especially along the border region two larger exploration gaps with areas > 400 km² exist. 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. Other regions also show a low covering by seismics and wells.

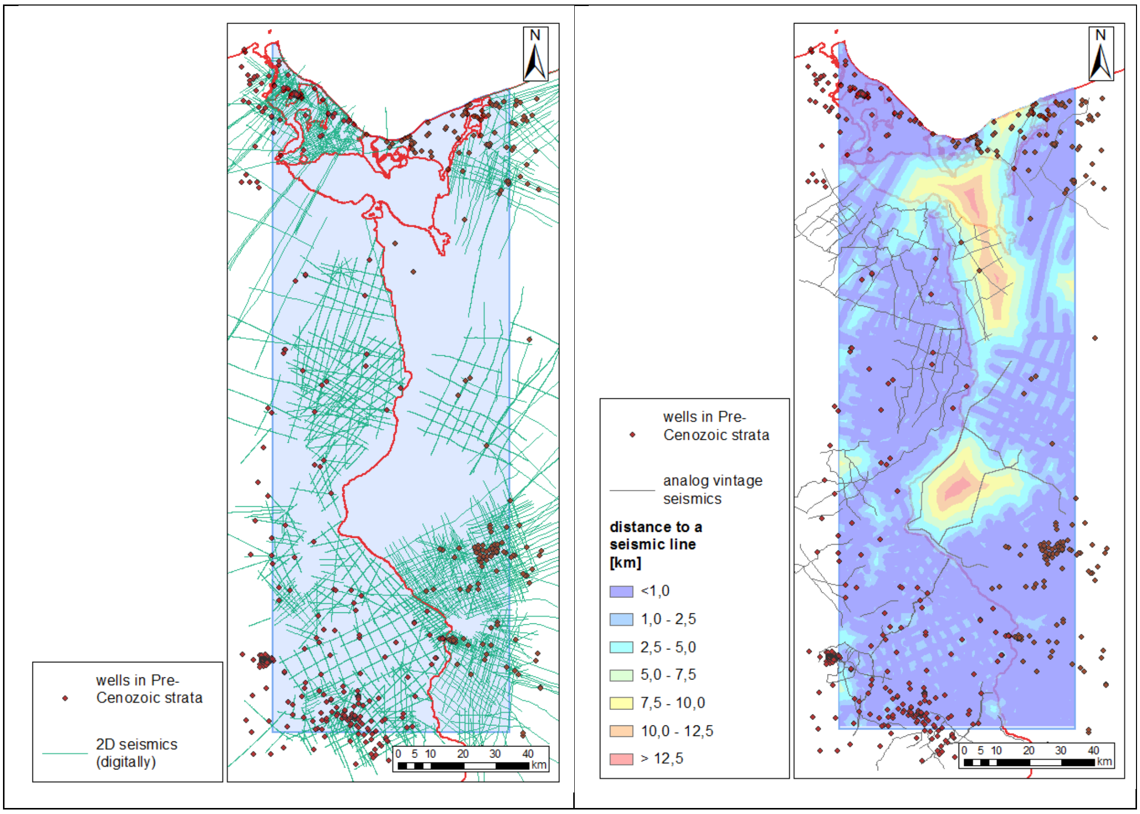


Figure 2: Left: digital 2D seismics and wells reaching the Pre-Cenozoic in the model area. Right: distance to the closest seismic digital 2D line (colored areas) and analog vintage 2D seismics.

Based on well data and seismic exploration a cross-border geological 3D model was developed and harmonized for the major litho-stratigraphic units, which are characterized in Table 1-1. Figure 3 gives an impression of the structure and geometry of the model in depth down to 5000 m b.s.l. (for more information see deliverables D2.2, D2.3 and D2.4 of WP 2; Jahnke et al. 2021a, b, c). In the exploration gaps the structure of the Pre-Cenozoic had to be interpolated based on uncertain (vintage) data or had to be extrapolated 10s of km. The drillings for the shallow Cenozoic layers (Quaternary and Tertiary) is more dens but not in the focus of this study.

Table 1-1: Litho-stratigraphic structure of the 3D model of the Polish-German border region

Model layer	**Major lithologies**
Cenozoic (Quaternary and Tertiary)	Clastics and marls, unconsolidated
Cretaceous	limestones and minor marls
Jurassic	siliciclastics and marls/limestones in the Upper Jurassic
Upper Triassic	siliciclastics and marls
Middle Triassic	limestones
Lower Triassic	siliciclastics
Zechstein Salt	salt with interlayers of anhydrite and clay
Basal Zechstein	anyhdrites and dolostones with interlayers of clay and salt

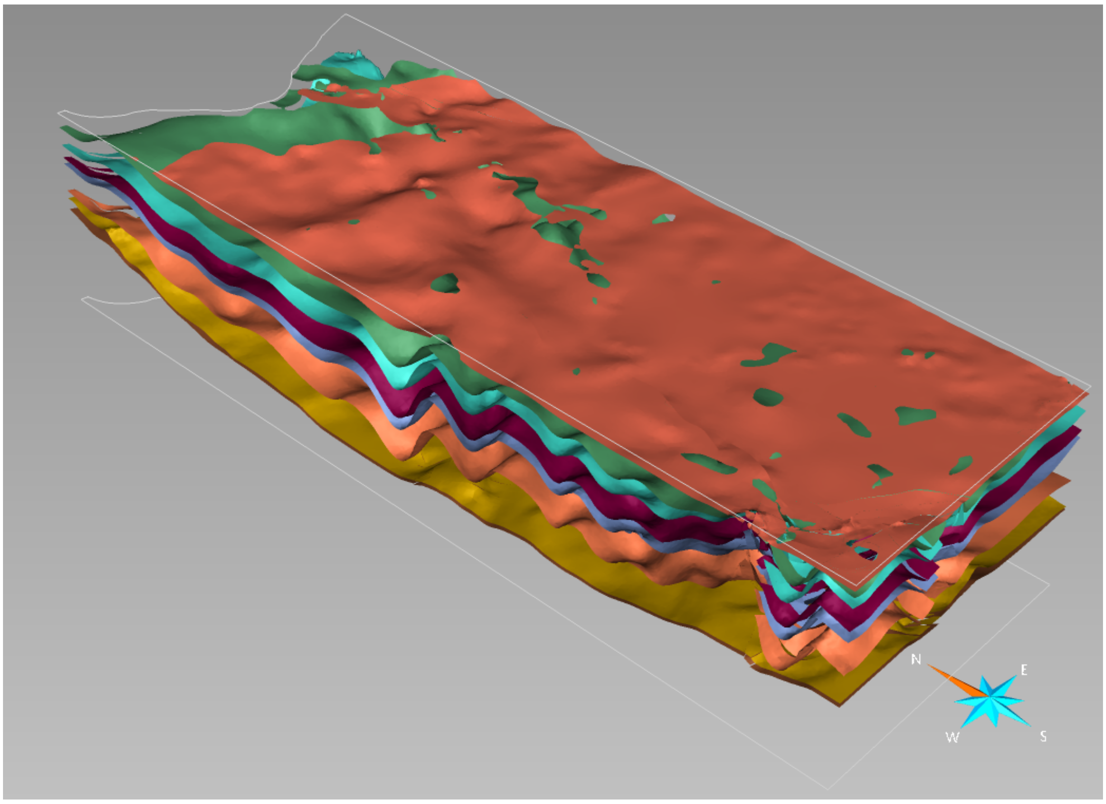


Figure 3: Horizons of the harmonized 3D model (base Zechstein to base Tertiary, faults not shown). View from SW. Vertical exaggeration 1:10.

Of special importance for the structural development is the Zechstein salt layer (Figure 4). The thickness of the Zechstein salt ranges from <500m at the northern and southern border up to 2000 m in salt pillows and reaches nearly 4000 m in the Goleniów diapir in the northeast. The halokinesis of the salt had a strong influence on the sedimentary succession (especially since the Upper Triassic) due the formation of local rises and sinks.

In the northern and southern parts of the model area an intense faulting is present (Guben-Fürstenwalde and Buckow fault zone in the southwest, Western Pommeranian Fault System in the northeast).

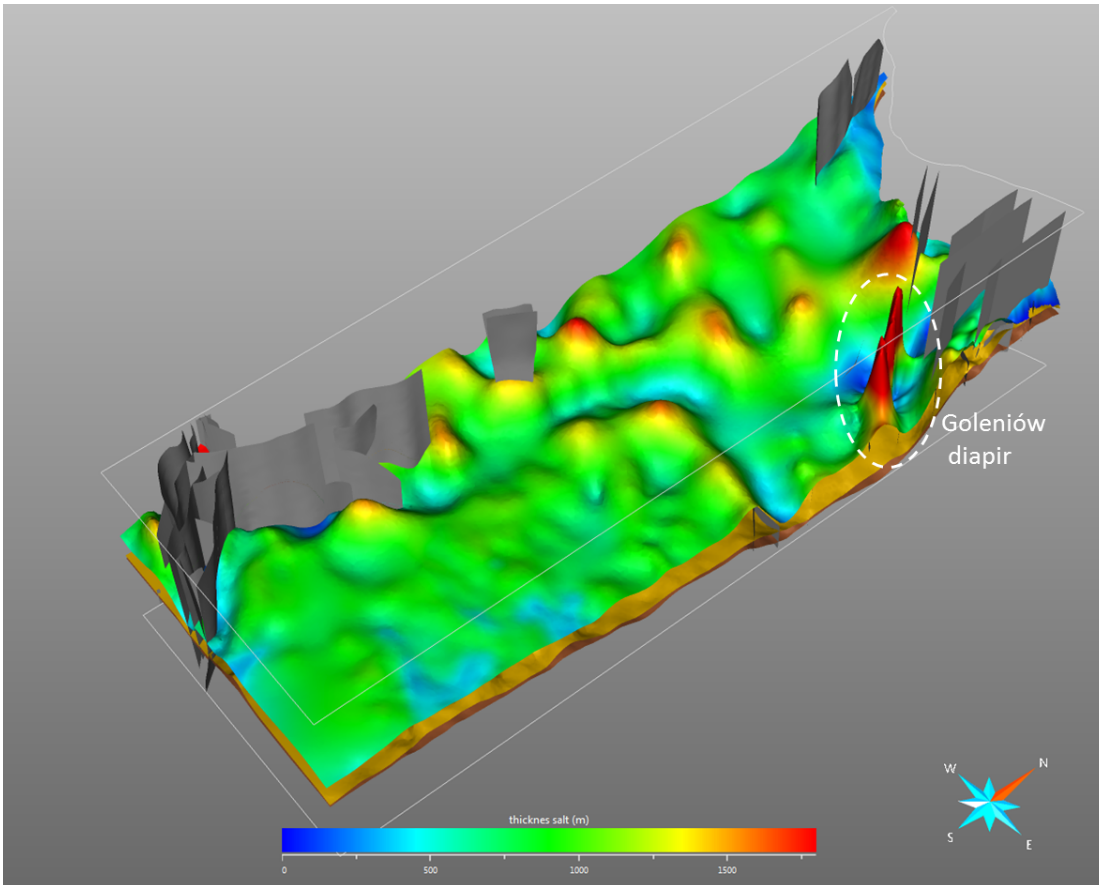


Figure 4: 3D model with the Upper Permian horizons: base Zechstein (brown), top Basal Anhydrite (yellow), top Zechstein salt (with colors representing the thickness, see legend) and selected faults in The Mesozoic succession. View from SE. Vertical exaggeration 1:10.

2 METHODOLOGY

We have followed and adapted the methodological approach proposed in D6.4 "**Optimized 3D reconstruction workflow based on gravimetric, structural and petrophysical data**" of WP6 (Pueyo et al., 2021) where additional details have been extensively described. That workflow is based on three main pillars: gravimetric data, robust petrophysical (density) data and serial cross sections (when 2D approaches are considered in the absence of seismic information). Furthermore, three different levels depending on the data processing level can be established (Figure 5):

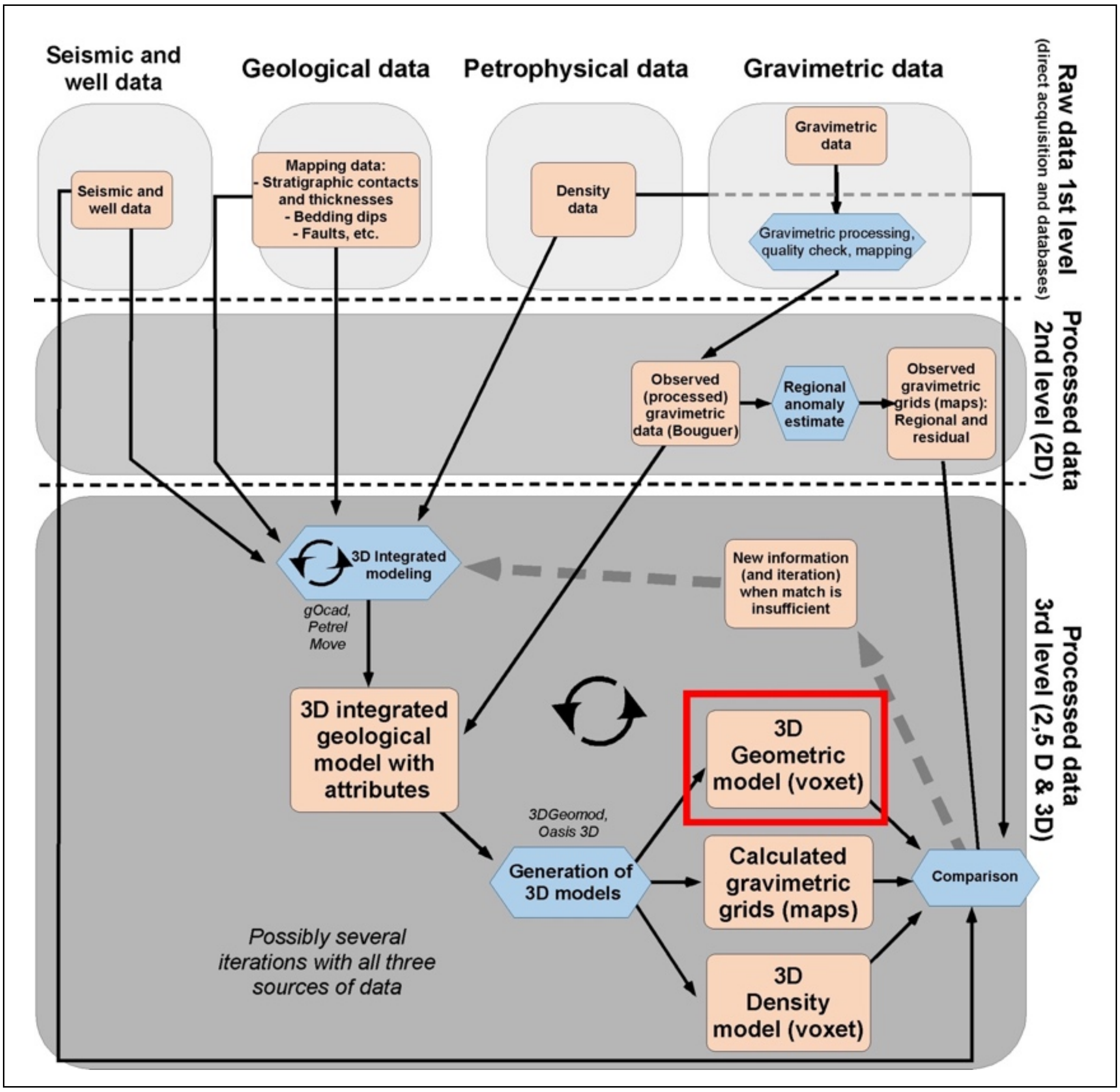


Figure 5: Synthetic workflow focused on the comparison between gravimetric models and seismic models.

1) Level 1 considers the raw data from different sources. First, structural and stratigraphic elements are derived, in this case from the 3D model based on the harmonized seismic exploration. Secondly, the gravimetric data harvested from the Polish and German data bases that underwent an important homogenization process is added. And finally, the harmonized petrophysical information for the target lithostratigraphic units (Table 1-1) is involved (including their response to depth). The data base for the gravimetric and petrophysical data is described in chapter 3.

2) Level 2 involves a certain degree of data processing. The 3D model of the target horizons is directly derived from the work done in WP2 (see aforementioned deliverables). The gravimetric data are harmonized and processed together to obtain the Bouguer anomaly as well as regional and residual components (only grid files are shared but not the raw data). In this level petrophysical data (density) are also grouped and processed together depending upon the final selection of stratigraphic horizons to be modelled.

3) Level 3 is focused on 3D forward and inverse modelling since the extensive seismic information allows us to skip any 2D approach. In level 3 an integrated 3D structural (initial) model is build merging all data together: the petrophysical and 3D seismic model (formation and structural trends, stratigraphic thicknesses, etc.) as well as the gravimetric grid. The main goal is to check the consistency of the initial model (seismic one) under the light of the harmonized gravimetric and petrophysical information. Joint 3D forward and inversion modelling procedures were applied by means of Oasis Montaj software.

3 HARVESTING OF EXISTENT INFORMATION

3.1 Gravimetric data

3.1.1 Germany (LUNG and LBGR)

3.1.1.1 Surveys and data base

The gravimetrical data from LUNG and LBGR come from two major sources:

- Base network and regional surveys (1960-1975; State Gravity Network SGN76 of the former GDR)
  - base network: irregular mesh, stations of 1st to 3rd order (point spacing: 1st order ≈ 50 km, 2nd ≈ 15 km, 3rd ≈ 5 km)
  - regional surveys: irregular mesh, points of 4th order, spacing ≈ 1,5 km (0,8 points/km²)

The area of Brandenburg (including the Eastern parts of Berlin) and Mecklenburg-Western-Pomerania is completely covered, except greater water areas (large lake, lagoons and offshore areas of the Baltic Sea). The base network was reorganized 1994-2001 (German Gravity Network, stations of 1st and 2nd order). The old data exist digitally in databases and were connected to the new German Gravity Network.

- Refined/semi-detailed surveys and exploration campaigns
  - irregular meshes, point spacing ≈ 500m (3-4 points/km²)
  - larger gaps exist (military properties, lakes)

Table 3-1 document the campaigns that were used in the German part of the study.

Table 3-1 Semidetailed gravimetrical surveys/campaigns in Eastern Germany used in this study

Survey/campaign	Year
Greifswalder Bodden	1970
Stralsund-Lütow	1970
Röbel/Neubrandenburg	1972
Randgewässer Usedom	1973
Usedom Land	1973
Jarmen	1974
Pasewalk-Penkun	1975
Lychen	1975
Eberswalde	1977
Frankfurt/Oder (incomplete)	1986

Data exist only on paper in various formats (primary measurement reports, compiled maps of Bouguer anomalies 1:50.000, 1:100.000, 1:200.000). The data are partially incomplete. Available primary measurement reports were digitized during the GeoERA-project at LBGR and LUNG. The data are not connected to the new German Gravity Network and have to be reprocessed (see 3.1.1.3 and 4.1.1).

Finally, a heterogeneous data distribution exists for project area on the German side (Figure 6). The analyses of the gravimetrical data and the compilation of a Bouguer map were done in a greater area than the 3D model in order to have a buffer region for the gravimetrical modelling (also at the Polish side). In the frame of the harmonized 3D model all semi-detailed surveys were used if the data are available (station density <0,2 km²/station to 0,7 km²/station). The gaps of the semi-detailed surveys were filled with regional data (density 0,7-2 km²/station). Gaps exist still in the Szczecin Lagoon and Baltic Sea. Here only compiled Bouguer maps from the 1980s were available. These maps were not used because 3D model was primarily developed for the onshore-areas. A connection of the onshore data with off-shore satellite data (Sandwell et al. 2014, data from https://topex.ucsd.edu/marine_grav/mar_grav.html) was not successful and showed large discrepancies and implausible anomalies.

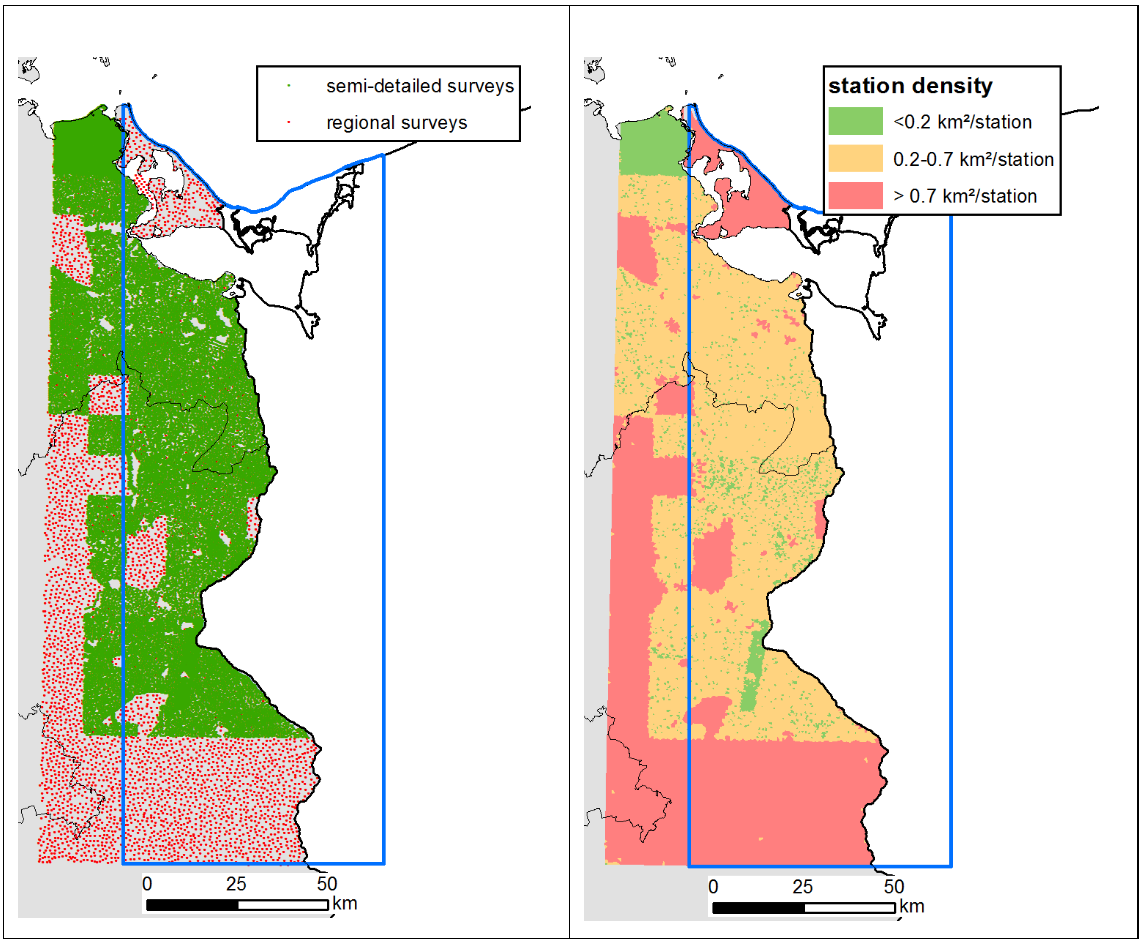


Figure 6: distribution (left) and density (right) of the German gravimetrical stations in the project area. Semi-detailed data (station density <0,2 km²/station up to 0,7 km²/station) and regional data (0,7-2 km²/station). Blue line: area of the harmonized geological 3D model auf 3DGEO-EU, WP2

3.1.1.2 Measurements and accuracy

The following measuring devices were used from the 1960s to the 1980s:

- Askania - gravimeter (GS 8 and GS 11)
- Sharpe - gravimeter (CG-2)

- Sodin - gravimeter (W 410)
- La Coste & Romberg - gravimeter (Model D)

The measuring accuracy ranges from ± 0,014 to ± 0,040 mGal depending on the device. The measurements include a correction of the gravimeter drift and tidal effects.

The topographic height was levelled in the field and related to Normal Sea Level (Amsterdam). The uncertainty is between <0,03m (stations 1st order) up to <00,25 m (stations 4th order) (Sommer et al., 2004).

The geographic position of the points of semi-detailed surveys were not measured in the field but were manually recorded in topographical maps 1:25.000. An uncertainty up to 75 m is estimated (especially in forest areas). Additional uncertainties (up to ≈ 25m) result from the digitizing of the points from these original analog maps (due to the referencing the distorted analog maps and digitizing errors). The total uncertainty in the geographic position of the data points of the semi-detailed surveys might be up to 100 m and more.

3.1.1.3 Processing

The gravimetric data before 1990 were related to the State Gravity Network SGN76 of the former GDR and processed with the following parameters and methods:

Table 3-2: Processing parameters of the gravimetrical data in Eastern Germany before 1990

Gravity datum	Potsdam
Geodetic datum	GRS80/WGS84
Vertical datum	Mean Sea Level (Amsterdam)
Reduction level	0 m NN
Normal gravity	after Helmert (1901)
Free-air correction	0,3086 * h (h = topographic height over Mean Sea level)
Bouguer-reduction	0,04193 * ρ * h (ρ = density = 2,0 * 10^3 kg/m^3)
Terrain correction	empirical estimates for the near field depending on topography and disturbances (buildings, steep local topography), no correction for the far field

After 1990 the base network SGN76 and the regional data were reprocessed by several institutions and authors and connected with the new German Gravity Network (Federal Agency for Cartography and Geodesy (BKG) in the 1990s, Conrad 1996, Skiba et al. 2010). Skiba et al. 2010 include a (far field) terrain correction basing on a 25m DEM. The processing by Skiba et al. 2010 were carried out with a differing density of 2.67* 10^3 kg/m^3 (general approach for entire Germany) so that these data could not be used directly.

A reprocessing and re-evaluation of the semi-detailed data were not published since 1990.

3.1.2 Poland (PGI-NRI)

3.1.2.1 Surveys and data base

Polish gravity data were acquired in many geophysical projects covering the whole Polish territory (over 300 projects and over 1.3 mln gravity points acquired up to the present). All the data are stored in digital form – most of them (about 98%) in the Central Geological Database (CBDG) managed by National Geological Archives (NAG) in the PGI-NRI. Mostly they are state property, however some data sets belong to other owners. Only state-owned data is described below as only these data was used for this study.

In the CBDG gravity data are stored in two digital datasets, named after spatial density of measurement points, with the following characteristics:

- Semi-detailed surveys database: irregular mesh, with average station density of 2.0 up to 10 points/km^2. This dataset covers whole area of Poland and its resolution appropriate and sufficient for the present study
- Detailed surveys database: covers local geological structures, is focused on detailed geological case studies; these measurements were not included in the present investigation.

Table 3-3 lists the campaigns that were used in the Polish part of the study.

Table 3-3 Semi-detailed gravimetrical surveys/campaigns in Poland used in this study

Campaign	**Instrument**	**Year**
Semi-detailed surveys, coordinates: Borowa Góra, transformed to 1942 coordinate system with irregular error (up to several hundreds of meters)		
Antyklinorium Pomorskie	Sharpe	1972
Gorzów-Jarocin	Sharpe	1972
Niecka Szczecińska i zewnętrzna strefa Monokliny Przedsudeckiej	Sharpe	1972
Kamień Pomorski	Sharpe	1973
Zalew Szczeciński	Sharpe	1975
Synklinorium Szczecińskie	Askania GS-11; Sharpe	1962

The final project data on the Polish side are shown in Figure 7. The analyses of the gravimetrical data and the compilation of a Bouguer map were done in a greater area than the 3D model in order to have a buffer region for the gravimetrical modelling. All data come from semi-detailed surveys (station density <0,2 km^2/station to 0,7 km^2/station). Gaps exist in the Szczecin Lagoon and Baltic Sea and onshore in lake/swamp areas. Off-shore data are available but not used in this case study.

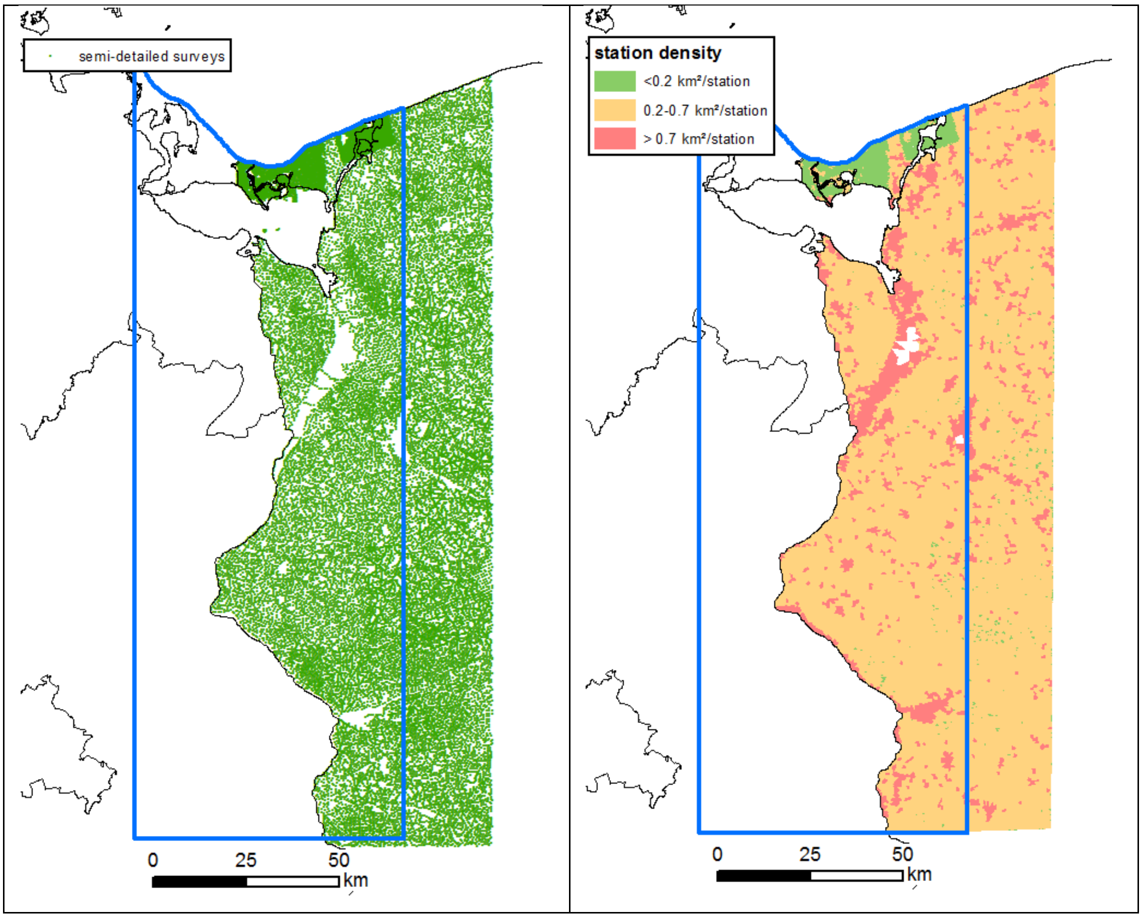


Figure 7: distribution (left) and density (right) of the Polish gravimetrical stations in the project area. Semi-detailed data (station density <0,2 km²/station up to 0,7 km²/station). Blue line: area of the harmonized geological 3D model auf 3DGEO-EU, WP.2

3.1.2.2 Measurements and accuracy

The following measuring devices were used in campaigns listed above:

- Askania – gravimeter (GS 11)
- Sharpe – gravimeter

The measuring accuracy of gravity force acceleration g was ±0.030 mGals (after introducing drifts and tidal correction).

The height/elevation of the gravity station was obtained from leveling measurements (normal height above MSL referred to Kronstdt60 height datum applied in Poland). The precision of the gravity stations leveling and elevations determination is better than ±0.05 m.

Primary coordinates datum for gravimetric surveys is Borowa Gora (BG), introduced for use in 1925 as the Polish National Datum (PND1925), currently out-of-use. In the case of gravity survey this system was obligatorily applied up to 1992 but in a practice up to 1995.

After 2005, coordinates of all gravity stations were transformed from BG system to PL CS92 system via Pulkovo42 system. Up to 2005 the semidetailed gravity stations coordinates were designed in precision better than ±50 m by the digitalization of the stations location drawn on documentary maps in scales 1:50k or 1:25k.

3.1.2.3 Processing

The absolute value of the gravity force acceleration at the gravity station location was related to the Potsdam gravity datum *(G_ABS_PIG62).* The values were designed by tying up gravity measurements to the official Polish state gravity network PIG62, which was linked to the Potsdam gravity datum via international fundamental points in Warsaw-Potsdam-Prague. At the PIG62 base stations net the errors of the gravity absolute values determination oscilate ±0.039÷0.070 mGal after net adjustment.

The absolute value of the gravity force acceleration at the gravity station location was recalculated in the reference to IGSN71 gravity datum (*G_ABS_IGSN71*) using the formula:

G_ABS_IGSN71 = G_ABS_PIG62 – 14.00 mGal

3.2 Petrophysical data

3.2.1 Germany (LUNG and LBGR)

The petrophysical data stem mostly from the 1960s to 1980s. Data of rock density data are documented in several ways:

a) core data
   Core data were the major source for density information in Eastern Germany. Only a few wells were sampled over the entire drilled sequence (Figure 8, example from Cretaceous to Bunter Sandstone). Usually only intervals of interest were investigated (since the 70s and 80s especially the Permian and Pre-Permian succession, Mesozoic data stem mostly from the 60s).
   Density data basing on wire line data (gamma-gamma/RHOB-densities as on the Polish side) are not available in the investigation area at the time.
b) density-depth functions
   Generalized relationships/correlation functions between stratigraphy, lithology and depth were developed based on core data for the eastern part of the North German Basin (Kopf 1967, Krauss 1972, Köhler & Eichner 1973).
c) litho-stragraphic density logs
   Synthetic density logs for wells based on lithology, core data and empirical relationships between density-lithology/stratigraphy-depth. Wire line logs (gamma, resistivity) were considered for defining lithologies.
d) density averages for stratigraphic units
   Averaged densities for stratigraphic units on different scale (Eratherm, Series, Stage) calculated from a), b) and c). For the Zechstein succession averaged densities were calculated additionally based on the proportions of the lithological components (rock salt, anhydrite, dolomite, clay) and density data for the components.

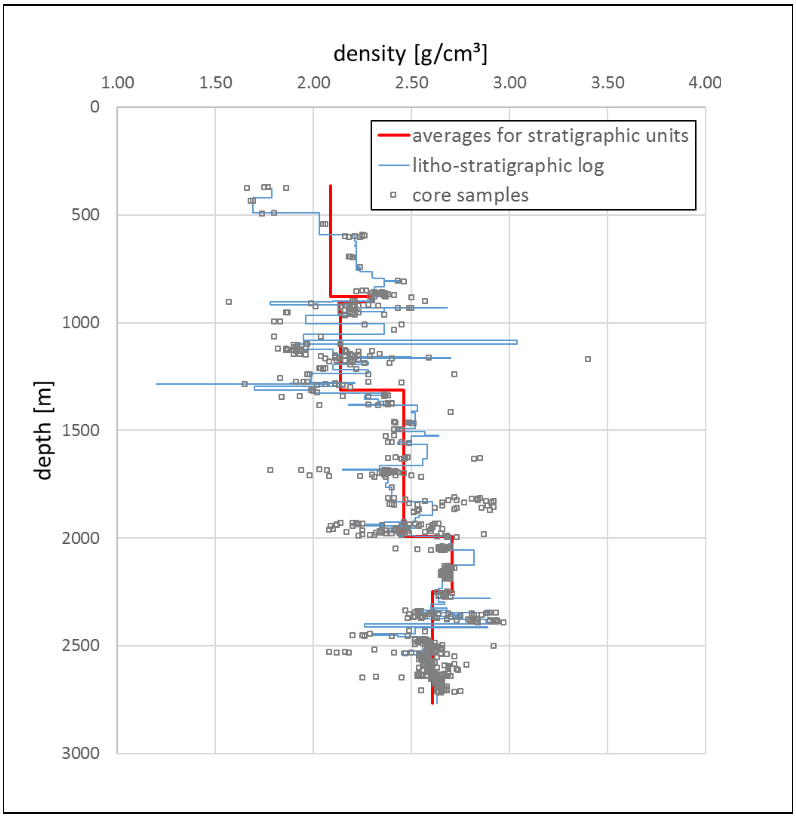


Figure 8: petrophysical data (density) in Eastern Germany. Example from one well (Mesozoic strata from Cretaceous to Lower Triassic):

- *core data,*
- *litho-stratigraphic log (based on core data, lithology and empirical relationships),*
- *averages for stratigraphic units (based on measured data and empirical relationships)*

Different kind of rock densities were measured and documented in the petrophysical data sets: dry density, wet density, saturated density, grain density. For the in-situ density always the saturated density was measured or calculated based on corrections charts (saturated with pore water with seawater-density 1,03 g/cm³). These saturated densities were used for the gravimetrical modelling. Averaged densities per well where calculated from the data c) and d) and used as input data for spatial interpolations for the horizons. Data from 33 wells are available in the investigation area (Figure 9).

3.2.2 Poland (PGI-NRI)

The petrophysical data stem (similarly as in Germany) mostly from the 1960s to 1980s. Data of rock density are documented as laboratory measurements at core samples or well-logging densities.

There are 16 boreholes with datasets of core density measurements (plus 3 wells with estimated core densities). Cores were sampled appx. every 25 cm, however in case of long intervals of uniform lithology, the sampling was less frequent. Core samples (30 cm^3) were saturated by the 1g/cm^3- dense fluid. All archive data were digitized by PBG (*Geophysical Exploration Ltd.*) and additionally worked out by Rosowiecka and Królikowski (2014). Lithology and stratigraphy was assigned to each sample, and the average values for each lithological interval were calculated.

Some more statistics (histograms, standard deviation) were calculated for the set of 14 boreholes, for each stratigraphy used in 3D density model.

Locations of these boreholes are shown in Figure 9.

Density data from g-g wire-line logs (RHOB logs) were collected from the database in 133 wells used for 3D modelling of the Gorzów Block in NW Poland, 78 of which fall into the extend of 3DGEO-EU project area (Figure 9). The profiled depth and quality varied significantly and for each particular litostratigraphic formation well logs were selected to represent rock density without error data. The table below shows number of wells used for exporting data for density modelling.

Formation	Number of wells with gamma-gamma wire-line data
Cenozoic	59
Cretaceous	105
Upper Jurassic	23
Middle Jurassic	78
Lower Jurassic	112
Upper Triassic	108
Middle Triassic	109
Lower Triassic	108
Zechstein (Stassfurt and above)	124
Zechstein (Werra)	125

Data from RHOB logs were used in 3D parametric model of the Gorzów Block along with stratigraphy, lithostratigraphy and lithology. Each cell of the grid had assigned litostratigraphic data, which were used in modelling of density distribution separately for each formation. The 3D density model was a base to calculate average density maps for each formation and those were used in further steps of harmonization.

3.2.3 Joint database for the density model

Figure 9 shows a very heterogeneous database for rock density:

Western Poland, PGI-NRI :

- gridded data with spacing of 500m: density model for the Gorzow block (in this region only the gridded data were used) – based on RHOB-logs of wells
- averaged well data based on cores especially in the north (19 wells),

Eastern Germany, LBGR and LUNG:

- averaged well data based on core measurements (33 wells)

Also data outside of the model area (up to a distance of 25 km) were used to support the interpolation and minimize data gaps. Some regions have a relatively dense data covering but also big data gaps exist especially in the middle and the southwest of the harmonization area.

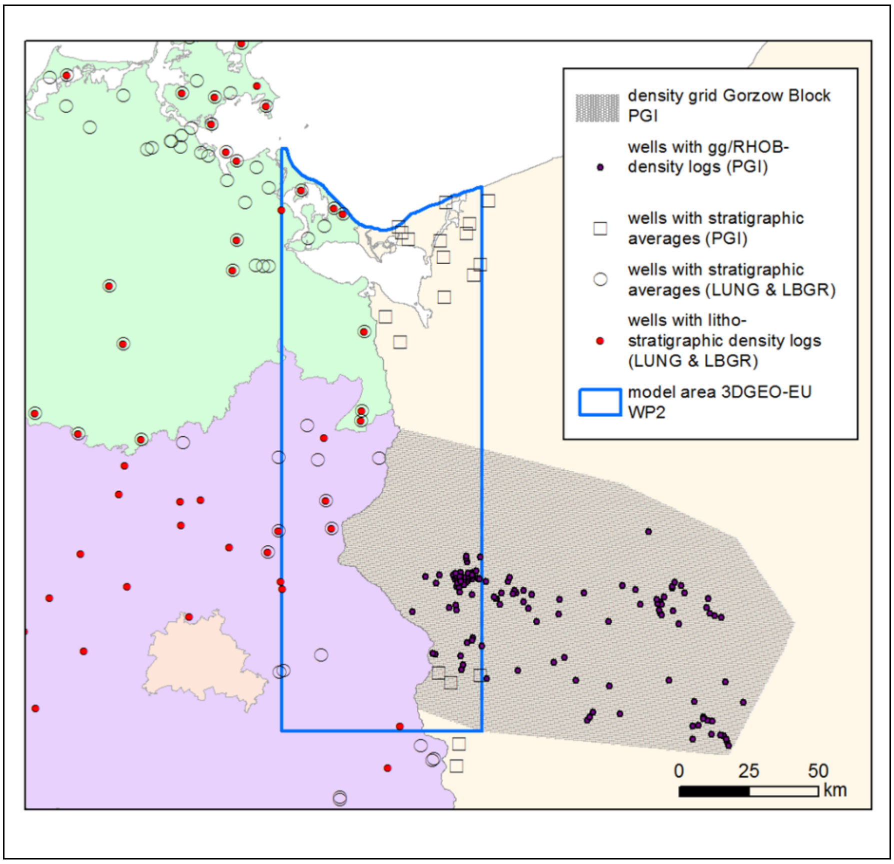


Figure 9: Wells with different density data used in the project.

3.3 Summary data base and harvesting

Comprehensive data exist at all partner institutions that allow gravimetrical and petrophysical analyses of the model area. The data were partially analog and had to be digitized in the frame of the GeoERA project, especially those from the German side (LBGR and LUNG: semi-detailed gravimetrical surveys, petrophysics). In detail, the data are still incomplete and had to be replaced by other information. In parts of the model area the data distribution is currently still heterogeneous with a varying spatial resolution. But the seismic and well data gaps (Figure 2) could be generally closed with gravimetrical data with high spatial resolution (spacing ≈500m). Data from the Szczecin lagoon and Baltic Sea are available but were not compiled and used during this project.

The exchange of primary data between the German and Polish side is restricted by laws (industrial data can internally used but not freely distributed). Only a minor amount of German primary material (e.g. regional gravimetrical data, petrophysics from a few of scientific drillings) could be provided The joint data analyses and harmonization had to be done with:

- anonymized data (e.g. data without coordinates)
- averaged data (e.g. density data from wells)
- interpolated data, e.g.
  - density grid of the Gorzow block
  - Bouguer map at the Polish side

4 CROSS BORDER HARMONIZATION OF DATA

4.1 Bouguer and residual anomaly maps

4.1.1 Harmonized processing

4.1.1.1 Germany (LUNG and LBGR)

The major tasks in harmonizing the gravimetrical data sets was the new processing of the semi-detailed data in Germany and the application of a harmonized terrain correction to all German data. The parameters and methods given in Table 4-1 were applied. The methods and parameters were used to be consistent with other Federal German States.

Table 4-1: Parameters for the reprocessing of the gravimetrical data in Eastern Germany

Gravity datum	International Gravity Standardization Net ISGN71
Geodetic datum	GRS80/WGS84
Vertical datum	Mean Sea Level (Amsterdam)
Reduction level	0 m MSL
Normal gravity	after Moritz (2000)
Free-air correction	after Heiskanen & Moritz (1967)
Bouguer-reduction	after Cogbill (1979) (reduction density 2.00*10^{-3} kg/m³)
Terrain correction	Terrain correction of the regional data from Skiba et al. (2010) were corrected to a density of 2 g/cm³ (Skiba et al. used 2,67 g/cm³) and interpolated to the semi-detailed data (with a geostatistical co-kriging approach using a 25m DEM as a Co-variable).

4.1.1.2 Poland (PGI-NRI)

Digital datasets were already available in Poland, so the major task was to agree on data processing, carry it on and verify the results. Choosing the right density for Bouguer correction was done by reviewing the density data available in shallow wells and some trial-and-error exercises with different densities to verify best fit and least topographic residuals in data. The parameters in Table 4-2 were used for processing the data.

Table 4-2: Parameters for the reprocessing of the gravimetrical data in Poland

Gravity datum	International Gravity Standardization Net ISGN71
Geodetic datum	GRS80/WGS84
Vertical datum	Mean Sea Level (Kronstadt60)
Reduction level	0 m MSL
Normal gravity	after Moritz (2000)
Free-air correction	0.3086 mGal/m * h mean correction (calculated at 45 deg latitude) where h is gravstation elevation above MSL
Bouguer-reduction	0.04193 * ρ * h where: ρ – density of Bouguer slab = 2.00*10^{-3} kg/m^3 h - gravstation elevation above MSL in meter
Terrain correction	$g_{tcor} = g_{tcor(0\text{-}100m)} + g_{tcor(100\text{-}1500m)}$ Terrain corrections were calculated at each gravimetric station as gravity force produced by terrain surface undulations within the circle area at 1500 m radius. Such calculations were performed in two circle

	zones: 0 – 100 m based on Lidar DEM 10x10 m and 100 – 1500 m radius based on official state DEM 100x100m. The final value was the sum attraction of gravity masses located within each zone. The undulations density taken into calculation was equal 2.00*10^3 kg/m^3

4.1.1.3 Comparison of the Processing

Cause of the slightly different processing 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 can be neglected in a joint Bouguer map.

4.1.2 Harmonized map of Bouguer anomalies

4.1.2.1 Approach

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.

4.1.2.2 Results

The resulting harmonized cross-border Bouguer map is shown in Figure 10. 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.

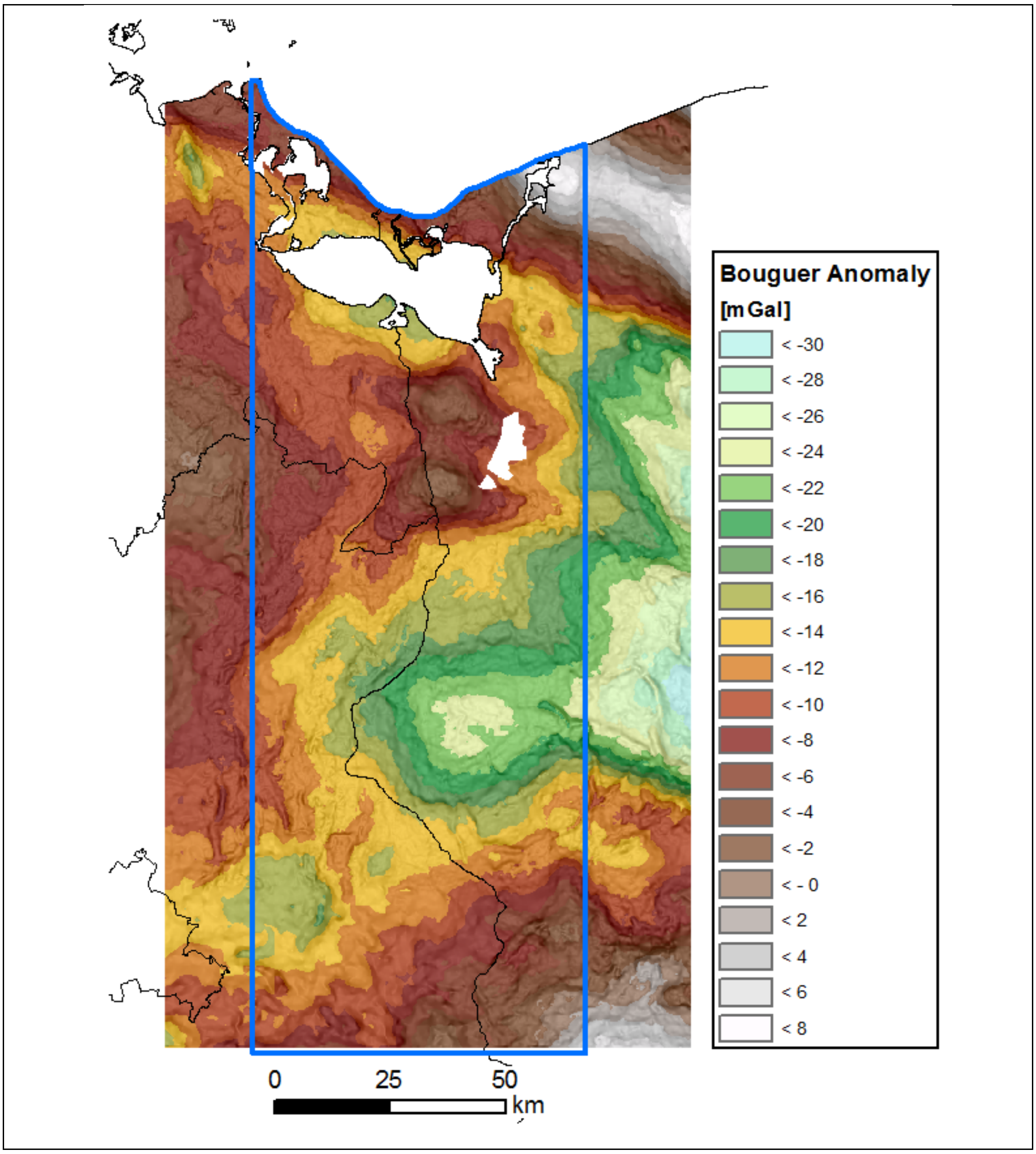


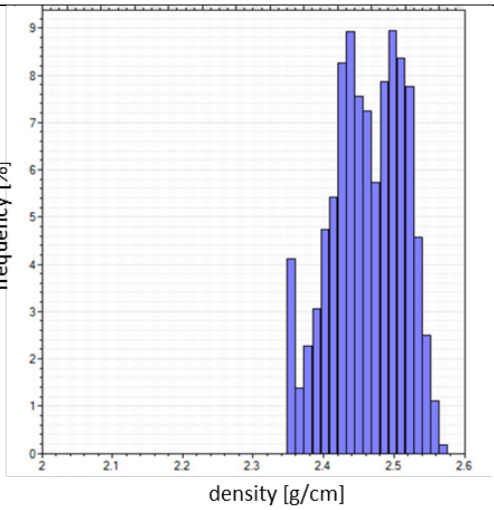
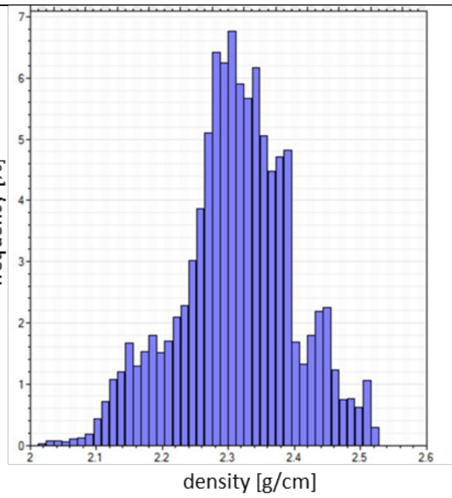
Figure 10: Final harmonized cross-border map of Bouguer anomaly

4.2 Joint petrophysical synthesis

4.2.1 Data analysis

An exchange of primary well data between the German and Polish project partners was not possible because of legal restrictions. The data could be exchanged only in an anonymized way (log data without coordinates), as averaged well data and as interpolated data. A comparison of the data was carried out in the following way:

In a first step both sides provide own spatial interpolations for the density as gridded data (Figure 11, 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 care measurement	*Histogram density data Upper Triassic (gridded data) Gorzow Block , Poland (PGI) – based on gg-logs*
	

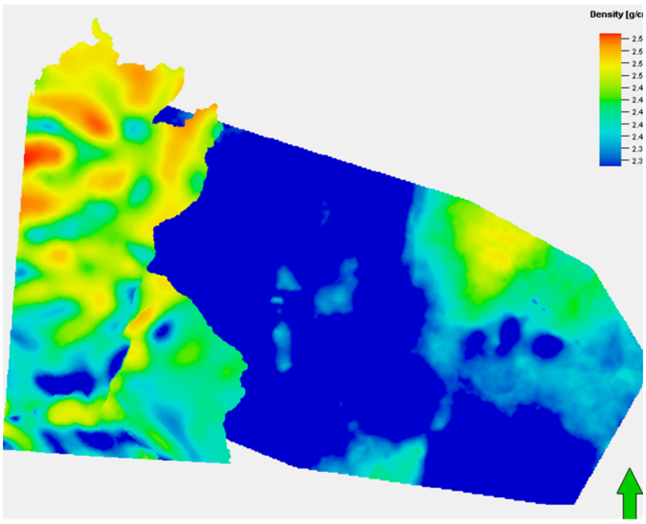


Figure 11:

Above: histograms of gridded density data of LBGR and PGI (Gorzow block model); gg = gamma-gamma

Left: Spatial distribution of the density in the Upper Triassic in Eastern Brandenburg, Germany (left) and Gorzow Block, Poland (right) initial interpolation on both sides

In a second step averaged well data and anonymized and averaged log data were plotted against the depth of each litho-stratigraphic layers in order to analyze the differences and compare density-depth-relations (Figure 12, example Upper Triassic and Lower Triassic). The densities based on core data in eastern Germany for the Layers Cretaceous to Middle Triassic are higher than the Polish data and also the density-depth-trends differ (especially at lower depths up to 1500m). The German data (based on core measurements and empirical density depth functions) represent only the higher range of density values compared to Polish data (based on gg-logs). The differences generally decrease with the density and depth. For the Lower Triassic the German and Polish data are comparable (Figure 12, right).

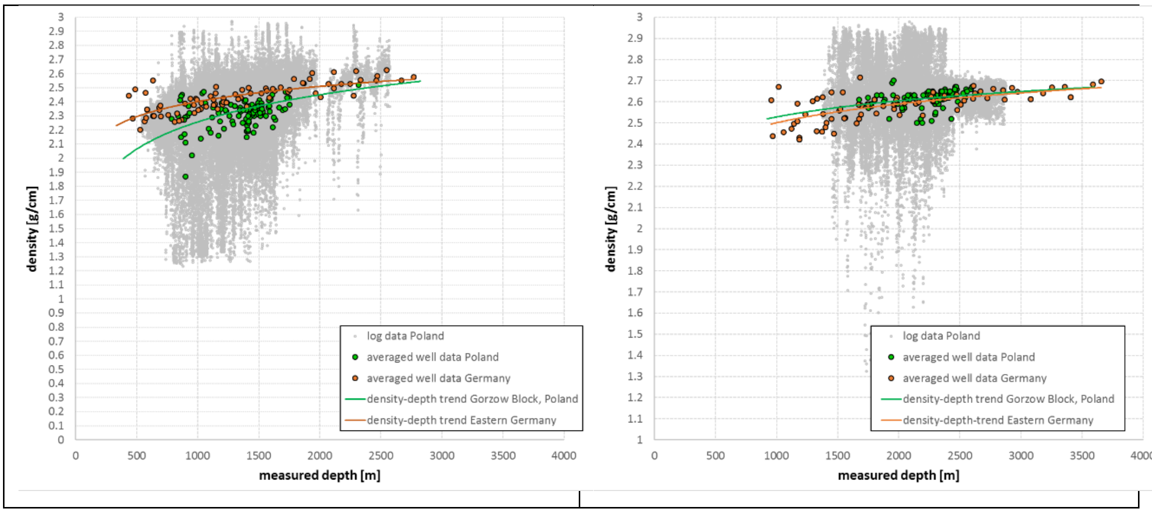


Figure 12: Density-depth data and trends for the Upper Triassic (left) and lower Triassic (right) – anonymized log data from Gorzow Block Poland (original and averaged) and averaged well data from Germany and Poland, interpolated (logarithmic) density-depth trends basing on the averaged data

The comparison of the data shows:

- different source of the density information:
    - Germany and northern Poland: stratigraphic averages based on core data, density-depth relations and lithostratigraphic interpretations
    - Poland, Gorzow Block: direct measurements based on gg-logs
- different results:
    - densities in Germany represent only the higher range of density values comparting to Poland
        - the data do not fit at the border
    - density differences decrease with depth and density
        - for the horizons at large depth with high densities the values are comparable

Possible causes for the differences between the data are:

a) Effects of the gg-measurement

- For several material the gg-density rho$_{gg}$ differs from the real (mass) density rho$_{mass}$. The gg-measurement is based on the scattering of photons by electrons in the atomic shell. The key parameter is the electron density of the material (proportional to the number of protons Z). The mass density rho$_{mass}$ is proportional to the atomic mass (protons + neutrons A). For the most rock-forming minerals is $Z/A \approx 0,5$. But some substances show significant different values:

  e.g. halite, barite: $Z/A < 0,5$ and rho$_{gg}$ < rho$_{mass}$

  e.g. gypsum, water, oil: $Z/A > 0,5$ and rho$_{gg}$ > rho$_{mass}$

  gg-devices are usually calibrated to a Z/A ratio = 0,5. For material with different Z/A-ratios other calibrations have to be used.

Figure 12 shows the gg-density for a Zechstein succession containing halite and anhydrite. The gg-density of anhydrite is correct (2,9 - 3,0 g/cm³), the density of halite (2,1 - 2,2 g/cm³) is underestimated in the gg-measurement.

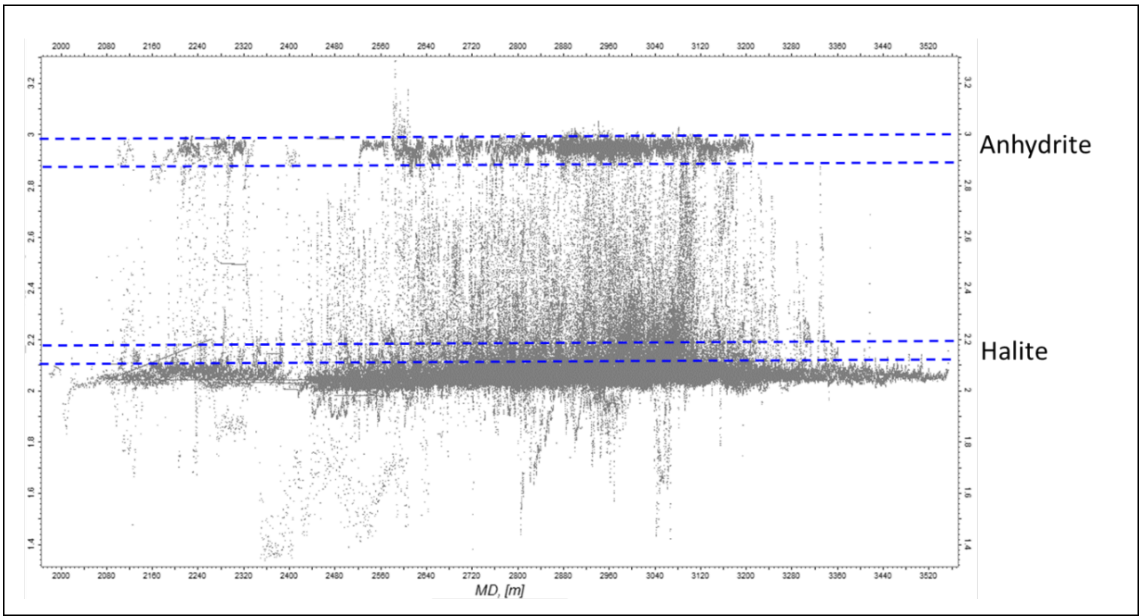


Figure 13: Example of gamma-gamma-densities in the Zechstein succession in comparison to mineral densities

b) biased density-depth relations
   - Problem: only core samples were investigated – not all parts of the borehole could be sampled - weak areas, areas with a core loss are not represented

   Cores come from hard and stable parts of the well bore column. Weak material is disturbed or destroyed due to drilling and to relaxation of the core cause of pressure reduction. Core data are representative for the hard and stable parts of the column and have higher densities cause of lower porosities in comparison to the weak parts of the strata.

The effect of the biased core data and the biased density-depth relations play a role for the German data for the Mesozoic layers (Cretaceous to Triassic). The effect of the gg-density plays a role for the gg-densities of the Gorzow Block data in the Zechstein succession.

4.2.2 Data harmonization

For the layers Cretaceous to Triassic the German density data were corrected with a depth-depending function based on the density-depth trend for the Gorzow Block (see Figure 12).

The corrected German data are comparable to the Polish averaged gg-data (Figure 14). A new interpolation at the German side fits very well at the border (Figure 15, compare Figure 11).

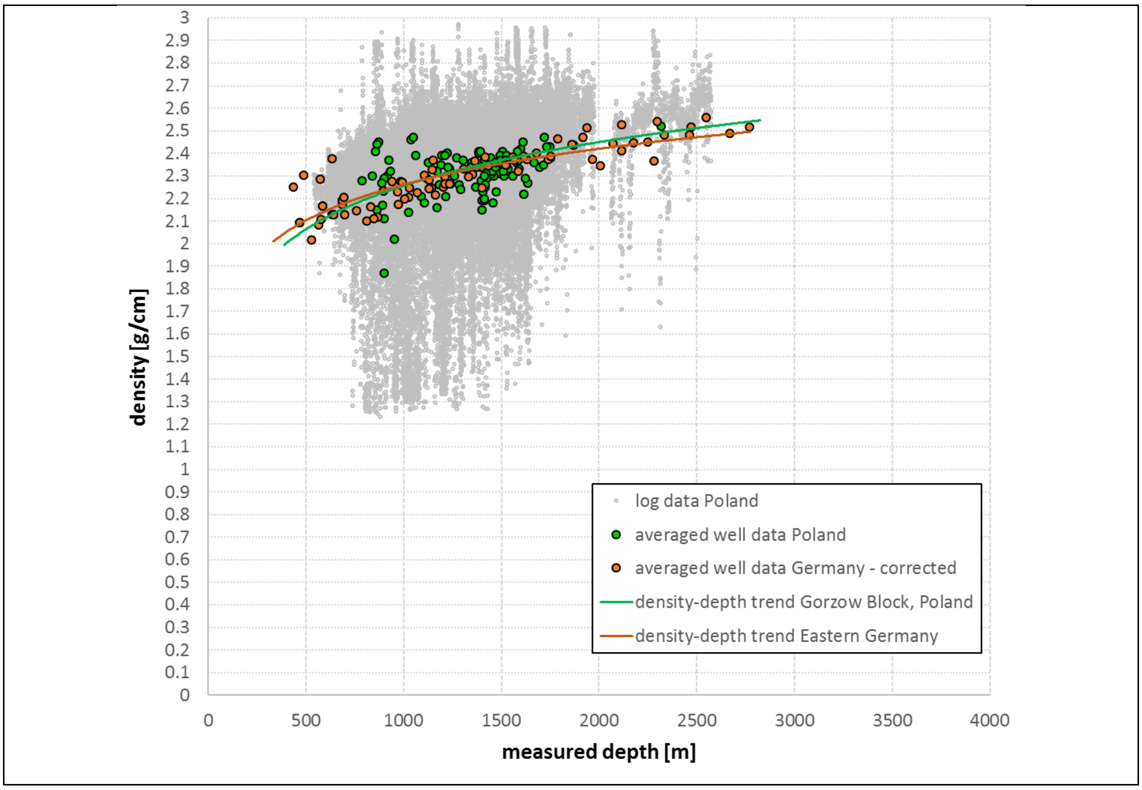


Figure 14: Density-depth data and trends for the Upper Triassic – anonymized log data from Gorzow Block Poland, corrected well data from Germany and Poland, interpolated (logarithmic) density-depth trends basing on the averaged data

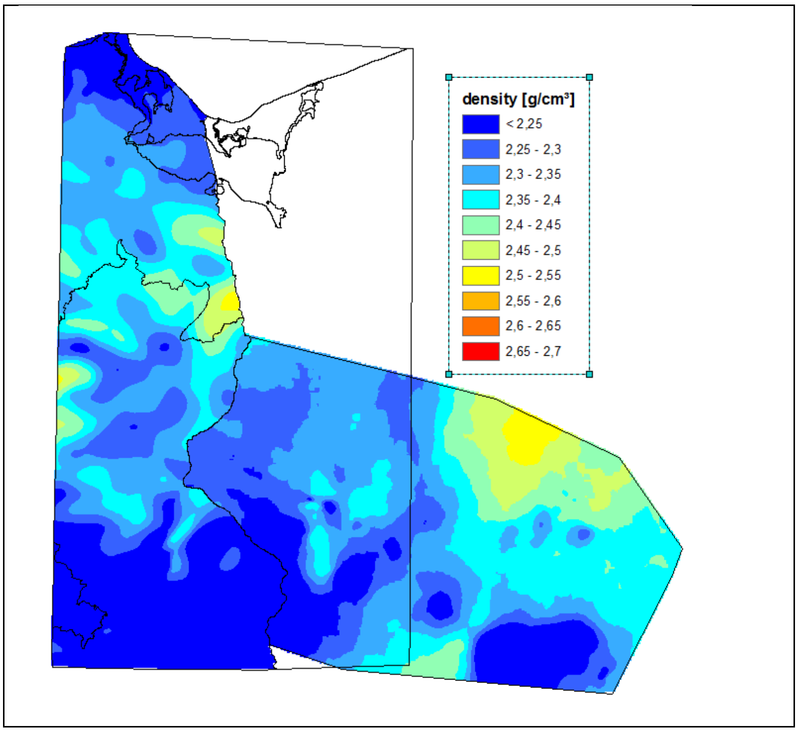


Figure 15: Spatial distribution of the density in the Upper Triassic. (Separate) interpolation for Eastern Germany (left, corrected density data) and Gorzow Block, Poland (right)

The same approach was used for the other horizons. For the Zechstein salt the thickness were used as a Co-variate instead of the depth because the density is negative correlated with the thickness (reason are halokinetic processes: the enrichment of light halite in salt pillows and diapirs and the enrichment of the heavy anhydrite, carbonate and clay in regions of salt depletion).

4.2.3 Joint petrophysical model

4.2.3.1 Approach

As mentioned the primary data could not be exchanged because of legal restrictions. In order to obtain harmonized data for the entire model area different data had to be used (see Figure 9):

- gridded data of the Gorzow Block from PGI in the southeast (based on RHOB-logs)
- stratigraphic averages from well data in the rest of the area (based on cores and litho-stratigraphic interpretations)

The spatial distribution of the data is very heterogeneous and large data gaps exist (Figure 9). To overcome this problem 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 the thickness of the layer was use as Co-variable). The geometries of the harmonized 3D model were used for depth and thickness, which are available for the entire model region (chapter 1). 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). Nethertheless, 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.

4.2.3.2 Results

<u>Density model of the layers Cenozoic to Basal Zechstein</u>

The interpolated harmonized densities for the model layers are shown in Figure 16. A statistical evaluation of the results is presented in Table 4-3 and Figure 17.

Despite the great differences in the primary data, the existing data gaps and the problems with the data exchange it was possible to develop harmonized density models for the entire investigation area. Small discrepancies at the border exist only for the Basal Zechstein were at the Gorzow Block higher amounts of Werra salt might exist in the succession (resulting in reduced densities of 2.7 to 2.8 g/cm³). This could be analyzed in further investigations. In relation to the overall density trends in depth and stratigraphy, these artefacts are insignificant.

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, typical decrease for the Zechstein and a further increase at the Basal Zechstein (Figure 17).

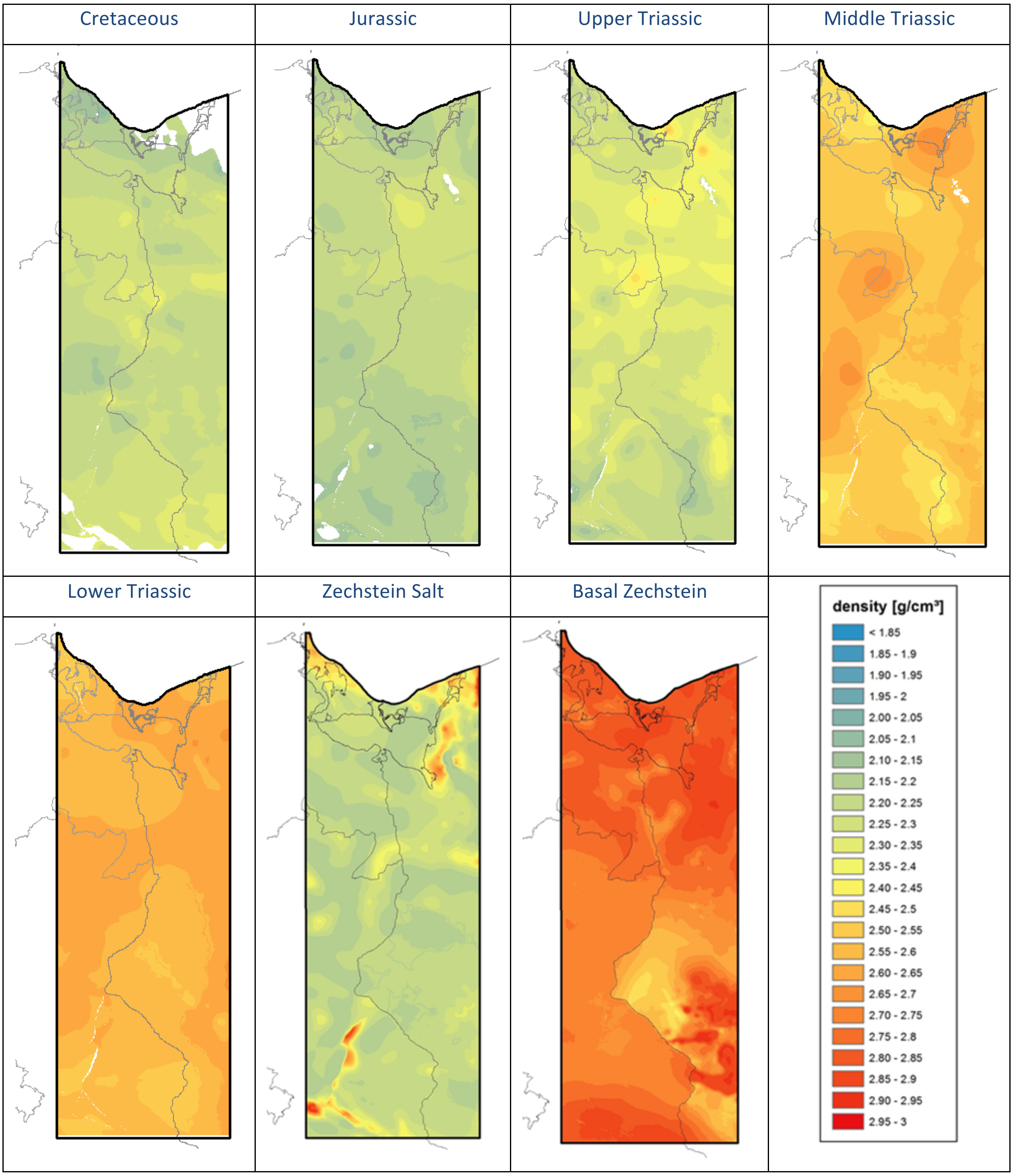


Figure 16: Final density model: spatial interpolation of densities for the layers Cretaceous to Basal Zechstein

Table 4-3: statistics of the density model

Density [g/cm³]	Cenozoic	Cretaceous	Jurassic	Upper Triassic	Middle Triassic	Lower Triassic	Zechstein Salt	Basal Zechstein
average	2.00	2.24	2.21	2.30	2.56	2.59	2.24	2.76
median	2.00	2.23	2.21	2.30	2.55	2.60	2.22	2.77
standard deviation	0.050	0.060	0.055	0.076	0.059	0.029	0.086	0.088

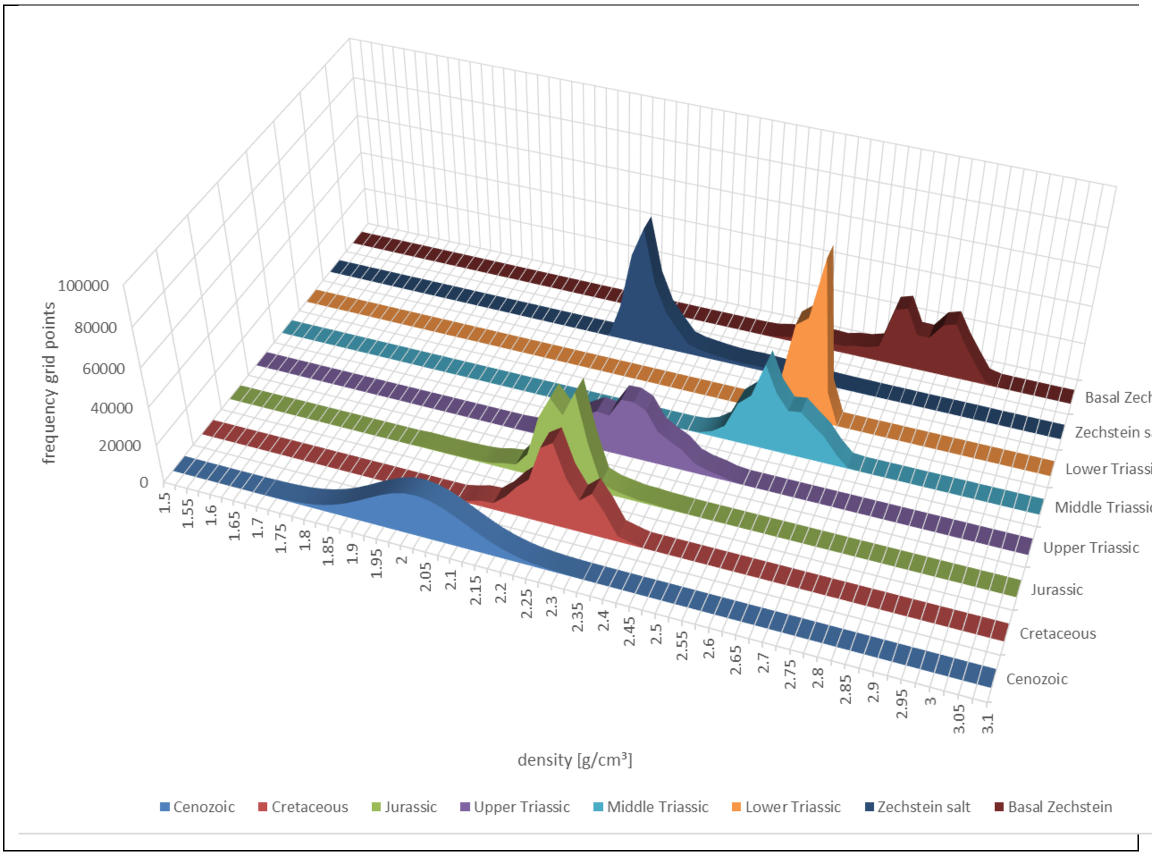


Figure 17: Histograms of the interpolated densities for the model layers

Prominent density contrasts occur at the following stratigraphic borders:

Table 4-4: prominent density contrasts at stratigraphic borders

Stratigraphic border	density difference [g/cm³]	density difference [%]
Cenozoic – Mesozoic	≈ + 0,25	+ 11%
Upper Triassic – Middle Triassic	≈ + 0,25	+11%
Lower Triassic – Zechstein salt	≈ - 0,35	-13%
Zechstein Salt – Basal Zechstein	≈ + 0,5	+23%

Preliminary model for the Pre-Zechstein succession

For the structure below the Zechstein estimates were used:

Table 4-5: model structure of the Pre-Zechstein succession

depth below the base of Zechstein [km]	Lithology	averaged density [g/cm³]
6	Paleozoic sediments and volcanics (acidic)	2.65
15	Proterozoic crust (volcanics/granites)	2.7
≈ 30	Proterozoic crust(granitic/dioritic)	2.85

The initial depth of the Moho were interpolated basing on the data of Grad et al. (2009).

4.3 Summary data harmonization

A cross-border harmonization of the gravimetrical and density data were possible – but with different success rate.

The gravimetrical data are available in high spatial resolution and are well defined in measuring and processing. They can be harmonized and connected cross-border without any problems (also as interpolated data in high resolution). The used approach (described in section 4.1) was successful.

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
- vintage core data from the 1960s to the 1980s and averages based on these

At one side no logs are available for the wells with vintage core data. At the other side 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. So both kind of data could not be directly compared (especially not for the Mesozoic and the Zechstein salt, see Table 1-1). Additionally the primary data could not be exchanged between the German and Polish institutions and so could not be analyzed in detail.

To overcome the differences it was decided to correct the German 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 log data were regarded to be more reliable. But the Gorzów Block is a special structure (e.g. with very low halokinetic dynamics) and it is not clear whether the relationships can be assigned to the whole model area with different salt layer evolution.

To solve the problems of the restricted data exchange the interpolation was done in a similar way as for the gravimetrical data. At the Polish side a gridding was carried out for the southeastern area of the model (Gorzów Block) and these grids were used together with the lithostratographic averages for the final interpolation in the entire area. The result are harmonized data (with some differences for the Basal Zechstein in the southern part of the model, which are related to different amounts of Werra salt in the succession). The stratigraphic averages and statistics of the density (Figure 17, Table 4-3) and the general density depth trends are plausible, but the spatial distributions (Figure 16) contain a lot of assumptions and uncertainties.

Therefore the density data are the most uncertain and critical parameter of the integrated 3D model. In areas with sparse (or no) seismics usually also a lack of density information occur (compare Figure 2 and Figure 9). Thus, in these regions the gravimetrical data are the only reliable information.

5 ANALYSES OF UNCERTAINTY AND HARMONIZATION OF THE 3D MODELLING AT THE GERMAN/POLISH BORDER USING GRAVIMETRIC DATA

5.1 Power spectra analyses of the Bouguer map

When modelling the upper crust, it is a standard procedure to obtain a residual Bouguer anomaly by subtracting from the Bouguer anomaly a regional (long wavelength) field that reflects the contribution from deeper sources. There are many techniques to obtain residuals (polynomial separation, filtering, upward continuation and so on).

In this study area, the power spectrum analysis of the Bouguer anomaly (Figure 19) indicates that the depth of the causative bodies is located at c. 20 km, so we have decided to carry out the gravimetric modelling using the complete Bouguer anomaly (Figure 18) instead of carrying out the regional-residual separation. This depth suggests that the Bouguer anomaly in this area does not have the contribution of the lower crust-mantle boundary (the Moho).

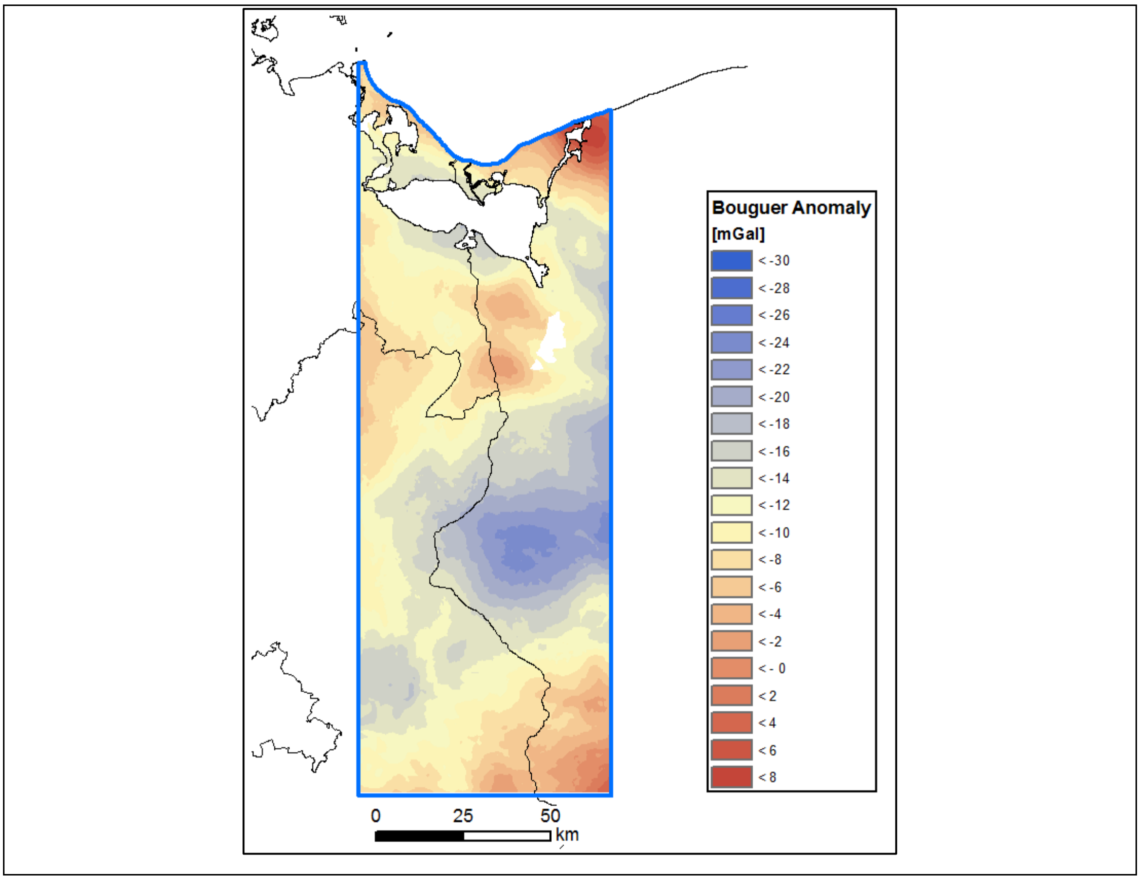


Figure 18: Bouguer anomaly in the model area

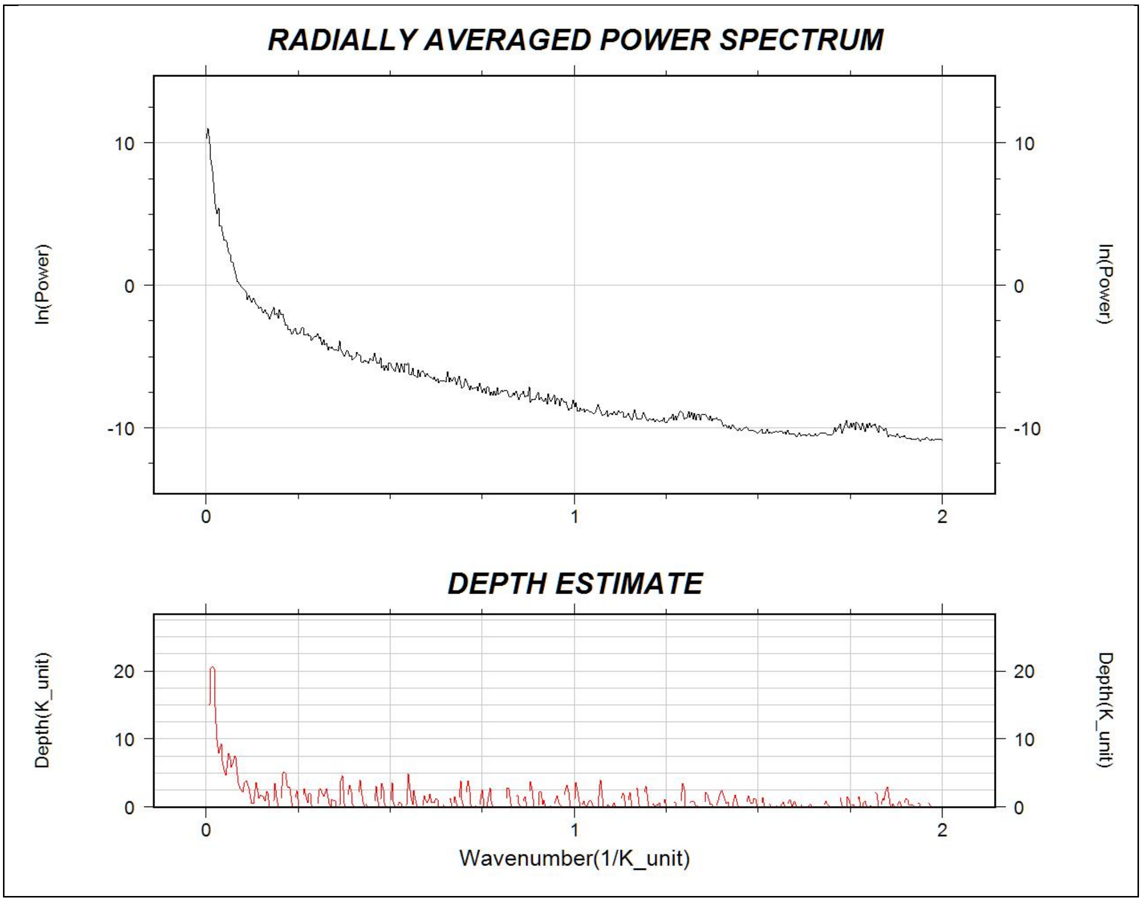


Figure 19: Radially averaged power spectrum of the Bouguer anomaly. The maximum depth of the causative bodies is c. 20 km.

The reason for this is simple: The long wavelength component of the Bouguer anomaly depends on the size of the study area. In this case, 72 km in the W-E direction by 210 km in the N-S direction. The width of the study area acts as a filter “removing” the contribution from deeper sources.

We have built up a model made of 11 layers (Table 1-1: Cenozoic, Cretaceous, Jurassic, Upper Triassic, Middle Triassic, Lower Triassic, Zechstein salt, Basal Zechstein; Table 4-5: Paleozoic and Proterozoic [Proterozoic is not vertically differentiated here]). We have assumed that the geometry is mainly well known from seismic interpretations (except the data gaps see Figure 2) whereas we have bigger uncertainties in the density values due to the inhomogeneous distribution of the data and methodological problems (see section 4.3).

Because this reason, we have developed a different modelling strategy from our usual workflow: We start by a forward modelling, then we analyze the origin of the misfits and then proceed with the inversion. We have carried out the different steps using Oasis Montaj software.

5.2 3D Forward modelling and inversion of the Paleozoic and Proterozoic densities

Forward modelling consists of calculating the gravimetric response of the model using the known parameters geometry and density. The differences between the observed and calculated anomaly (misfits) are shown in Figure 20 A. The misfits are very large and the modelling does not provide a satisfactory result, there is an unacceptable mismatch between the initial model (seismic) and its gravimetric signal (misfit range from -15 to 20).

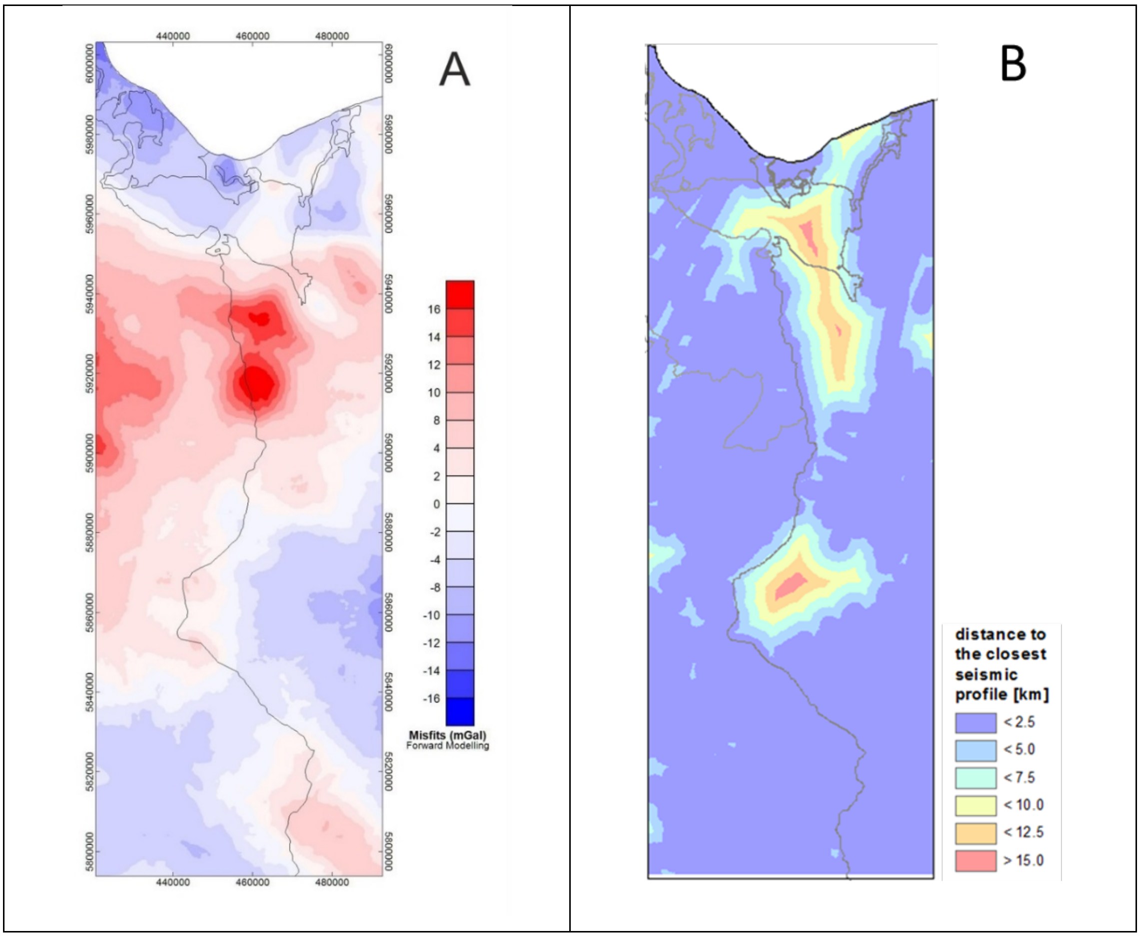


Figure 20: A) Misfits from the Forward Modelling in mGal (difference between observed and calculated anomaly). B) data density of the seismics (distances among 2D-lines)

There are two prominent anomalies in the northern border region with a high positive misfit up to >14 mGal. A positive misfit means that the mass in the initial model is too low either because densities and/or thicknesses of the model layers (from Cenozoic to Basal Zechstein) are underestimated or deeper structures contain additional mass. These anomalies are situated in the northern seismic data gap near the border (Figure 20 B, cf. Figure 2). The misfits in the second data gap in the center of the model area (compare Figure 2) are much lower (-4 … +4 mGal). For this second gap the integrated 3D model of geometries and densities fits roughly the measured gravimetric signal.

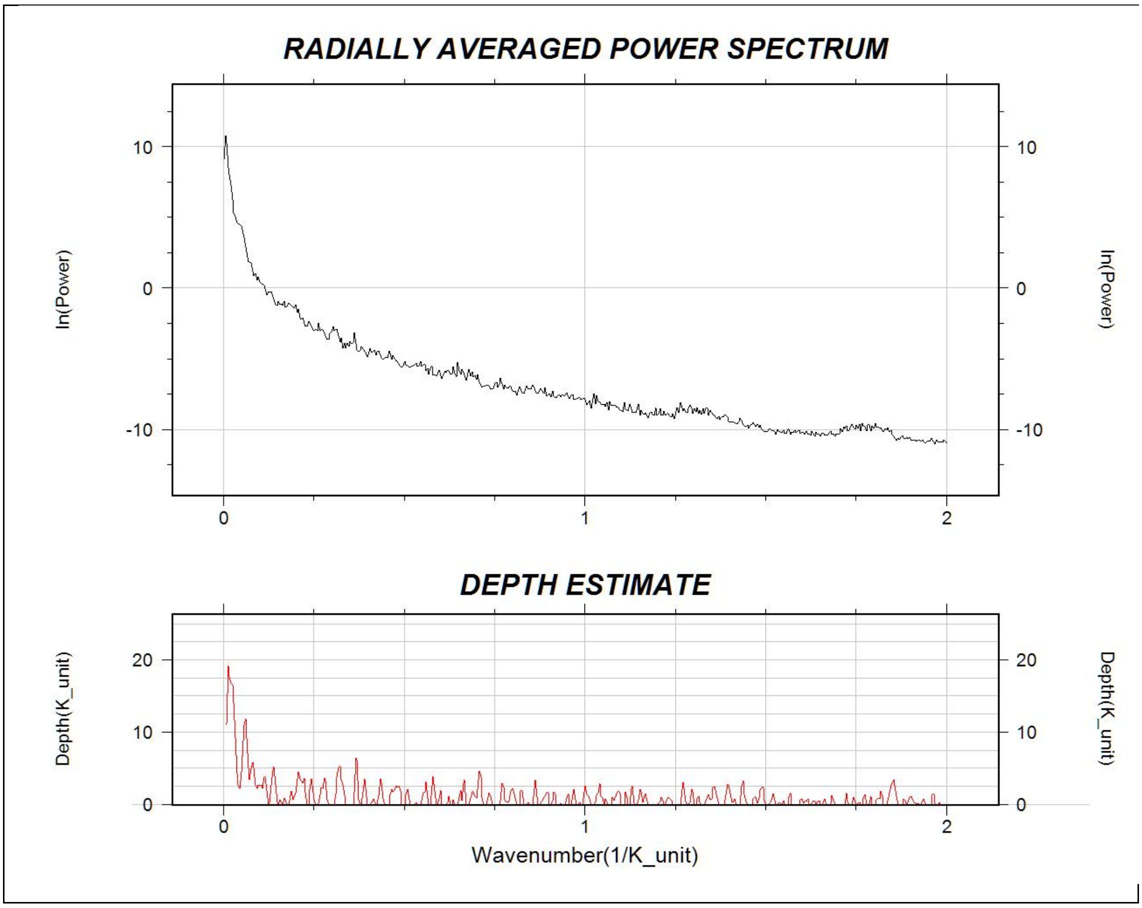


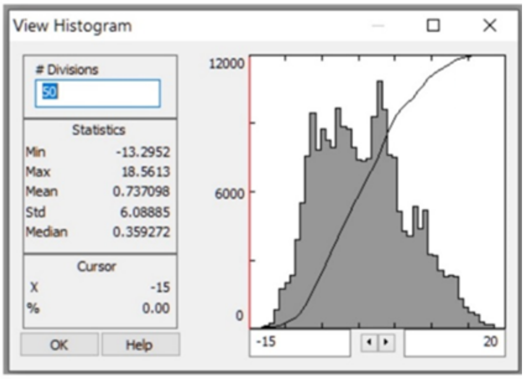
Figure 21: Radially averaged power spectrum of the misfits from the forward modelling. The maximum depth of the causative bodies is c. 18 km.

The power spectrum of the misfits (Figure 21) suggests that these anomalies come from the first 18 km of the crust. Therefore, since the major uncertainties are from the Paleozoic and Proterozoic densities, we have inverted both layers, first the Paleozoic and then the Proterozoic.

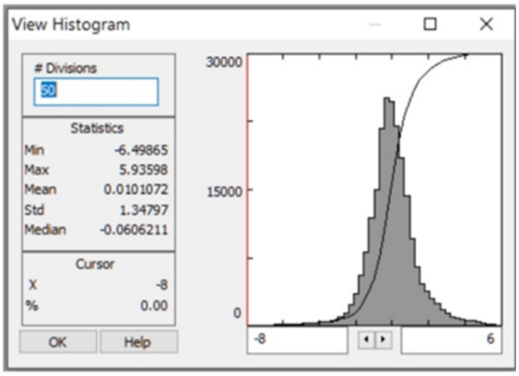
We have done so in two steps:

1. Inversion of the Paleozoic density starting from a constant density of 2.65 g/cm^3 (Table 4-5)
2. From the results of step 1. inversion of the Proterozoic density starting with a constant density of 2.7 kg/m^3

The misfits obtained after the inversion of Paleozoic and Proterozoic are much more satisfactory and range from -8 to 6 mGal (much lower now), being most of them below 2 mGal in absolute value (Figure 22).

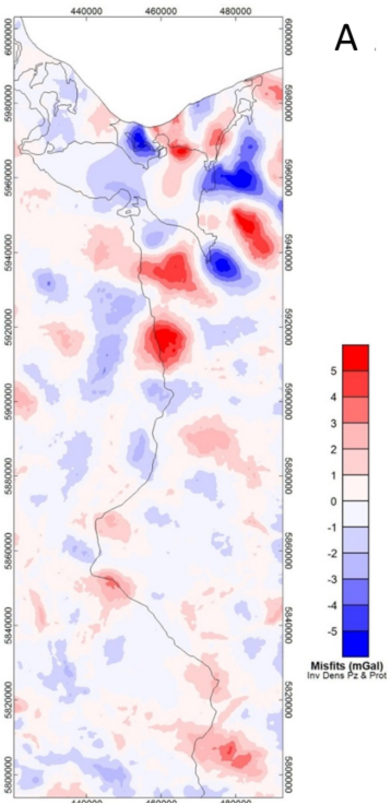


Misfits after forward modelling of the original model



Misfits after inversion of densities of Paleozoic and Proterozoic

Figure 22: Histograms of the misfits after forward modelling (left) and after inversion of densities of (1) Paleozoic and (2) Proterozoic (right)



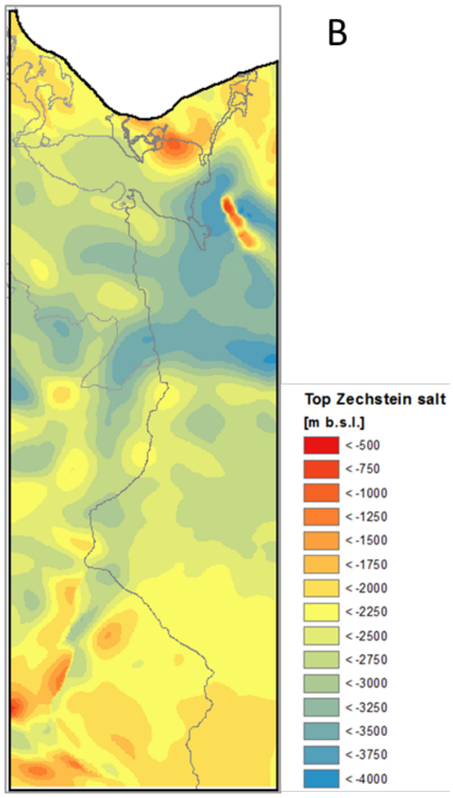


Figure 23: A) Misfits (in mGal) from the inversion of Paleozoic and Proterozoic densities (difference between observed and calculated anomaly). B) Depth of top Zechstein salt/base Triassic

The misfits show short wavelength anomalies (Figure 23 A) that we assume are mainly due to localized and not well-constrained densities and/or thicknesses from the upper layers of the model. Beside the still existing anomalies in the northern border region obtained after the forward modelling (see Figure 20), additional localized maxima and minima occur especially in the northeast with absolute amplitudes up to 6 mGal. They can be correlated to the Goleniów diapir (positive misfit >5 mGal, compare Figure 4) and the surrounding marginal sinks (negative misfits <5 mGal) and to halokinetic structures in the north at the islands Usedom and Wolin close to the Baltic Sea (Figure 23 B and Figure 4).

The resulting Paleozoic and Proterozoic densities are shown in Figure 24. In the regions with a larger misfit of the model (Figure 23 A) 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 be probably attributed to crustal structures with different densities. A further - in depth - interpretation in the frame 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.

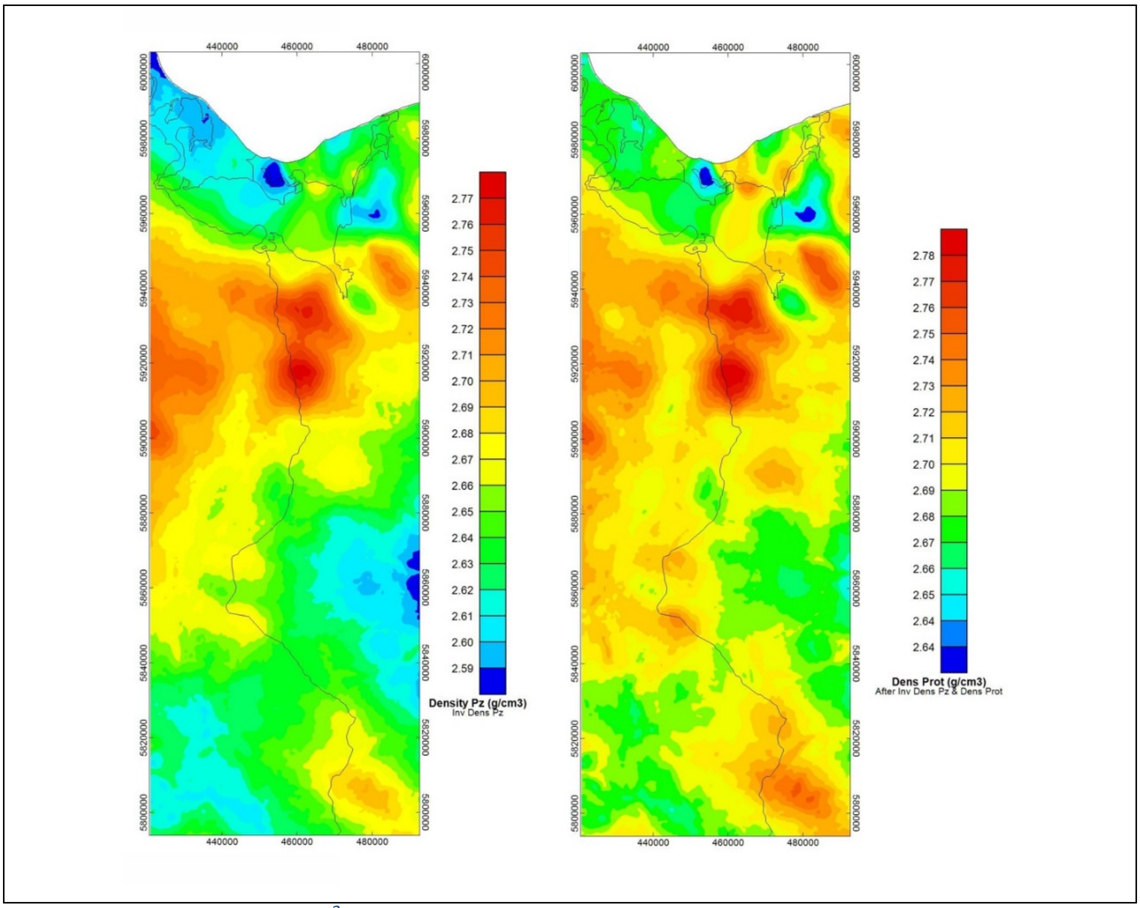


Figure 24: Densities (g/cm^3) of the Paleozoic (left) and Proterozoic (right) after the two steps inversion.

5.3 3D Inversion of the Zechstein levels and densities

The main assumption behind the workflow of the previous section is that the model surfaces and the densities are well constrained. Although the sequential inversion results of the basement layers were satisfactory in large areas of the model, we can still argue that there are some inconsistencies within the model (larger misfits especially in the northeast).

It is well known from the borehole records that the Zechstein salt displays very variable density values ranging from anhydrite (2.9 g/cm^3) to gypsum and halite (2.1 g/cm^3) (Figure 13). The density average for the layer of the Zechstein salt and the Basal Zechstein (which is used for the gravimetrical modelling) depends on the proportion of halite, anhydrite, carbonates in the succession what depends on the primary sedimentation but also on the halokinesis (salt enrichment in salt pillows or diapirs, anhydrite enrichment in salt depletion areas). The petrophysical information come only from a few (more or less) vertical drillings that give only very rough and incomplete picture of the internal structure of the Zechstein layers and the real density distribution especially in regions with halokinesis.

The seismic signals from the Zechstein layers are usually good and well defined (several prominent reflectors at top, base and within the Zechstein succession, prominent reflectors above in the Buntsandstein, see D2.2 of WP2, Jahnke et al. 2021a). But these reflections can be troubled because of a disturbed internal structure of the salt due to halokinesis. An additional, problem of 2D seismics (the major source of information in the model area) are steep flanks, tight sinks and salt overhangs that are typical for diapirs and their surroundings.

Thus, taking into account all these, we here hypothese that this layer is likely the main causative body for the uncertainty and thus, the better candidate to focus on additional modelling aiming to reduce its uncertainty, or at least to get insights on their possible origin. Therefore, another possible source for the misfits seen in the forward modelling (as well as in the inversion of the basement densities) could be related to an inaccurate distribution of Zechstein volumes and densities (Basal Zechstein and the Zechstein salt layer, see Table 1-1).

As the consensus, the top surface of Basal Zechstein was the worst constrained geometry. Accordingly, in a third step of the inversion process the top of the Basal Zechstein was inverted. The misfits of the model are shown in Figure 25 (left). The improvement is not as good as expected. The misfit map resembles a bit the Bouguer Anomaly (Figure 18) and some persistent anomalies to the North-North East are even more highlighted (also visible in Figure 20 and Figure 23).

Since the improvement is not as good as expected, another approach was tried: After the first two steps inversion, the density of the Zechstein salt was inverted (step 3) and then the geometry of the Top Basal Zechstein (step 4). The misfits (Figure 25, right) range now between -4 and 4 mGal with more than 90% showing values below 1 mGal. Thus, the adjustment is significantly improved (compare the histograms of the misfits in Figure 22 and Figure 25 (left).

This is the best result attained during the project life, but further improvements could be done in the near future. The persistent anomalies in the N-NE of the target area are the smallest of all modelling series. There is now remarkable negative misfit in the north-central part of the German side (although its magnitude is not that large; 3 mGal). The meaning of it is an overestimation of dense bodies in the geological model in that regions.

The initial and inverted densities of the Zechstein salt are shown on Figure 26. The initial and inverted geometries of top Basal Zechstein surface are shown on Figure 28. The estimated density of the Zechstein salt layer after all this sequence of inversion steps, resembles very much the initial density distribution and its anisotropy, an observation that is validating the initial model. The inverted densities of the Zechstein salt are generally higher than the initial ones. The averaged density is increased by 0.05 g/cm³ (initial average 2.19 g/cm³, inverted average 2.24 g/cm³, Figure 27). Comparing this result with the range of the densities in the Zechstein succession (Figure 13) the shift is low and in the range of the uncertainty of the petrophysical data (averages from logs and cores), but it shows a remarkable effect on the gravimetrical signal.

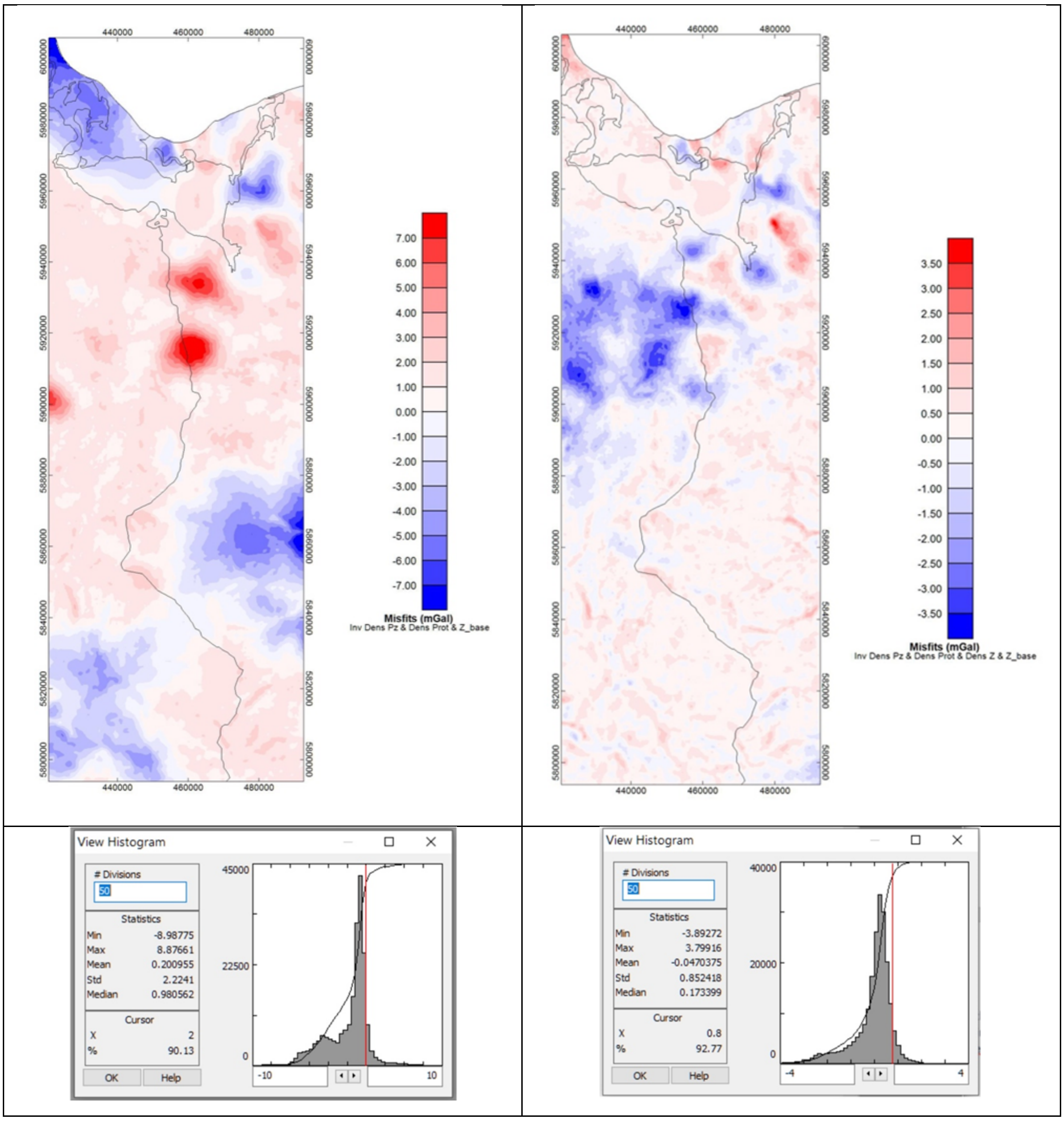


Figure 25: Map of Misfits and histogram (in mGal) (difference between observed and calculated anomaly). Left: from the inversion of (1) Paleozoic and (2) Proterozoic densities and (3) the geometry of the top of the Basal Zechstein. Right: from the inversion of (1) Paleozoic and (2) Proterozoic densities, (3) densities of the Zechstein salt and (4) the geometry of the top of the Basal Zechstein.

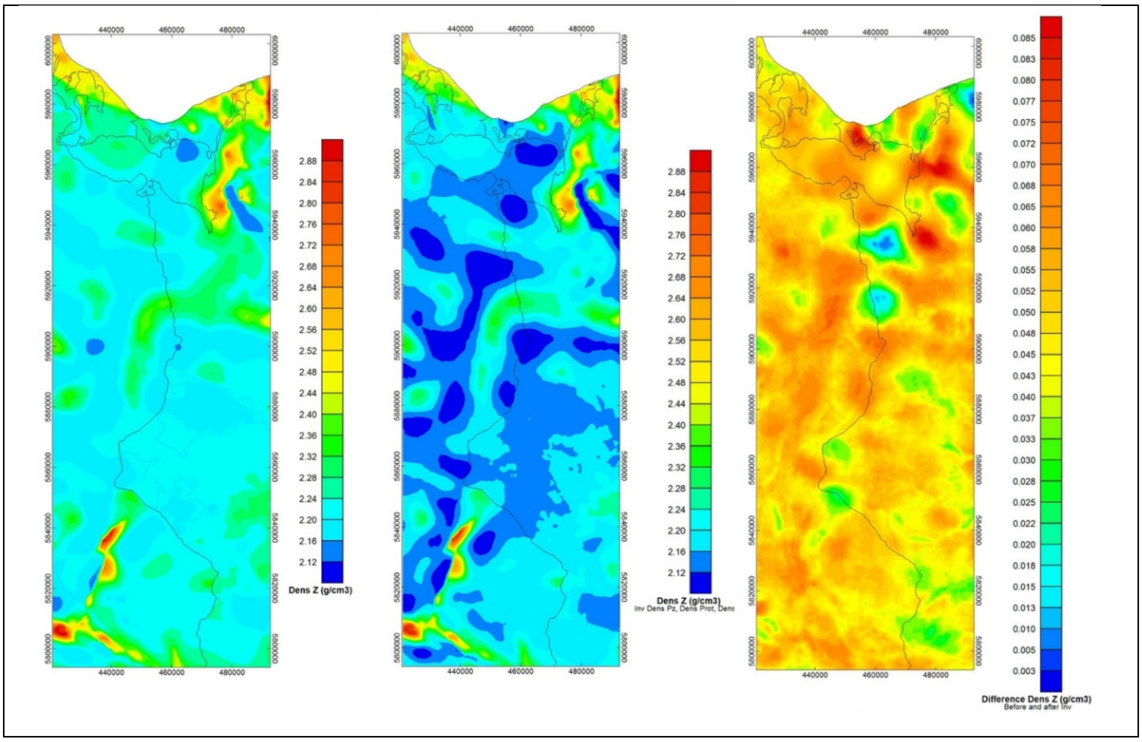


Figure 26: Left: Initial Zechstein salt layer density. Middle: Zechstein salt layer density after four steps inversion (1 - Density Paleozoic, 2 - Density Proterozoic, 3 – Density Zechstein salt, 4 - Geometry Top Basal Zechstein). Right: Differences between initial and inverted Zechstein salt layer density.

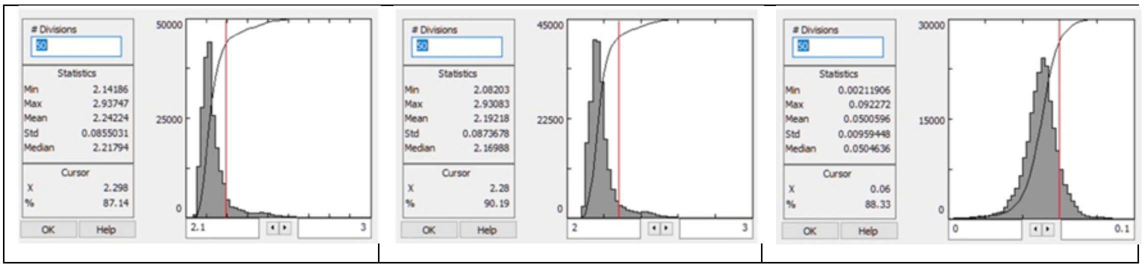


Figure 27: Histograms of the densities of Zechstein salt. Left: initial distribution. Middle: inverted distribution. Right: histogram of the differences initial – inverted density

Focusing on the inverted Intra-Zechstein horizon (top of Basal Zechstein, Figure 28, middle) the estimated geometry seems to be more complex than the initial geometry from the seismics (Figure 28 left). This is entirely possible because the Basal Zechstein contain local platforms and highs of sometimes relatively small extend, that probably cannot be all detected by seismics. The differences between initial and inverted surface (Figure 28, right) show an upward shift of the inverted surface in the northwestern part in a range of 50-150m and a downward shift by -50 - -150m in the southeast. In regions, where the surfaces are constrained only by seismics and not exactly by wells, these shifts ($\pm$ 150-200m in depth of 2500-4500m) are also entirely possible. However, some of the differences are likely impossible (e.g. up to more than 400m in the northeast - although the seismics here is very sparse and the wells in this area did not always reach the top of Basal Zechstein). But it should be taken into account that these shifts change the mass of the Basal Zechstein by changing the thickness. The mass could also be changed by the density, so parts of these changes are probably related to deviations in the density of the

Basal Zechstein, which was not inverted in the modelling procedure. In any case, all these differences are helpful to review the initial model.

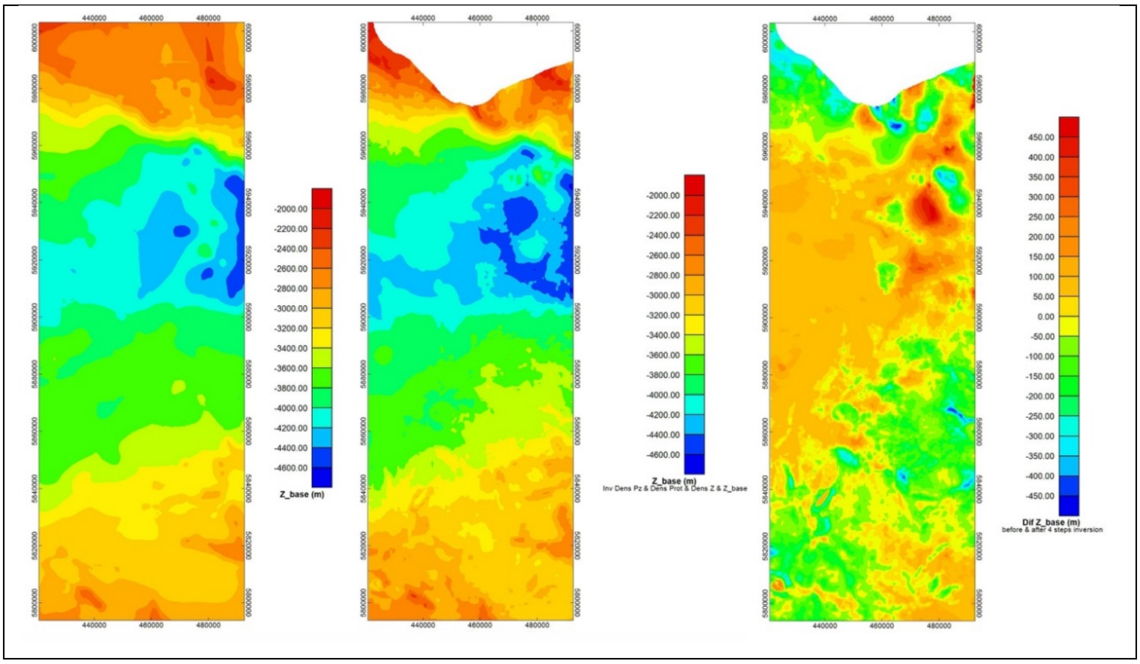


Figure 28: Left- Initial surface of top Basal Zechstein. Middle: inverted surface of top Basal Zechstein after four steps inversion (1 - Density Paleozoic, 2 - Density Proterozoic, 3 – Density Zechstein salt, 4 - Geometry top Basal Zechstein). Right: differences between initial and inverted surface

6 SUMMARY AND CONCLUSIONS

In this report we introduce the results of the joint modelling of harmonized gravimetric and petrophysical data (performed in the frame of this case study) together with the initial 3D geological model based on seismic and well data derived from WP2 results.

The harmonizing of the gravimetrical and petrophysical data showed that the restrictions in direct exchange of data hamper the data analyses and result in increased effort because anonymized and interpolated data have to be produced and to be used. The harmonization based on these kind of data can be nevertheless successful (especially if the data are exact 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 to 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 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.

The gravimetric modelling based on the preliminary harmonized data (geological 3D model, density model, Bouguer map) follows (slightly modified) the workflow proposed in D6.4 (WP6) entitled “Optimized 3D reconstruction workflow based on gravimetric, structural and petrophysical data”. The gravimetrical modelling could define regions of implausibilities and uncertainties in the initial models and show ways to overcome these. The main conclusions of the gravimetrical modelling in the German-Polish border region are:

- Complex and relevant signature of the basement of the model (Paleozoic + Proterozoic) is demonstrated in first forward modelling results (misfits between observed and calculated anomaly) which are very large and could only be reduced to acceptable values by inverting the Paleozoic and Proterozoic levels.
- Misfits remaining after inverting the model basement can be interpreted as indicators of possible inaccuracies in the initial model. These inaccuracies may come from two possible sources (or the combination of them):
  - the imprecise density distribution; especially critical for the Zechstein layer (with very variable density distribution) and for parts of the Mesozoic because of the uncertainties in the primary data of this layer
  - partial incorrectness of the initial model geometry in some regions and some layers (especially in gaps in the seismic exploration and lack of or too shallow drillings in parts of the area).
- To test that an inversion of Zechstein salt layer (density and base) was performed because of its structural importance (halokinesis exert a key control on structural geometries in the area) and strongly varying thicknesses and densities of this layer. The results are:

- A new density distribution which could inform us about missing salt pillows (low density zones) or salt depletion ones (high density zones) or underline (expected) density variation between salt pillows and salt depletion zones.
- A new geometry of the base of the Zechstein salt layer that helps validating the model reconstruction, it is of great help to localize possible problems in the initial reconstruction in data-sparse areas and also offers higher areal resolution than 2D seismics, thus permitting to delineate potential previously undetected anhydrite platforms or highs in Basal Zechstein.
- Both modelling results are coherent since the observed anisotropies follow the initial model ones and the larger misfits are located in areas with poor seismic and well coverage.

Therefore, the results of this exercise are promising and validate the gravimetric modelling approach as a useful harmonization tool.

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