3D Geomodelling for Europe

Project number: GeoE.171.005

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Deliverable 2.1

State of the Art Report

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Version: 2019-04-30

This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 731166.

Deliverable Data		
Deliverable number	D2.1	
Dissemination level	Public	
Deliverable name	State of the Art	
Work package	WP2	
Lead WP/Deliverable beneficiary	LBGR/LUNG	
Deliverable status		
Submitted (Author(s))	2019/04/30	Jahnke (LBGR), Obst (LUNG) Szynkaruk (PGI)
Verified (WP leader)	2019/04/30	Jahnke (LBGR), Obst (LUNG)
Approved (Project leader)	2019/04/30	Stefan Knopf (BGR)

GENERAL INTRODUCTION

Harmonization of geological data across geological, topographical, but especially across national borders is one of the most important work steps to create a base for trans-European assessments of resource potentials and possible conflicts of use of European subsurface. In the last decades a variety of different thematic maps were developed, but often not on a similar and consistent data base. Differences in the geological & geophysical interpretation (e.g. stratigraphy, velocity-model, structural interpretation, different methods of assessments) across the borders remain unchanged and were masked by generalizations in an overview scale. In the last years these "border-discontinuities" have become obvious by a variety of 3D-modeling projects. But workflows for harmonization of different geological 3D models are yet not established and proofed.

The project "3D geomodeling for Europe (3DGEO-EU)" in the framework of the transnational GeoERA association will show on the example of cross-border pilot areas how harmonization across the borders can be established and maintained with the progress of the national models. The methodologic advantages (agreements on best practices, optimized workflows, etc.) and the gain in experience on cross-border 3D harmonization work will be a keystone for further transnational harmonization projects.

The aim of work package 2 (WP2) in the project 3DGEO-EU is the development of harmonized geological 3D models for selected horizons and structures in the Polish-German cross-border region (horizons and structures in the Mesozoic and Permian strata; for energy storage, geothermal use, partially potential hydrocarbon reservoirs). The work will focus on two pilot areas of the Polish - North German Basin System covering a broad area of the Polish-German border: 1) the Gorzów-block and 2) the near border part of Szczecin Trough and their extension to the German side. The goals are to harmonize and update existing data inventories and interpretations in Poland and Germany; to establish harmonized (stratigraphical, seismostratigraphical, structural, geometrical) geological 3D models at the Polish and German border region using existing data inventories and (in close connection to WP6) employing potential field methods (gravimetry, magnetics) in addition to seismic investigations in less explored areas (cooperation with IGME and WP6).

The following State-of-the-Art report evaluates the existing national data bases in the project area, the previous national work (national geological/ geophysical data inventories, existing maps and 3D models), interstate cooperation Eastern Germany/Poland (before 1990) and international projects after 1990 with Polish-German participation/cooperation.

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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 is created for 13 selected stratigraphic horizons from the base Upper Permian (base Zechstein salt) 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) at the time. This project is a cooperation of the Federal Institute for Geosciences and Natural Resources (BGR) and the state geological survey organizations (GSOs) of the north German federal states. The Polish Geological Institute (PGI-NRI) is developing models for two structure regions in Poland at the time (Gorzów Block and the Szczecin Trough) for similar strata.

The areas of the models border on each other for Poland and Eastern Germany (federal states Mecklenburg-Western Pomerania and Brandenburg, Figure 1).

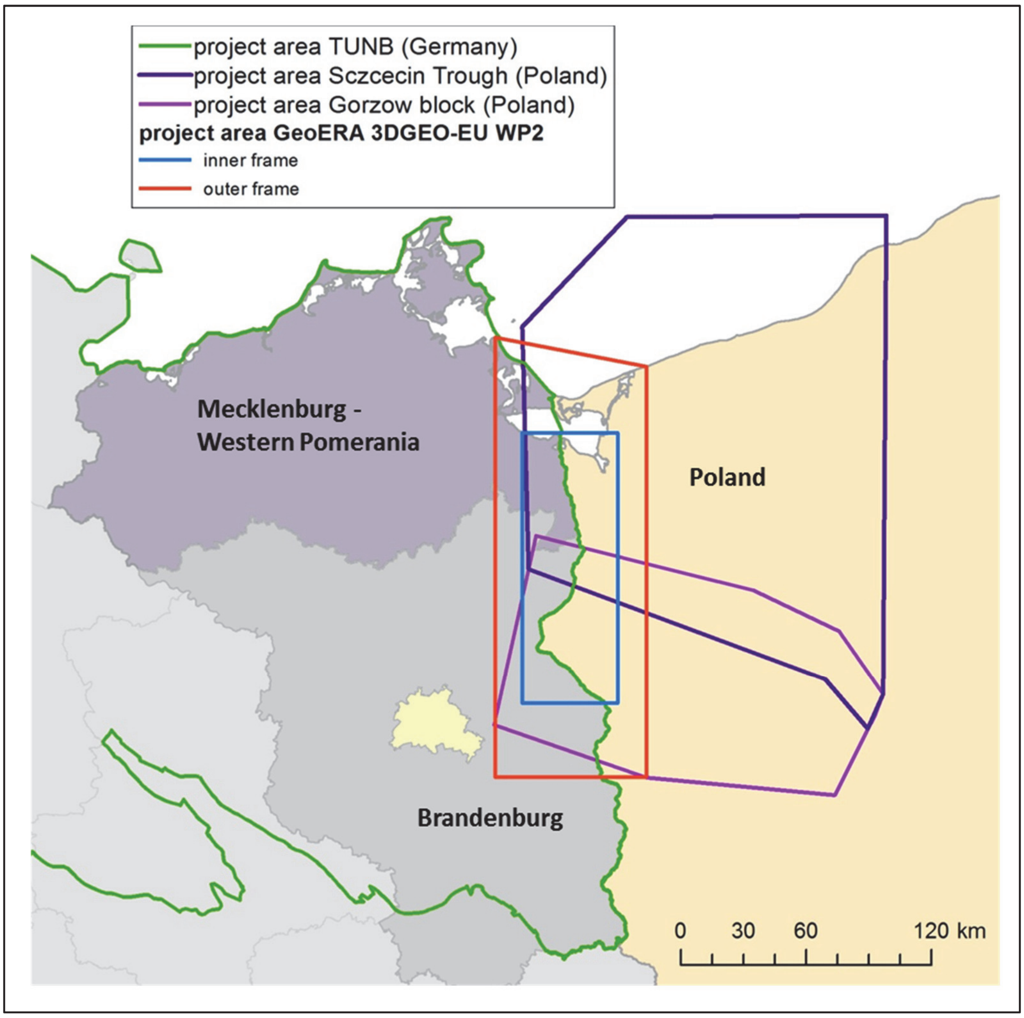

Figure 1 GeoERA-project Geomodeling for Europe (3DGEO-EU): Project area WP2, 3D-model Polish-German border region

The goal of the work package 2 in the GeoERA project “3D geomodeling for Europe (3DGEO-EU)” is to harmonize the data inventory and its interpretation and to develop a transnational geological 3D model for selected horizons and structures in the Polish-German cross-border region. The work will be focused on Mesozoic and Permian horizons and structures and so the model will reach several km depths.

For these purpose a project area was defined that includes the border regions of the different national projects (project area 3DGEO-EU WP2, see Figure 1). In the outer frame of the transnational project area the work will be done basing on existing data, in the inner frame additional investigations are planned and will be carried out if it’s possible in the financial frame and the timeline.

2 DATA BASES

2.1 Overview

Figure 2 gives a general overview about existing well data and seismic surveys in the Polish-German border region (according the focus on Mesozoic and Permian strata only boreholes that reach Pre-Cenozoic strata are shown). The overview illustrates the good covering with well data and seismic in the southern and western part, but also two important data gaps: region surround Chojna in the center of the project area and region Szczecin Lagoon - Stargard-Szczecinski - Gryfino in the north. At the German site the seismic is general 2D, at the polish site 2D and several 3D surveys exist.

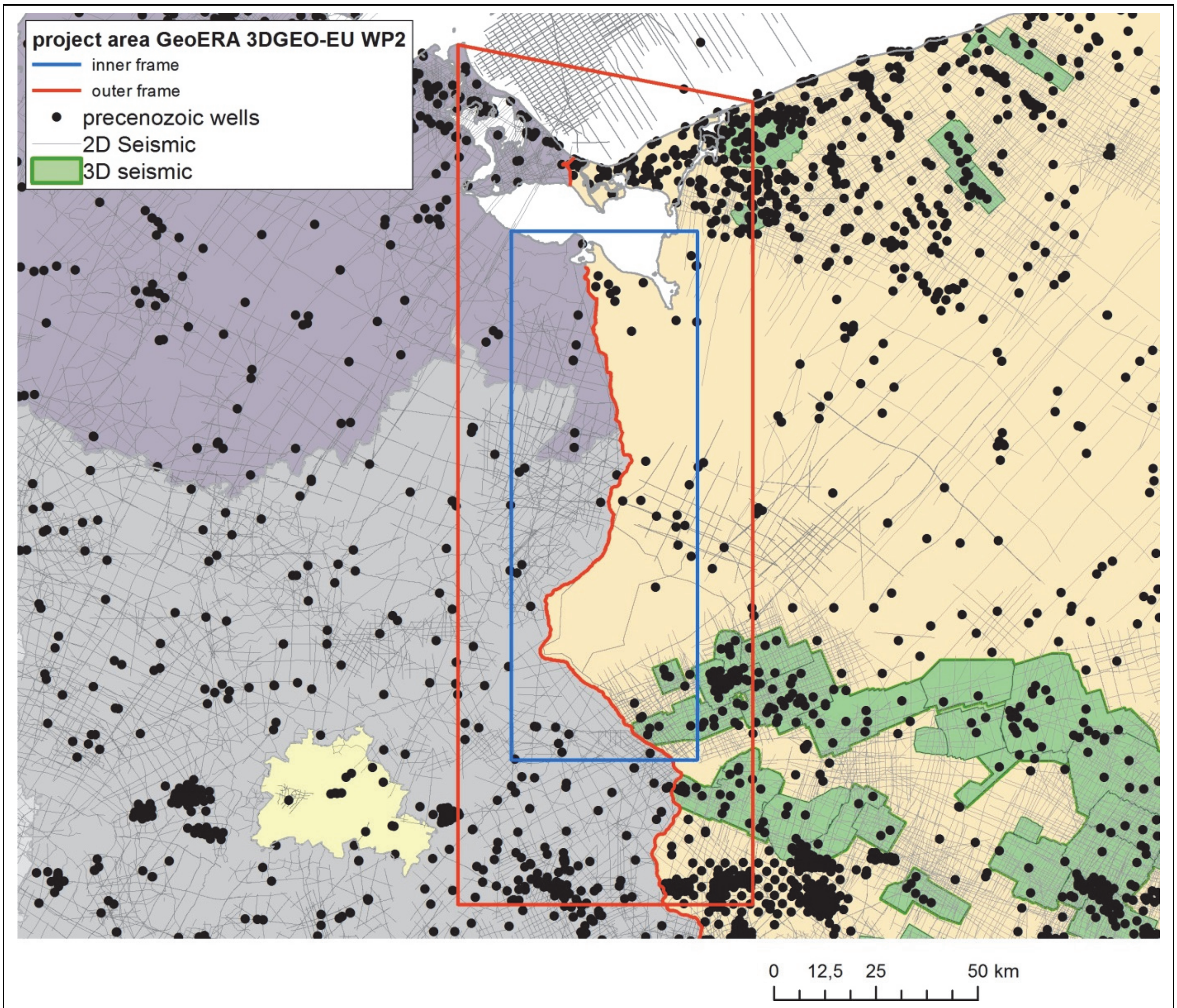

Figure 2: Data base Pre-Cenozoic boreholes, 2D-seismic and 3D- seismic in the Polish-German border region

In order to close the data gaps in seismic and well exploration at the Polish-German border region the use of gravity data is planned. Gravity data cover the whole project area except for the water areas of the Baltic Sea and the Szczecin lagoon.

The data bases of the partners are specified in detail in the following sections.

2.2 Brandenburg – State Office for Mining, Geology and Raw Materials Brandenburg (LGBR)

2.2.1 Well data

About 200 wells reaching Pre-Cenozoic strata exist in the project area in Brandenburg. They were mostly drilled between 1960 and 1990 in the framework of national surveying campaigns and exploration of resources (hydrocarbons, lignite, limestone, geothermal). Different stratigraphy and depth were reached due to the purpose of the drillings (Table 1):

Table 1: Wells in Eastern Brandenburg, transnational project area of 3DGEO-EU, WP2. Reached stratigraphy and depth

stratigraphy		number of wells	minimum depth	maximum depth
Cretaceous		58	168,9	631,4
Jurassic		22	123	1078,2
Triassic	**Upper (Keuper)**	20	190	1500
	Middle (Muschelkalk)	67	5	1450
	Lower (Bunter)	12	12	2950
Permian		30	173	4552
Pre-Permian		3	2945,5	5100

Most of the wells (160) have depths below 500 m. The boreholes of the national surveying from the 1950th and 1960th and also the lignite exploration of the 70th and 80th were drilled only down to the top of the Pre-Cenozoic (depth of some 100 meters). Limestone exploration where focused on the Middle Triassic strata at the top of a single salt diapire.

39 wells reach depth > 1000 m. 33 boreholes (hydrocarbon exploration, research, national surveying) reach Permian and Pre-Permian strata and explore the whole stratigraphic sequence of the planned models (Figure 1).

Because of legal restrictions only a part of the well data can be shared in the project and published (public research and national investigation wells). In the defined transnational project area the following wells with depths >500m will be shared with the partners.

Table 2: Open access wells with depth > 500m in Eastern Brandenburg, transnational project area of 3DGEO-EU, WP2

borehole	year	depth	deepest reached stratigrapy	XCOORD_UTM	YCOORD_UTM
Grt 1/65	1965	1534,2	Triassic	459805	5898193
Am 1/68	1968	5100	Pre-Permian	436521	5876098
Su 1/63	1963	807,5	Triassic	430529	5818321
Müg 1/61	1961	537	Cretaceous	439664	5823920
Ggs 1/1a/70	1970	3278,1	Permian	468853	5822583
HzfeSu 4/63	1963	1078,2	Jurassic	424497	5811347
Fu 1/61	1961	512	Triassic	440326	5797916
Boß 2/63	1963	630	Cretaceous	455142	5796860
SrwPk 2/60	1960	500,2	Triassic	434508	5794040
GrRt 3/63	1963	596,4	Triassic	449877	5794162

The non-public wells can only be used in the internal work of the LBGR (but will be used in the development of the model).

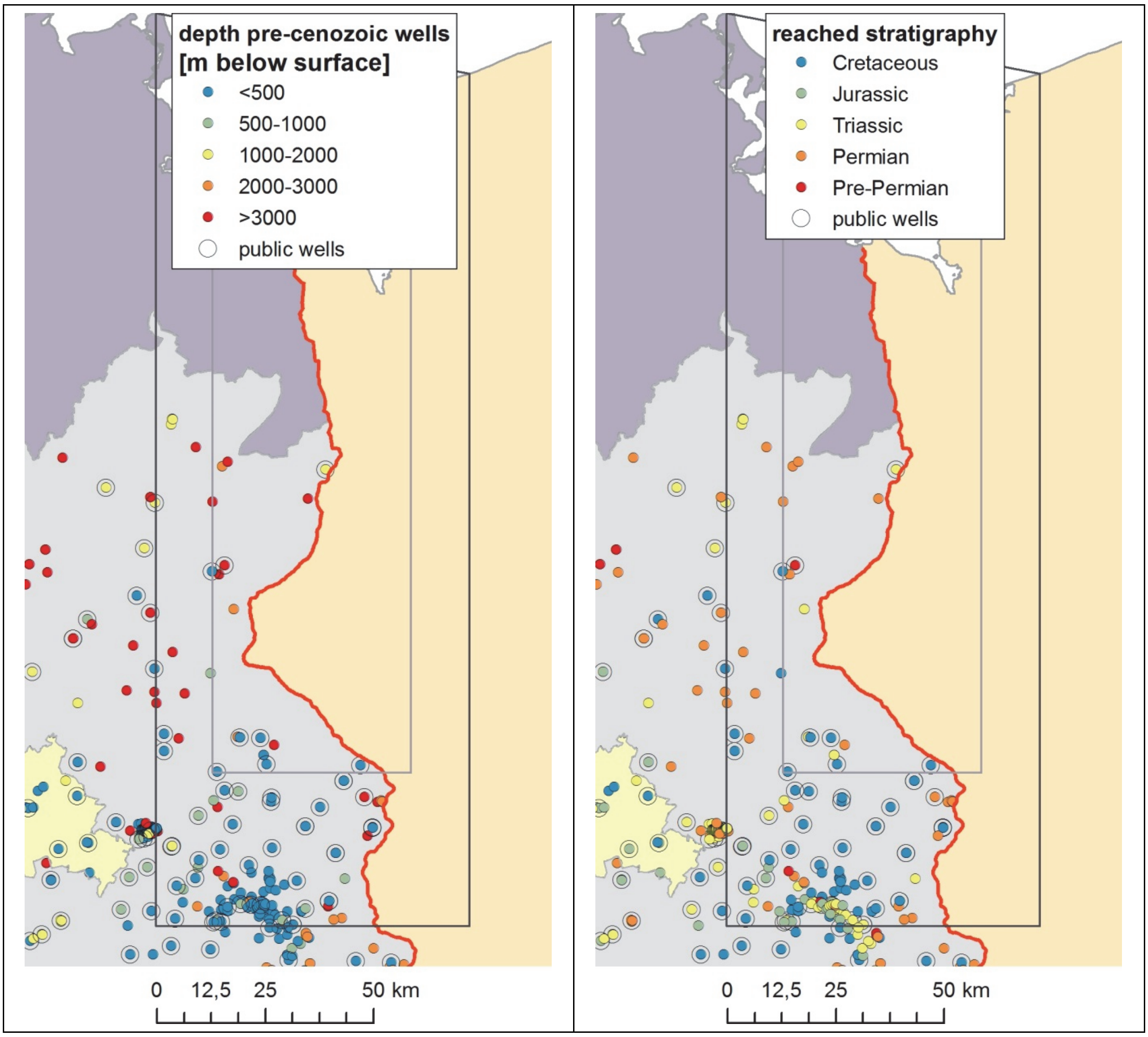

Figure 3: Wells reaching Pre-Cenozoic strata in Eastern Brandenburg, depth (left) and deepest stratigraphic horizon (right). Open access (public) wells : national research and investigation wells

2.2.2 Seismic investigations

Figure 4 shows the seismic investigations in Brandenburg including cross-border data to Mecklenburg-Western Pomerania in the project area. Most of the seismic campaigns in the region were carried during the oil and gas exploration between 1980 and 1990 (Table 3) and were focused to the deep Zechstein reservoirs. The Mesozoic strata and the structural situation were documented too. All data are 2D.

Check-shots and vertical seismic profiles VSP are documented for 25 wells from the 1970th and 1980th (Figure 4, right,). Basing on these data harmonized interpretations concepts and velocity models are documented for the most of the seismic surveys.

Table 3: seismic investigations in Eastern Brandenburg, transnational project area of 3DGEO-EU, WP2: surveys, profiles and total length

Year of seismic survey	Number of surveys	number of profiles	total length [km]
before 1970	>6	>54	>887
1971-1975	2	3	35
1975-1980	5	27	466
1981-1985	5	46	594
1985-1990	14	276	3946
after 1990	6	20	605

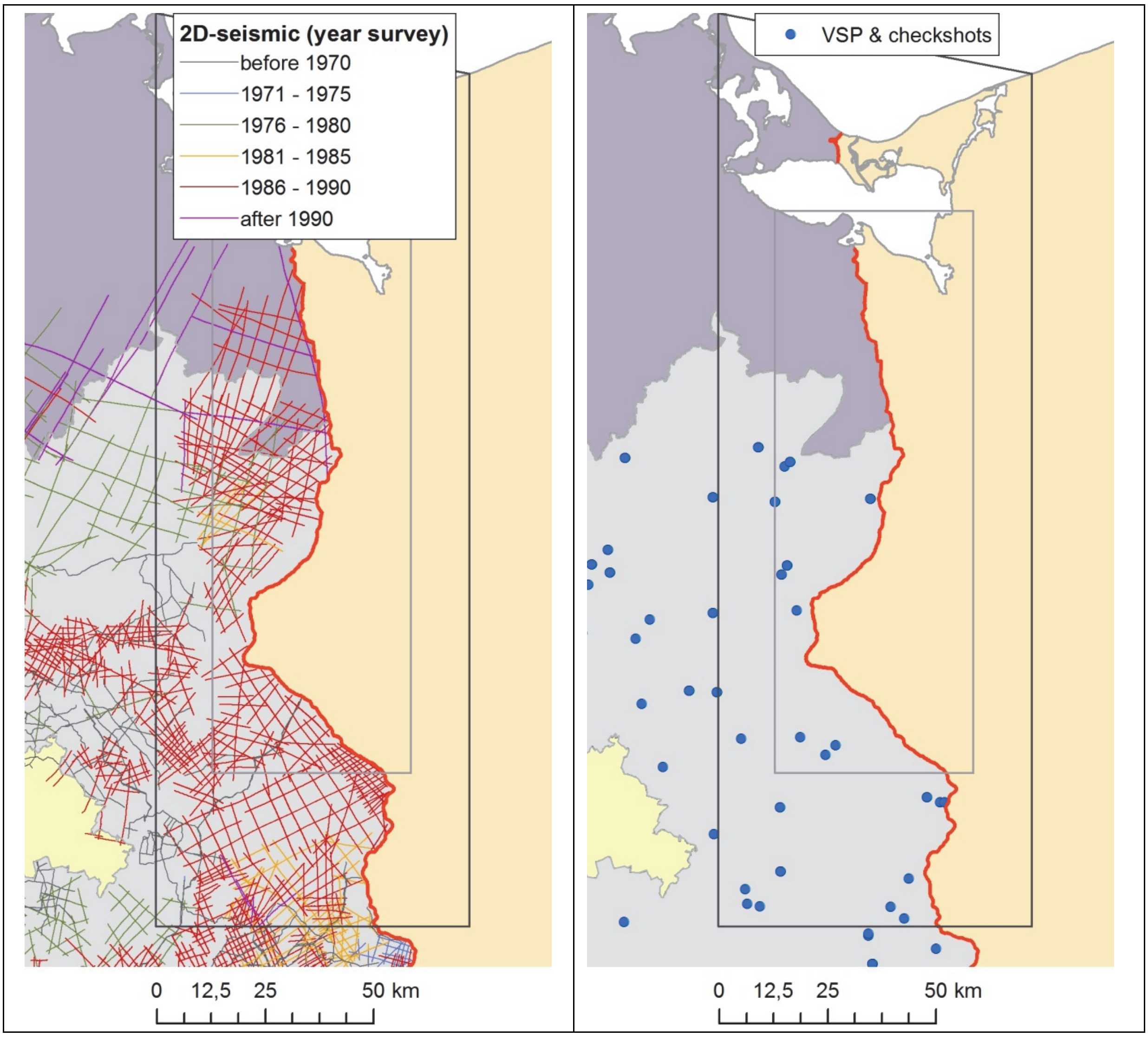

Figure 4: Seismic investigations in Eastern Brandenburg: left: 2D-profils area grouped by the year of the survey, right: check-shots and vertical seismic profiles VSP

The interpretation of seismic reflectors and seismic velocities were continually developed and regional harmonized between 1965 and 1990 from the Geophysical Survey of the former GDR. A lot of profiles measured after 1971 were linked to wells and/or to each other and were re-evaluated in case of new measurements (and have often several interpretations). Basing on the seismic data regional harmonized maps of seismic reflectors were generated for Eastern Germany (including Brandenburg and Mecklenburg - Western Pomerania) and periodically updated (Reinhardt 1965, 1993). Nevertheless older data (especially before 1980) are not always up-to-date.

In summary a good coverage with profiles and a reliable interpretation of seismic material exist in the Eastern part of Brandenburg that is suitable for a regional geological model (even if the seismic material is mainly older than 30 years). There are a lot of cross-bordering data to Mecklenburg-Western Pomerania (seismic profiles and interpreted maps). A larger number of profiles in the eastern part of Brandenburg were measured close to the German-Polish border but there is a general lack of cross-bordering profiles between Germany and Poland at the time.

Because of legal restrictions in Germany the seismic data can only be used in the internal work of the LBGR and cannot be shared in the project and published.

2.2.3 Gravity

2.2.3.1 Base networks

A first national gravity base network was developed from 1960 to 1971 in Eastern Germany (**Figure 5** left). It includes points of 1st to 3th order (point spacing: 1st order ≈ 50 km, 2nd ≈ 15 km, 3rd ≈ 5 km). Points were marked with plates, pillars or ground spikes. Gravity base net was the reference station Potsdam ("Potsdamer Schweresystem 1971", shift to the International Gravity Standardization Net ISGN71: +14 mGal). The precision was ± 0,048 mGal for the points 1st and 2nd order (Sommer et al. 2004). The spatial reference was the Pulkovo datum (Krassowsky spheroid , EPSG 4284). The vertical datum was Baltic 1977 height (EPSG 5705). The bases are in principle still available (but have to be checked).

After 1990 the different national networks in Germany were connected and reorganized. The current german gravity network in Brandenburg consists of bases of 1st and 2nd order with point distances of 10-20 km. The bases of 1st order were organized in primary bases with absolute gravity measurements (1994-2011) and secondary bases with relative measurements (1996-2011). The points of 2nd order are basing on relative measurements too. The gravity base net is DSGN94 ("Deutsches Schweregrundnetz 1994", comparable to IGSN71). The spatial reference is ETRS89 UTM33 (EPSG 25833) and the vertical datum is DHHN92/DHHN2016 (EPSG 5556).

The absolute measurements are included in the International Absolute Gravity Database (AGrav), a joint development of Federal Agency for Cartography and Geodesy Germany (BKG) and Bureau gravimétrique international (BGI) (http://agrav.bkg.bund.de/agrav-meta/).

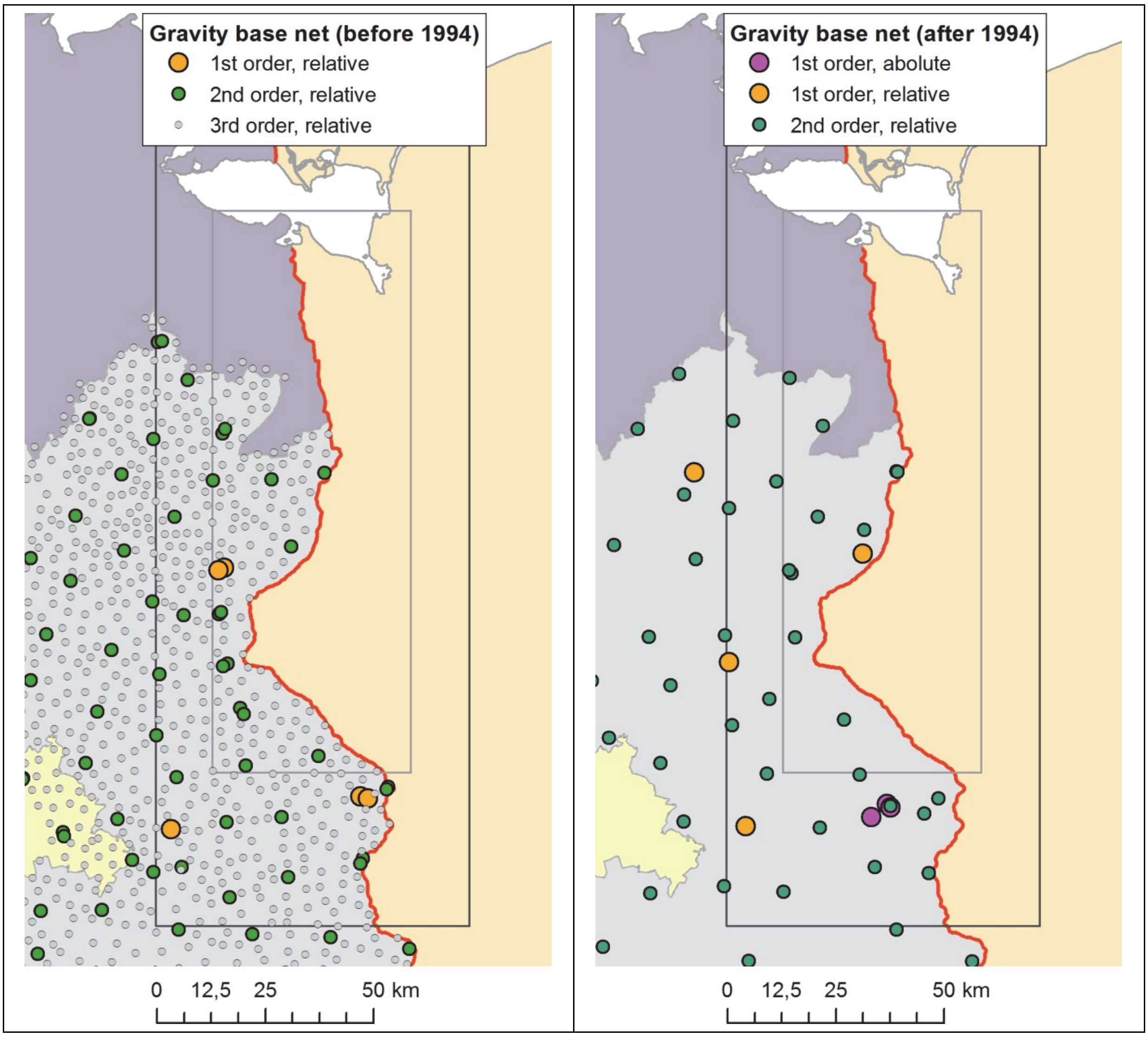

Figure 5: Gravity base network in Brandenburg. Left: bases 1st to 3rd order 1960-1994, right: bases 1994 - now

2.2.3.2 Regional and refined gravity surveys and interpretations

The **regional surveys** were carried out 1960-1971 in combination with the development of the base network. The measurements cover whole Eastern Germany (except for the water areas) in irregular meshes with an average point density of ≈ 0.8 points/km² (point distance ≈ 1,5 km). The measurements were corrected for gravimeter drift, moon-solar, elevation, latitude (Helmert-Ellipsoid 1906), free-air and partially topography. The data of the regional surveys where reprocessed after 1994 and connected to the new gravity base network (see 2.2.3.1) (Conrad 1996; Skiba et al. 2010; Skiba 2011). The data are digital available (measured gravity, Bouguer anomaly, corrections including processing parameters) and can be shared and published.

Refined gravity surveys were carried out from 1970 to 1990 and were related to various exploration campaigns (hydrocarbons, lignite). The **semi-detailed investigations** (Figure 6) are basing on irregular meshes with point densities of 3-4 points/km² (average point distance ≈ 500 m). The measurements cover the whole project area of 3DGEU-EU, WP2 (surveys from 1972 to 1986). The processing and correction were similar to the regional surveys. The primary data are partially incomplete (coordinates of points are missing in surveys the south of the project area). Complete datasets exist only for the inner frame and the northern outer frame of the project area in Brandenburg. Interpolated maps of Bouguer-anomaly (scale 1:50.000) are available for the whole area. **Detailed surveys** were carried out in regular meshes with point distances from 50 to 200 m (surveys from 1969 to 1990). The primary data are incomplete at the time. Interpolated maps of Bouguer-anomaly (scale 1:25.000, processing 1975-1990) are available for smaller parts project area only in the southern outer frame.

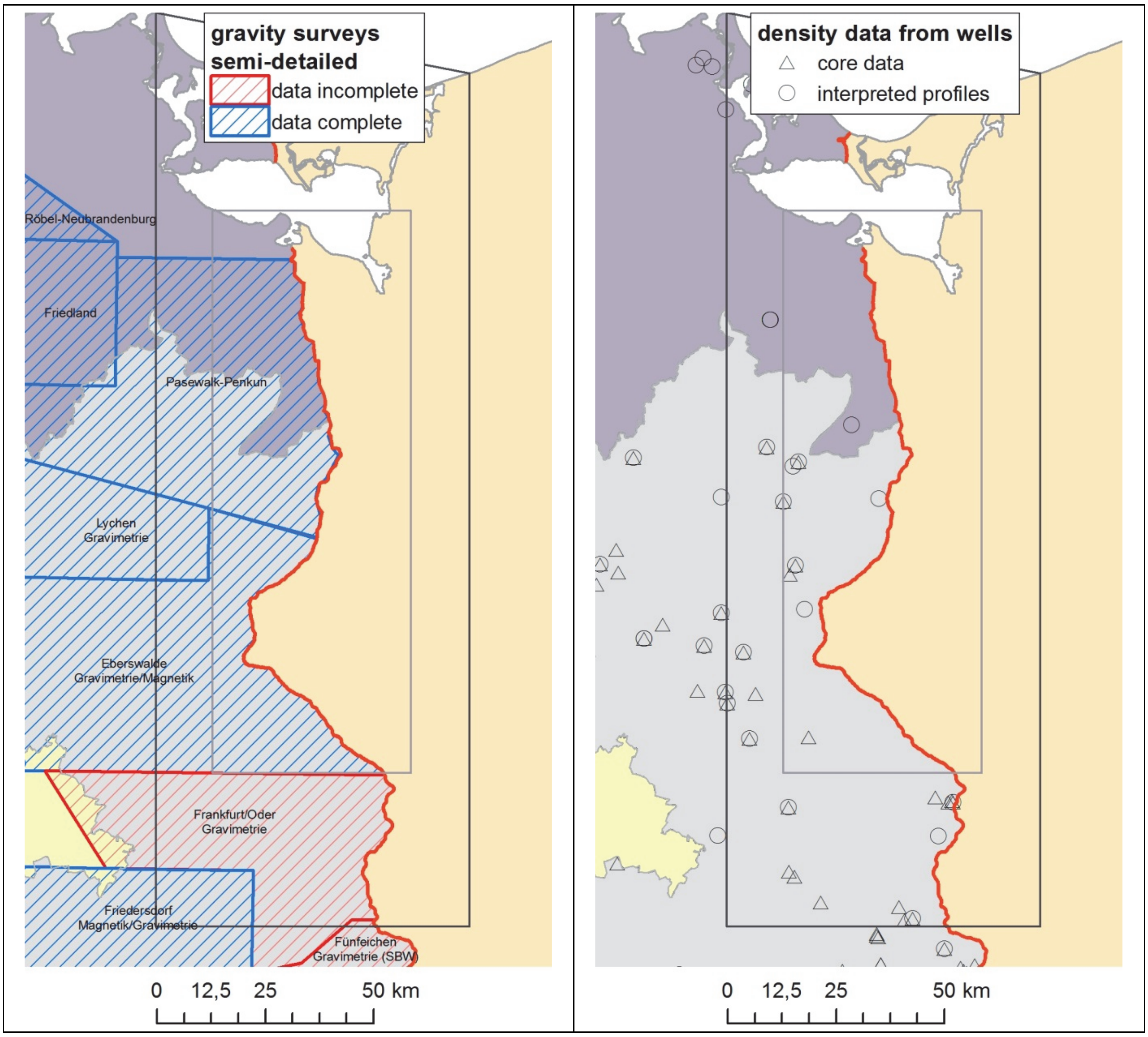

Figure 6: left: Data availability of semi-detailed gravity surveys in Eastern Brandenburg. Right: wells with petrophysical data (density), core data and interpreted profiles

The data of the refined surveys exist only on paper and have to be digitized, reprocessed and connected to the new gravity base network. In the regions with incomplete refined data the regional surveys in combination with the existing Bouguer maps have to be used. The possibility of new measurements in these regions will be explored.

The surveys partially include gravimetrically interpreted cross-sections basing on local density models. The latter where developed from petrophysical investigations. Core data and density profiles exist for more than 20 wells in the project area (Figure 6, right).

2.3 Mecklenburg-Western Pomerania – State Authority for Environment, Nature Conservation and Geology (LUNG)

2.3.1 Well data

About 85 wells reaching Pre-Cenozoic strata exist in the project area in Mecklenburg-Western Pomerania. They were mostly drilled between 1960 and 1990 in the framework of national surveying campaigns and exploration of resources (hydrocarbons, lignite, limestone, geothermal resources). Different stratigraphy and depth were reached due to the purpose of the drillings (Table 4):

Table 4: Wells in Western Pomerania, transnational project area of 3DGEO-EU, WP2. Reached stratigraphy and depth

Stratigraphy		number of wells	minimum depth	maximum depth
Cretaceous		5	89	139
Jurassic		14	275	1600
Triassic	**Upper (Keuper)**	4	93	1094
	Middle (Muschelkalk)	–	–	–
	Lower (Bunter)	2	1760	1830
Permian		58	2481	6015
Pre-Permian		2	4683	7555

65 of the wells have a depth > 1000m. 60 wells reach Permian or Pre-Permian strata and explore the whole stratigraphic sequence of the planned model. Because of legal restrictions only a part of the well data can be shared in the project and published (public research and national investigation wells). The following wells with depths >500m listed in Table 7 will be shared with the partners. The non-public wells can only be used in the internal work of the LUNG (but will be used in the development of the model).

Table 5: Open access wells with depth > 500m in Western Pomerania, transnational project area of 3DGEO-EU, WP2

well	depth	deepest reached stratigrapy	XCOORD_UTM33	YCOORD_UTM33
Kb Ud 2/1961	512	Jurassic	33435353	5975039
Kb Rbk 2/2a/1964	530	Jurassic	33421085	5976022
Kb Hrid 4/1963	601	Jurassic	33443830	5979435
Kb Khn 1/1a/1962	601	Jurassic	33425406	5993825
Kb Ud 1/1960	602	Jurassic	33430110	5970718
Kb Ud 3/3a/1964	714	Jurassic	33423272	5969047
Kb Loek 1/1a/1963	745	Jurassic	33449064	5926219
Kb Loek 1E/1963	1094	Triassic	33449109	5926280
Kb JOmb 10/1966	1600	Jurassic	33449329	5904895
Kb JOmb 4/1966	1600	Jurassic	33450329	5937285
E Pkn 1/1h2/1971	6015	Permian	33449444	5908508
E Pud 1/1h/1986	7555	Pre-Permian	33442658	5979824

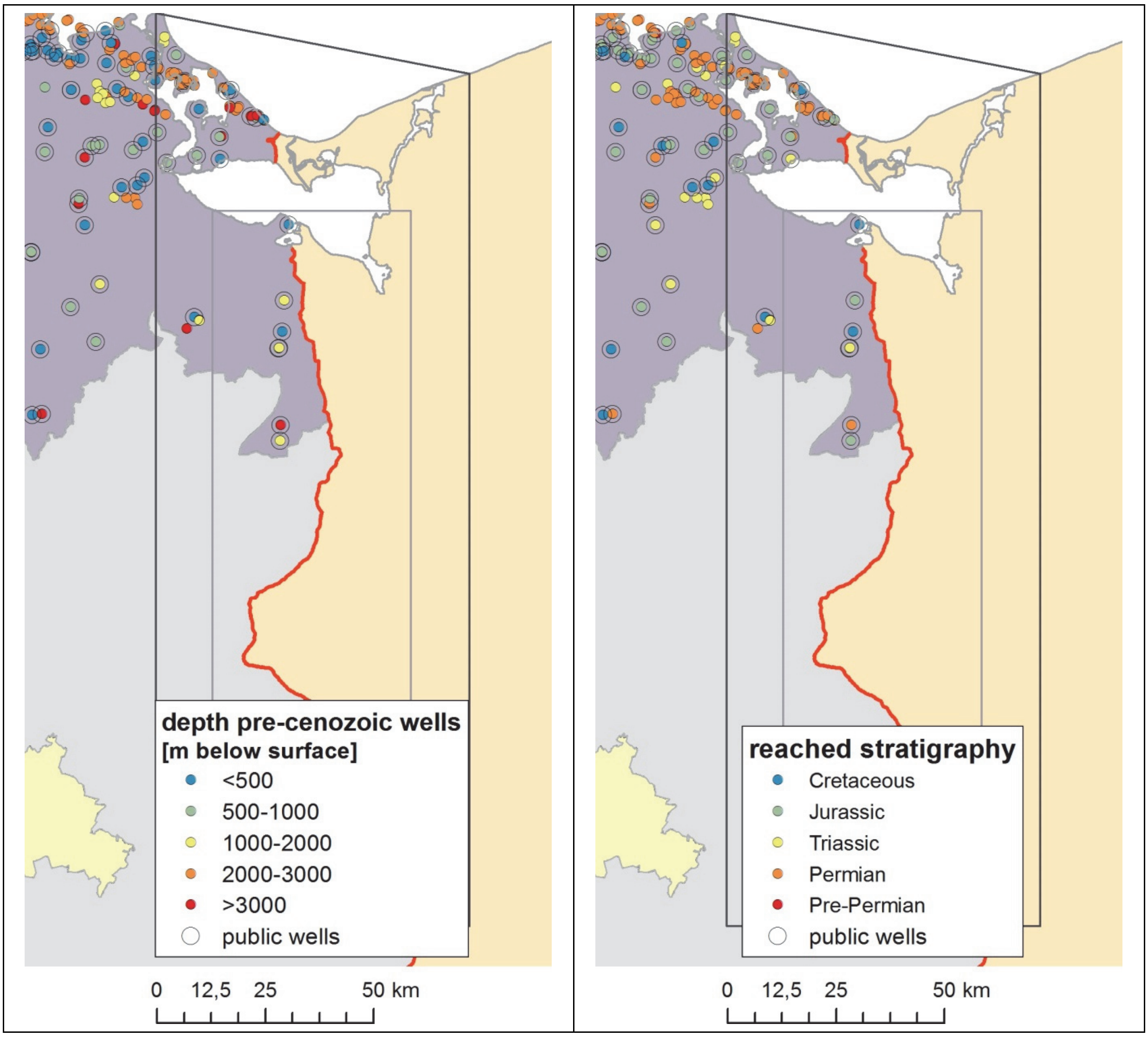

Figure 7: Wells reaching Pre-Cenozoic strata in Eastern Mecklenburg-Western Pomerania, depth (left) and deepest stratigraphic horizon (right). Open access (public) wells : national research and investigation wells

2.3.2 Seismic investigations

Figure 8 shows the seismic investigations in Mecklenburg-Western Pomerania including cross-border data to Brandenburg in the project area. Most of the seismic campaigns in the region were carried out during the oil and gas exploration between 1960 and 1980 and were focused to the deep Zechstein reservoirs. The Mesozoic strata and the structural situation were documented too. All data are 2D.

Check-shots and vertical seismic profiles VSP are documented for 18 wells from the 1970s and 1980s (Figure 8, right,). Basing on these data harmonized interpretations concepts and velocity models are documented for the most of the seismic surveys.

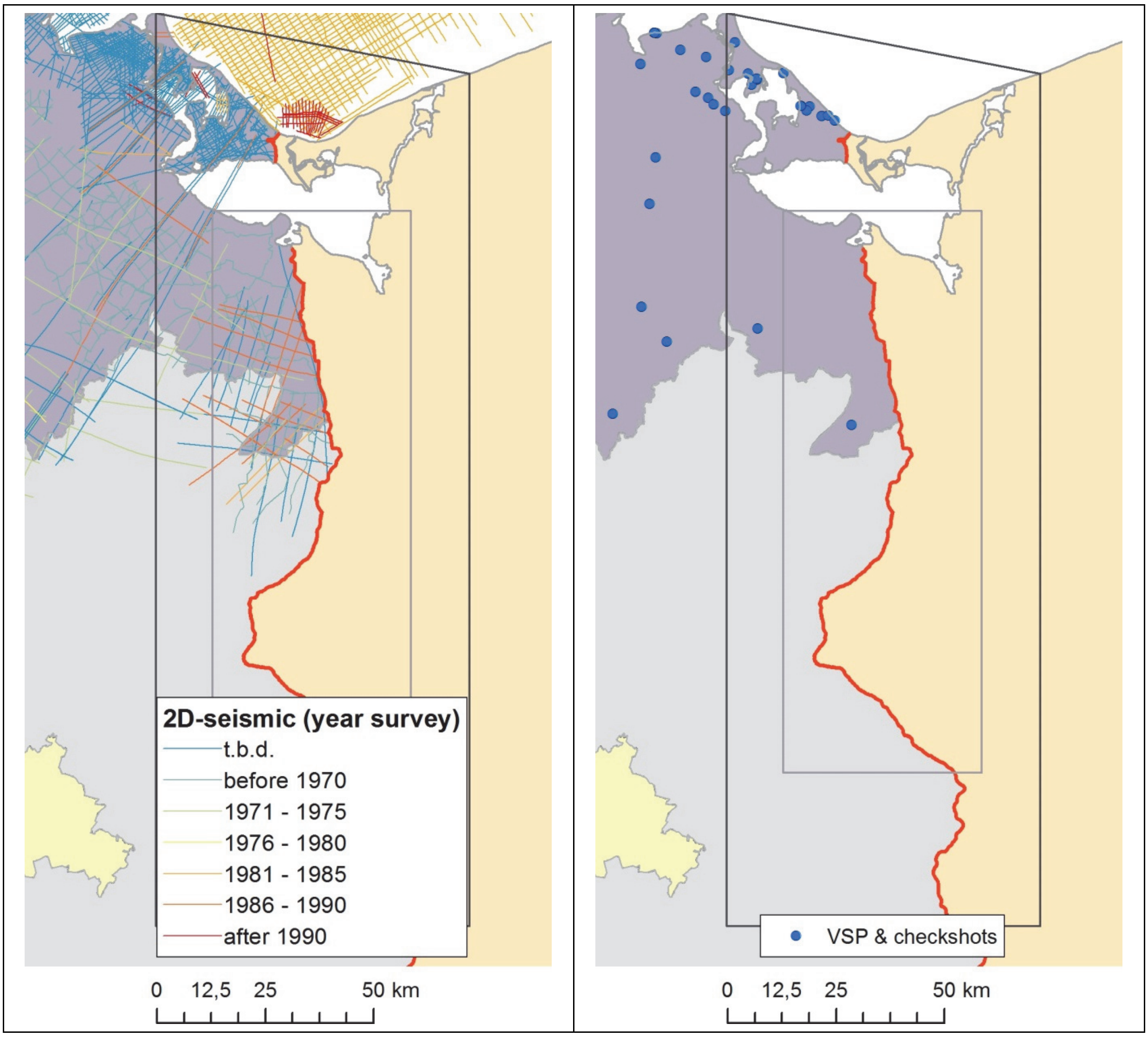

Figure 8: Seismic investigations in Eastern Mecklenburg-Western Pomerania: left: 2D-profils area grouped by the year of the survey, right: check-shots and vertical seismic profiles VSP

2.3.3 Gravity

2.3.3.1 Base networks

A first national gravity base network was developed from 1960 to 1971 in Eastern Germany (**Figure 9**, left). It includes points of 1st to 4th order. Points were from the 1th to the 3rd order marked with plates, pillars or ground spikes. Gravity base net was the reference station Potsdam ("Potsdamer Schweresystem 1971", shift to the International Gravity Standardization Net ISGN71: +14 mGal). The precision was ± 0,048 mGal for the points 1st and 2nd order (Sommer et al. 2004). The spatial reference was the Pulkovo datum (Krassowsky spheroid , EPSG 4284). The vertical datum was Baltic 1977 height (EPSG 5705). The bases are in principle still available (but have to be checked).

After 1990 the different national networks in Germany were connected and reorganized. The current German gravity network in Mecklenburg-Western Pomerania consists of bases of 1st and 2nd order with point distances of 10-20 km (Figure 9, right). The gravity base net is DSGN94 ("Deutsches

Schweregrundnetz 1994", comparable to IGSN71). The spatial reference is ETRS89 UTM33 (EPSG 25833) and the vertical datum is DHHN92/DHHN2016 (EPSG 5556).

The absolute measurements are included in the International Absolute Gravity Database (AGrav), a joint development of Federal Agency for Cartography and Geodesy Germany (BKG) and Bureau gravimétrique international (BGI) (http://agrav.bkg.bund.de/agrav-meta/).

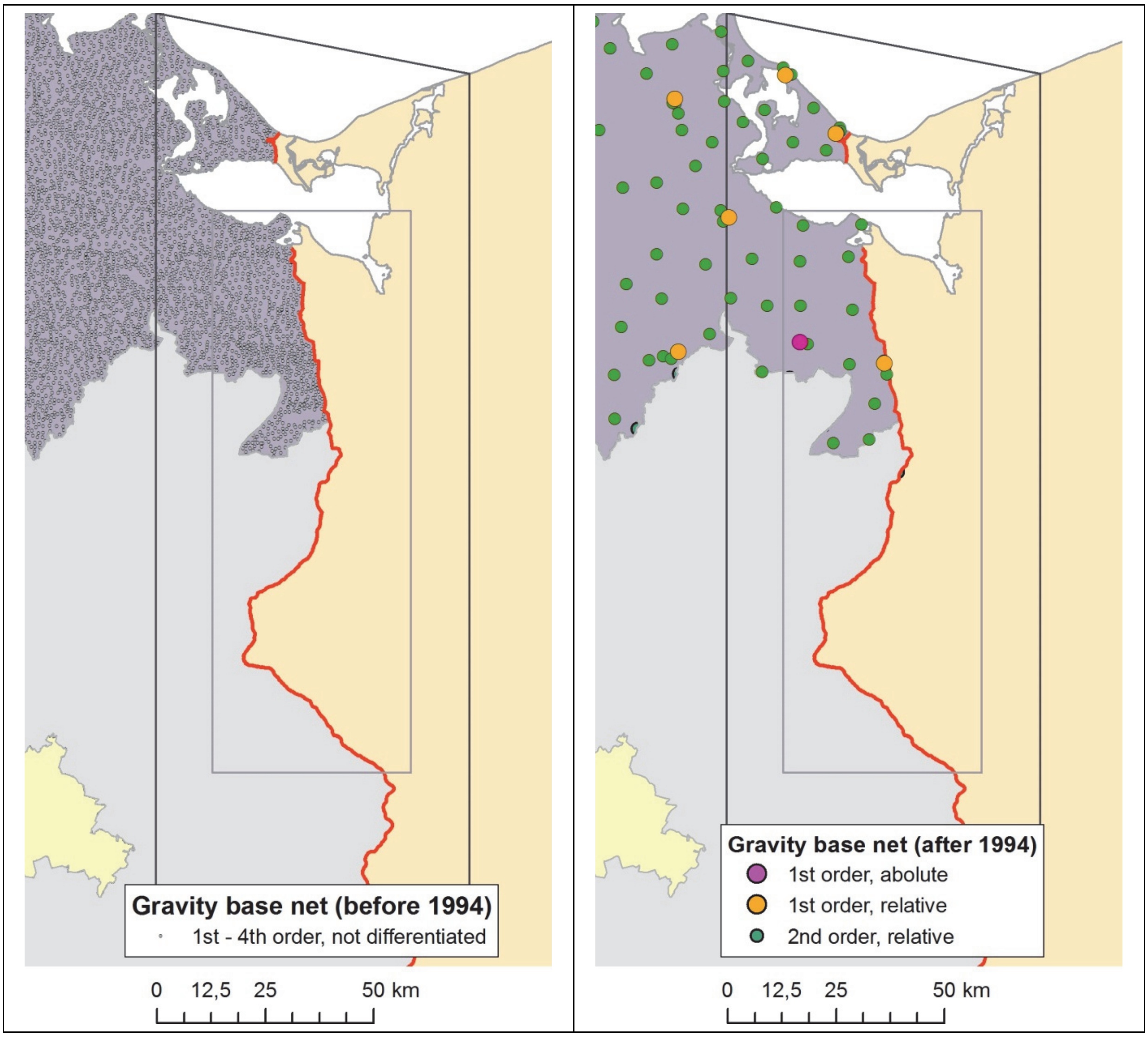

Figure 9: Gravity base network in Eastern Mecklenburg-Western Pomerania. Left: bases 1st to 4th order 1960-1994 (undifferentiated), right: bases 1994 -now

2.3.3.2 Regional and refined gravity surveys and interpretations

The **regional surveys** were carried out 1960-1971 in combination with the development of the base network. The measurements cover whole Eastern Germany (except for the water areas) in irregular meshes with an average point density of ≈ 0.8 points/km² (point distance ≈ 1,5 km). The measurements were corrected for gravimeter drift, moon-solar, elevation, latitude (Helmert-Ellipsoid 1906), free-air and partially topography. The data of the regional surveys where reprocessed after

1994 and connected to the new gravity base network (see 2.3.3.1) (Conrad 1996; Skiba et al. 2010; Skiba 2011). The data are digital available (measured gravity, Bouguer anomaly, corrections including processing parameters) and can be shared and published.

Refined gravity surveys were carried out from 1970 to 1990 and were related to various exploration campaigns (hydrocarbons, lignite). The **semi-detailed investigations** (Figure 10) are basing on irregular meshes with point densities of 3-4 points/km² (average point distance ≈ 500 m). The measurements cover the whole project area of 3DGEU-EU, WP2 (surveys from 1972 to 1986). The processing and correction were similar to the regional surveys. The primary data are partially incomplete. Interpolated maps of Bouguer-anomaly (scale 1:50 000) are available for the whole area. Bouguer-anomaly in a scale 1:25 000 (processing 1975-1990) are available in the area south of the Szczecin lagoon.

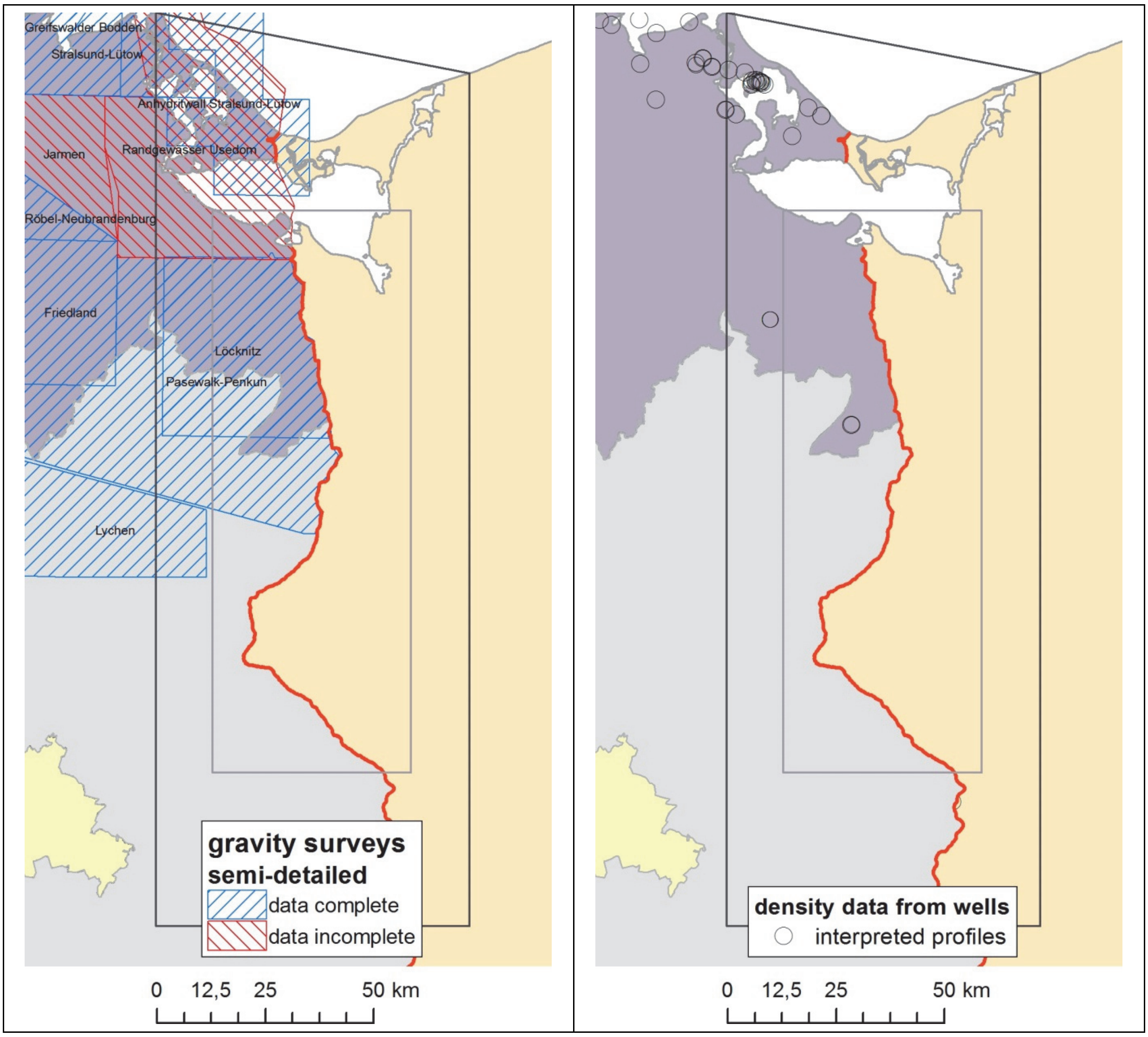

Figure 10: Left: data availability of semi-detailed gravity surveys in Eastern Mecklenburg-Western Pomerania. Right: wells with petrophysical data (density), core data and interpreted profiles

The data of the refined surveys exist only on paper and have to be digitized, reprocessed and connected to the new gravity base network. In the regions with incomplete refined data the regional surveys in combination with the existing Bouguer maps have to be used. The possibility of new measurements in these regions will be explored.

The surveys partially include gravimetrically interpreted cross-sections basing on local density models. The latter where developed from petrophysical investigations. Core data and density profiles exist for about 17 wells in the project area.

2.4 Poland – Polish Geological Institute (PGI-NRI)

2.4.1 Well data

About 400 wells reaching Pre-Cenozoic strata exist in the project area in Poland (Figure 11). Except a few oldest wells they are being drilled from mid-fifties within the framework of national surveying campaigns and commercial exploration of resources (hydrocarbons, lignite, geothermal). Different stratigraphy and depth were reached due to the purpose of the drillings (Table 6):

Table 6: Wells in Poland, transnational project area of 3DGEO-EU, WP2. Reached stratigraphy and depth.

stratigraphy		number of wells	minimum depth	maximum depth
Cretaceous		166	10	457
Jurassic		55	17,1	1865,9
Triassic	Upper (Keuper)	4	1013	1900
	Middle (Muschelkalk)	2	1760	2090
	Lower (Bunter)	0		
Permian		153	2246,4	4950
Pre-Permian		9	3127,3	4722

Most of the wells (289) have depths greater than 200 m and 170 are deeper than 1 000 m. Boreholes less than 135 m deep (78 wells) are either hydrogeological (for groundwater abstraction) or research, including 1:50k geological mapping campaign wells. Boreholes 136–580 m deep are either hydrogeological (including those drilled for mineral waters), research, cartographic or lignite surveying wells.

Of the 170 wells over 1 000 m deep all but 7 are actually over 2 090 m deep. They were predominantly drilled for exploration and production of hydrocarbons, thus are reaching Permian or pre-Permian strata and explore the whole stratigraphic sequence of the planned models.

68 wells (most of them over 3 000 m deep) have been drilled during the ’90 so have never become property of the Polish State. Sharing of data from these wells is subject to approval of the data owner (Polish Oil and Gas in most cases). Sharing of data owned by the State is subject to approval of the State.

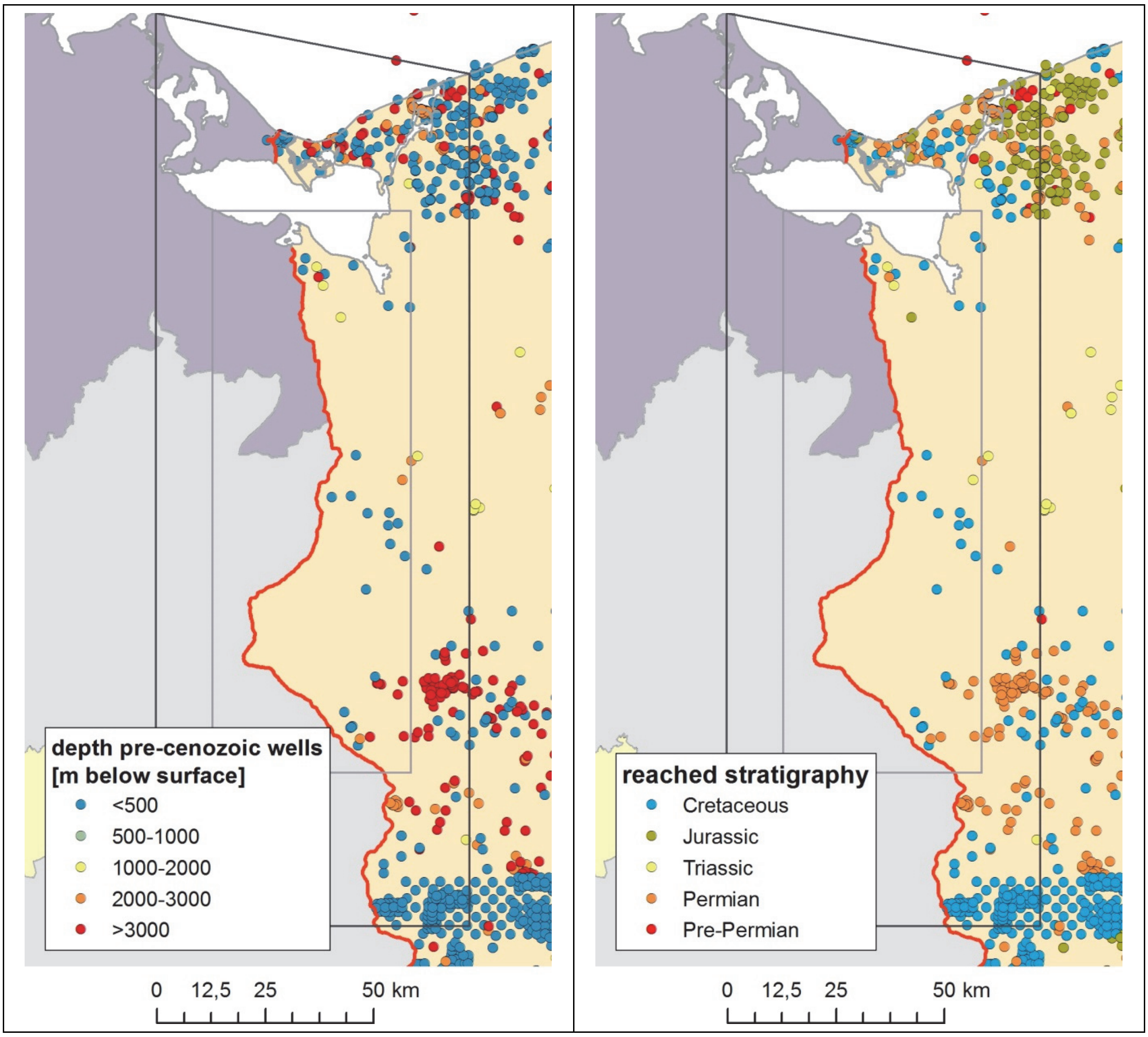

Figure 11: wells reaching Pre-Cenozoic strata in Poland, depth (left) and deepest stratigraphic horizon (right).

2.4.2 Seismic investigations

Figure 12 shows the seismic investigations on Polish side of the study area. Most of the seismic campaigns in the region were carried out during the oil and gas exploration since the ’70 and were focused on the deep Zechstein reservoirs of the Main Dolomite. Some Triassic horizons were also traced and many faults and depositional architecture were surveyed. 2D data were mostly collected until the end of the ’90 during the second half of the ‘90 the bulk of the 3D data was collected, primary in the Gorzów block area (Table 7 and Table 8).

Table 7: 2D seismic investigations in Poland, transnational project area of 3DGEO-EU, WP2: surveys, profiles and total length

Year of seismic survey	Number of surveys	number of profiles	total length [km]
1976-1980	8	85	1168
1981-1985	3	25	211
1986-1990	11	86	911
after 1990	16	176	1836

Table 8: 3D seismic investigations in Poland, transnational project area of 3DGEO-EU, WP2: surveys and total area

Year of seismic survey	Number of surveys	total area [km^2]
1993-1995	2	180
1996-2000	5	351,4
2001-2005	2	233
2006-2010	1 (reprocessing)	102,6

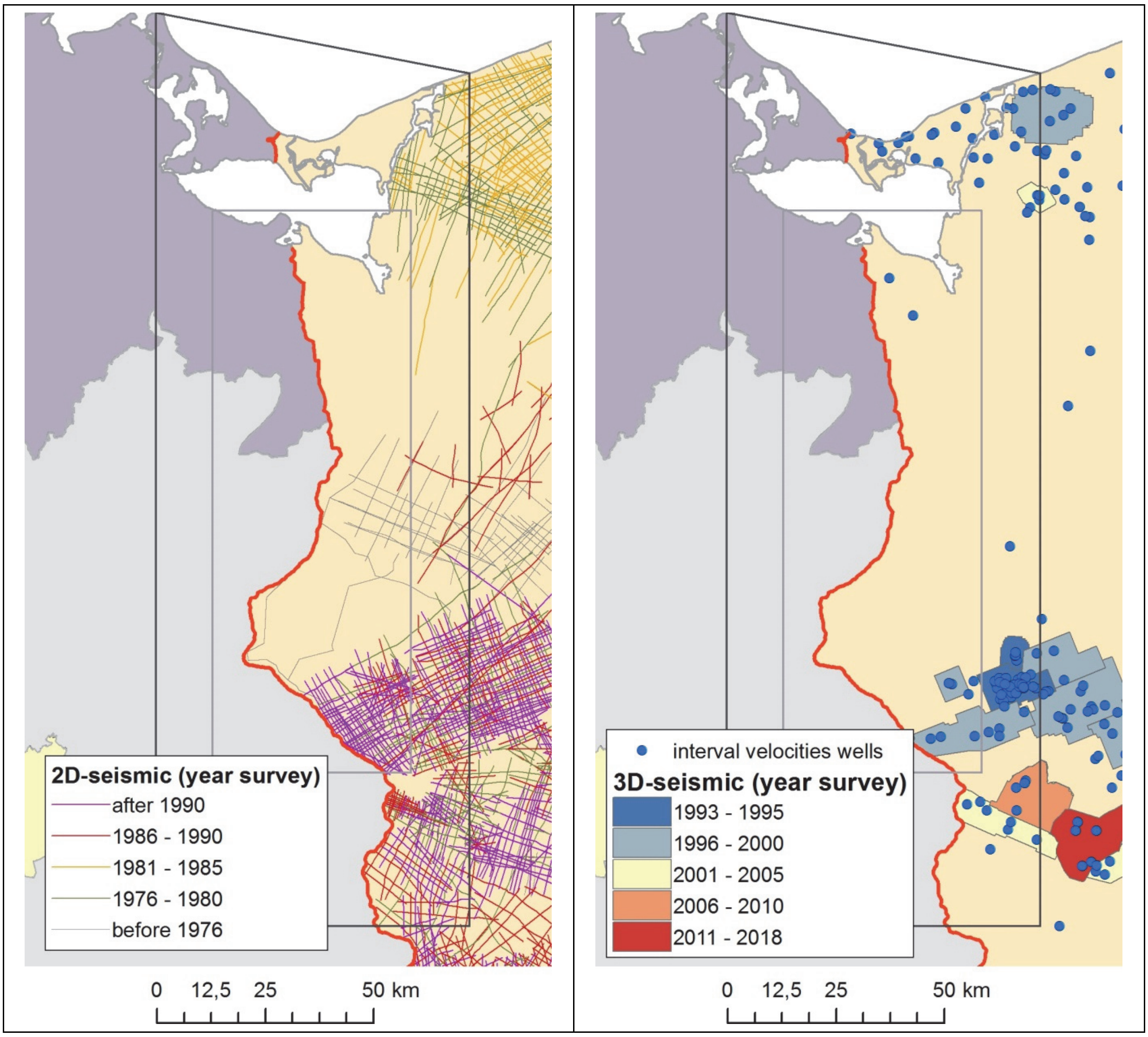

Figure 12: Seismic investigations in Poland: left: 2D-profiles grouped by the year of the survey, right: 3D surveys grouped by the year of the survey and wells with average velocities.

Average velocities based on checkshots and VSP logs were calculated for 94 wells drilled since the 1976 till 2010 (Figure 12, right). Interpretations of target horizons and velocity models are documented for most of the seismic surveys. Large number of 2D and 3D seismic surveys made it however impossible to harmonize velocity models at the regional level. Although in most cases (especially for newer surveys) seismic reference datums and processing schemes were unified, significant edge effects can be observed on overlaps of the surveys in depth domain. As processing and interpretation were focused on target hydrocarbon reservoirs, in most cases only Permian and lower Triassic horizons were interpreted in original documentations with some younger reflectors picked sporadically. Several surveys were later linked to new wells and each other and reprocessed by oil and gas companies or their subsidiaries, resulting in harmonized interpretations covering various, although still sub-regional, areas. Some seismic profiles and 3D seismic surveys were thus reevaluated several times.

In summary, a good coverage with 2D and 3D seismic and a reliable interpretation exist in north-eastern and southern part of the Polish side of the study area. Unfortunately, there are significant data gaps over much of the central study area, where only a few vintage seismic profiles exist in analogue version (dating from the sixties, light grey lines on Figure 12). In this gap area model building and harmonization efforts will need to be aided by gravimetric and magnetic data.

Most of the near-border seismic data is State-owned and its sharing within the project is subject to a separate approval by the Polish State.

2.4.3 Gravity

2.4.3.1 General characteristic of gravimetric datasets in Poland

Gravity data were acquired in many geophysical surveys covering the whole Polish territory (over 300 projects from 1957 and over 1.3 mln gravity points acquired up to the present). Such projects (“campaigns”) were carried out for investigations of geological structures. All the data acquired are stored in digital form, about 98% in the Central Geological Database (CBDG – Centralna Baza Danych Geologicznych) managed by National Geological Archives (NAG – Narodowe Archiwum Geologiczne) in the Polish Geological Institute (PGI-NRI). All of the gravity data stored in the CBDG were acquired by one geophysical survey enterprise. Thus the data, independently of acquisition time, were acquired with the same methodology and methodic regarding official (state) and internal (enterprise’s) regulations and rules. However, some techniques of acquisition, data processing and documentation principles developed over time of the data acquisition and database feeding. In the Central Geological Database (CBDG) gravity data are stored in two digital datasets: semidetailed and detailed.

The main gravity database is the gravity dataset obtained from semi-detailed gravity surveys. Within the study area this database contains 17539 measurement points. It is a homogenous (seamless) collection of gravity data. Each data files selected from main set may be reprocessed and presented independently of source projects, their borders and other details.

The second gravity data base is the gravity data set obtained from detailed gravity investigations directed for detailed, local geological structures investigation. The detailed gravity database isn’t homogenous with main, semi-detailed data base. It is possible to join this data with data from main, semi-detailed database with additional, time consuming preparation and data reprocessing.

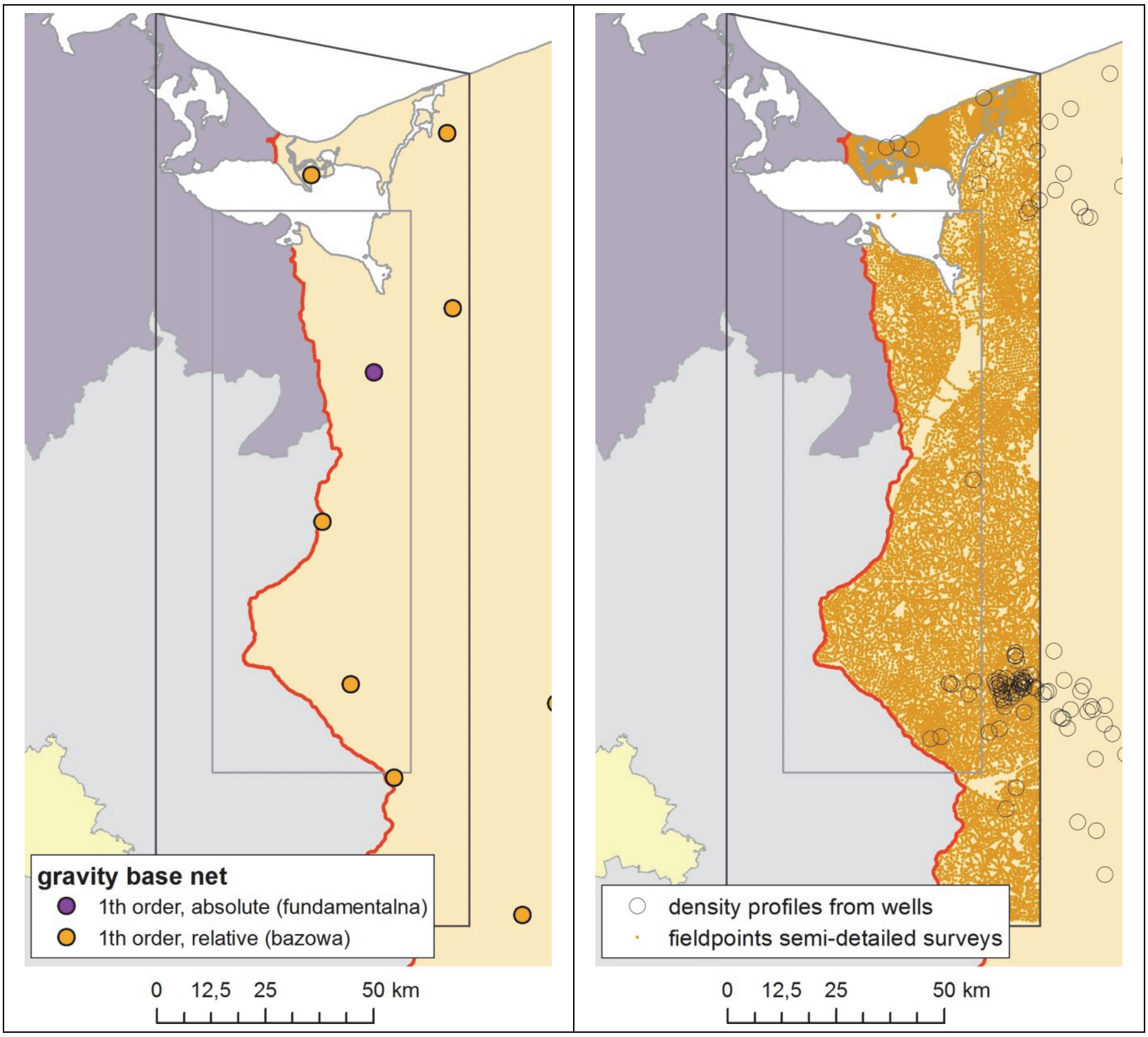

Figure 13: Left: current gravity base network in Poland. Right: seamless semi-detailed gravity measurement points + wells with density profiles

2.4.3.2 Semi-detailed and detailed gravity surveys and interpretations

The stacked, **semi-detailed** stations cover Poland territory with average station density of 2.0 up to 10 st./sq. km (see **Figure 13**). The semi-detailed gravity measurements within NW part of Poland were executed using Sharpe, Sodin, Scintrex CG-2 and Master Worden relative gravitymeters. In each project the gravity force acceleration g was measured with error less than ±0.030 mGals (after introducing drifts and tidal correction). The errors of measurements were calculated on a base of repeated measurements. 5-10% of the stations were repeated in the course of gravimetric projects execution.

After 2005 coordinates of all gravity stations were transformed step by step from older coordinate system to current PL CS92 system via Pulkovo42 system. Up to 2005 the semi-detailed 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. The height/elevation of the gravity stations were obtained from leveling measurements. The precision of the gravity stations leveling and elevations determination is better than ±0.05 m.

The absolute value of the gravity force acceleration at the gravity station location is in the reference to Potsdam gravity datum. 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.

Several **detailed** gravimetric surveys have been obtained within the study area. Nonetheless, these datasets are non-evenly distributed nor could they easily be combined with semi-detailed dataset covering continuously the entire study area (Figure 13). Taking into consideration the areal extend of the project and the vertical pile represented in the models to be harmonized, these data are deemed not useful for further analysis within the scope of the current project.

Given the existence of digital, seamless gravimetric database, interpreted/map data, however useful for general overview, will not directly aid analytical effort in this project. Overview gravimetric maps are available in paper format only (Królikowski C., Petecki Z., 1995; Gravimetric map of Poland in the scale 1:200k and 1:50k 1973–1994 several authors).

Finally, within the study area density data exists in 62 wells over 2 000 m deep to aid gravimetric modelling. This data is however highly clustered (Figure 13).

3 COOPERATION PROJECTS IN THE PAST

3.1 Cooperation before 1990

3.1.1 Seismic velocity analyses and models, interpretation and harmonization of seismic reflectors (1973-1980)

First co-operations between Eastern Germany and Poland in the investigation of the North German-Polish Basin took place in the 1970th. The results of the investigations were not published and only used in internal reports. The cooperation was stopped obviously in the beginning of the 1980th.

In the former Eastern Germany seismic velocity models were developed and systematically updated basing on available check-shots and VSP from the 1960th to the 1980th (Reinhardt 1968a)(Reinhardt 1967, 1968b, 1969, 1970, 1972, 1973, 1977, 1988). Within the scope of this investigations also a seismic velocity model was developed for the Polish-German border region on the basis of data from 60 wells from Eastern Germany and 19 wells from Poland (Reinhardt 1977). The model defines stepwise velocity functions v = f(z) for two different layers (Figure 14):

1) NN-M_1: from Cenozoic to Top of Middle Triassic (reflections horizon M_1) and

2) M_1-Z_1(Z_2): from Middle Triassic (Muschelkalk) to Top Basal Anhydrite Staßfurt-Formation (reflection horizon Z_1 in Eastern Germany, Z_2 in Poland). For the second layer two slightly different curves were developed depending on the depth of the reflector Z_1/Z_2.

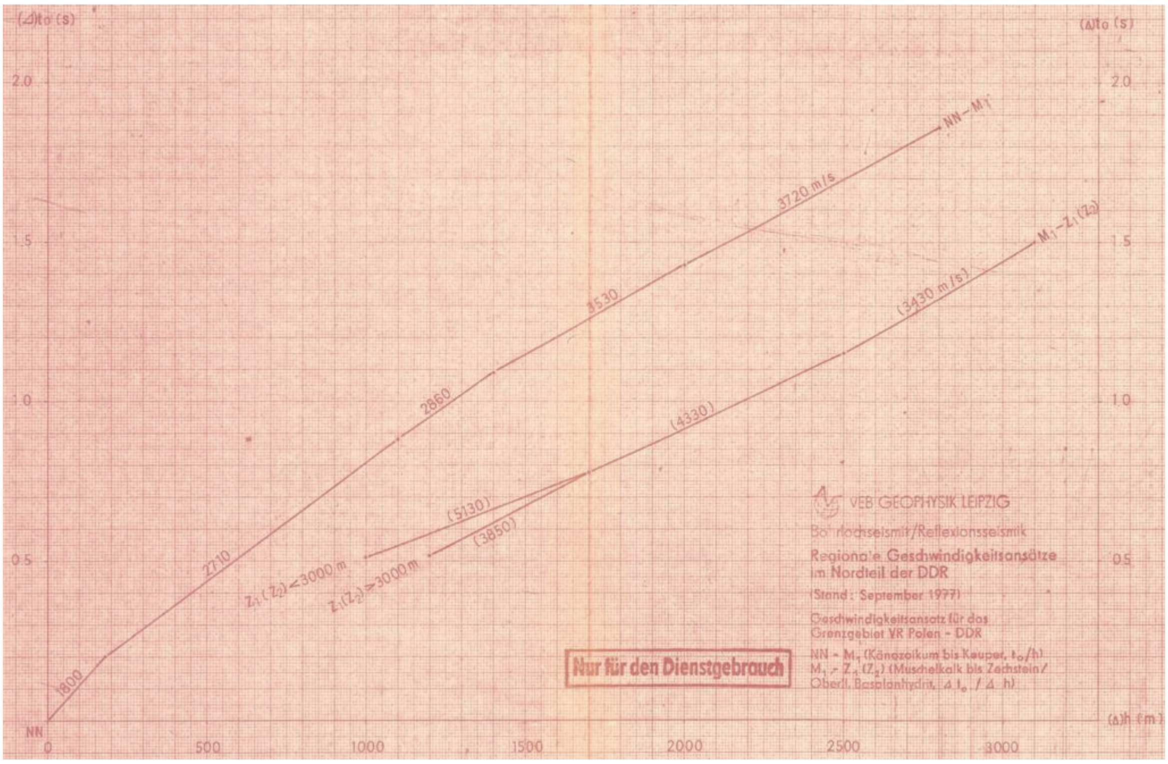

Figure 14: Simplified velocity model for the German-Polish border region (Reinhardt 1977)

The simplified approach was possible because of the relative simple geological structure of the region (less intensive salt tectonics and faulting, relative flat layering, similar lithology at both sides). For the Pre-Zechstein strata the data base was insufficient at that time.

The validity range of the velocity model spreads from the northern border of the basin (from south of the “Grimmener Wall”) to the southern border (Reinhardt 1977) with a width of 70-120 km along the border. It covers the nearly the whole project area of the WP2, 3DGEO-EU (Figure 15).

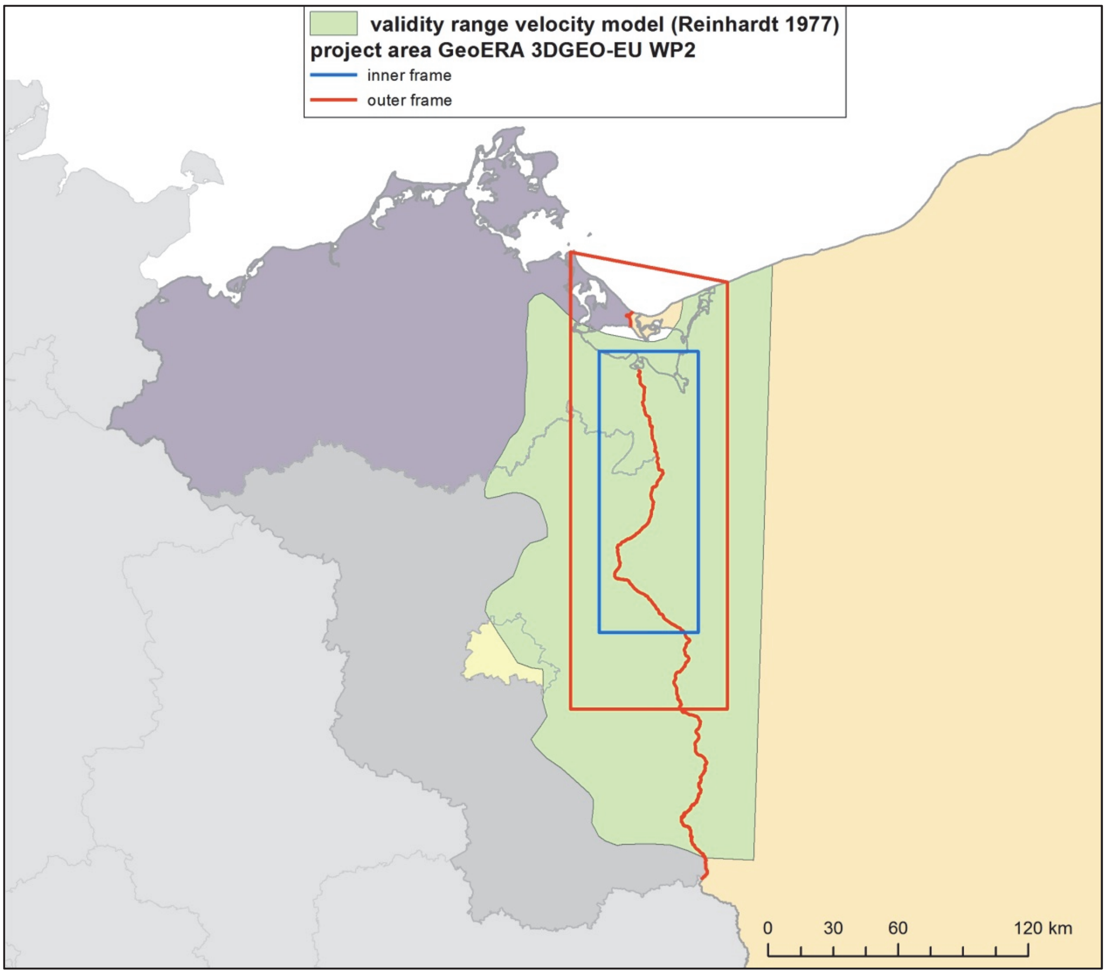

Figure 15: Validity range of the velocity model for the German-Polish border region (Reinhardt 1977)

In a region with a width of 70 km along the border between Eastern Germany and Poland the results of the seismic investigations were harmonized (Figure 16) by means of a common interpretation of the material from both countries. Cross-border investigations have not been performed. Joint maps were compiled and updated between 1973 and 1980 for the following reflectors in the scale of 1:100.000 (VEB Geophysik Leipzig, Abteilung Seismik 1978, 1980):

Reflection horizon	Stratigraphic interpretation
S1	Top of Sulfates Salinarröt (Upper Bunter, Lower Triassic)
X1	Top Zechstein Salt
X2	Top Main Anhydrite, Leine Formation, Zechstein
Z1	Top Basal Anhydrite Staßfurt Formation, Zechstein
Z3	Base Werra-Anhydrite, Werra Formation, Zechstein

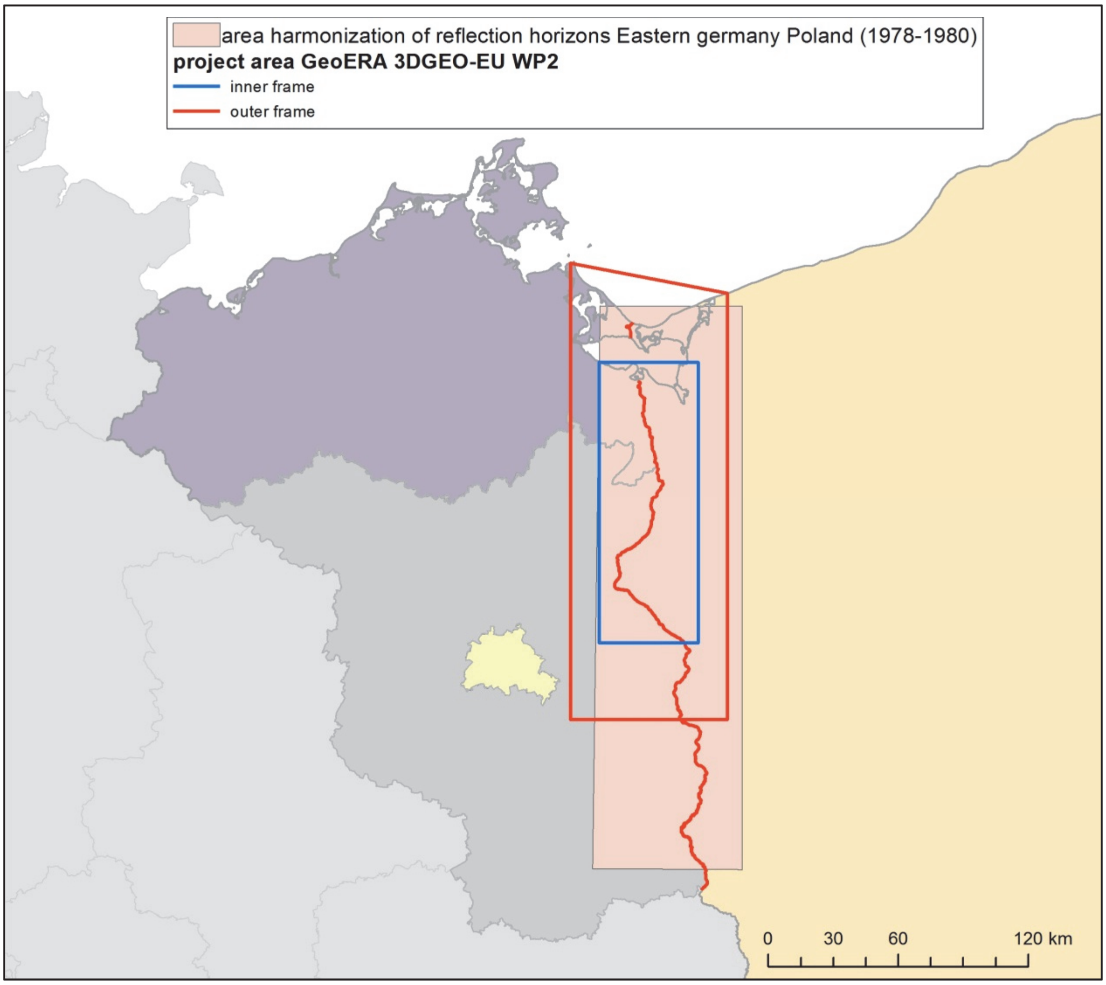

Figure 16: Cooperation Eastern Germany – Poland: Area of harmonization of seismic reflectors (1973-1980)

The depth contour maps show in principle the same data gaps as shown in Figure 2. Partially data seemed to be extrapolated or older data were used in these regions that are not in the current databases of PGI-NRI, LBGR, LUNG.

The work of the German-Polish cooperation was done with seismic material from the 1960th and 70th. So the seismic exploration in the 1980th and after 1990 (especially at the Polish side) is of course not incorporated. The maps are showing general depth tendencies of reflectors, major structures and fault inventory at both sides without or only very little inconsistencies at the border (**Figure 17**). The maps roughly match the younger investigations. The cooperation showed that a harmonization of the material is possible on the basis of common interpretation at both sides of the border even if direct cross-bordering data don't exist.

Figure 17: German-Polish harmonization of seismic reflectors 1978-1980, reflector S1, depth contours (detail), scale 1:100.000, border region Brandenburg-Poland (VEB Geophysik Leipzig, Abteilung Seismik 1980)

3.1.2 Adjustment and joint interpretation of gravity data (1976-1983)

Also co-operations between Eastern Germany and Poland in the harmonization and interpretation of gravity data took place during the 1970th and the beginning of the 1980th. The work was carried out in two projects (Szczecin-Frankfort/O. completed 1978 and Frankfurt/O.-Szary completed 1983). The project area covers especially the border region between Brandenburg and Poland (**Figure 18**). The results were documented in internal reports (Jamrozik et al. 1978, 1984).

The cooperation based on existing gravity surveys at both sides but also included joint measurements to connect the national networks of Eastern Germany and Poland (field campaigns 1976 and 1979). A constant difference of $\approx 0,2$ mGal between the German and Polish data were determined. For network adjustment the polish data were reduced by this value in the project areas. The corrections/reductions of the gravity measurements at both sides were done in different ways. E.g. for the Bouguer-Reduction in Eastern Germany a constant density 2 g/cm³ was used, in Poland variable densities from 2,18 to 2,21 g/cm³. For the adjustment a continuous reduction of the density from 2,18-2,21 g/cm³ down to 2 g/cm³ were done in a distance of 10 km from the border at the polish side.

The primary data (including regional surveys with point distances of 1,2 - 1,5 km and semi-detailed surveys with point distances 500-750m) had a different degree of detail. For finalization all data were interpolated to consistent Bouguer maps in scale 1:100.000.

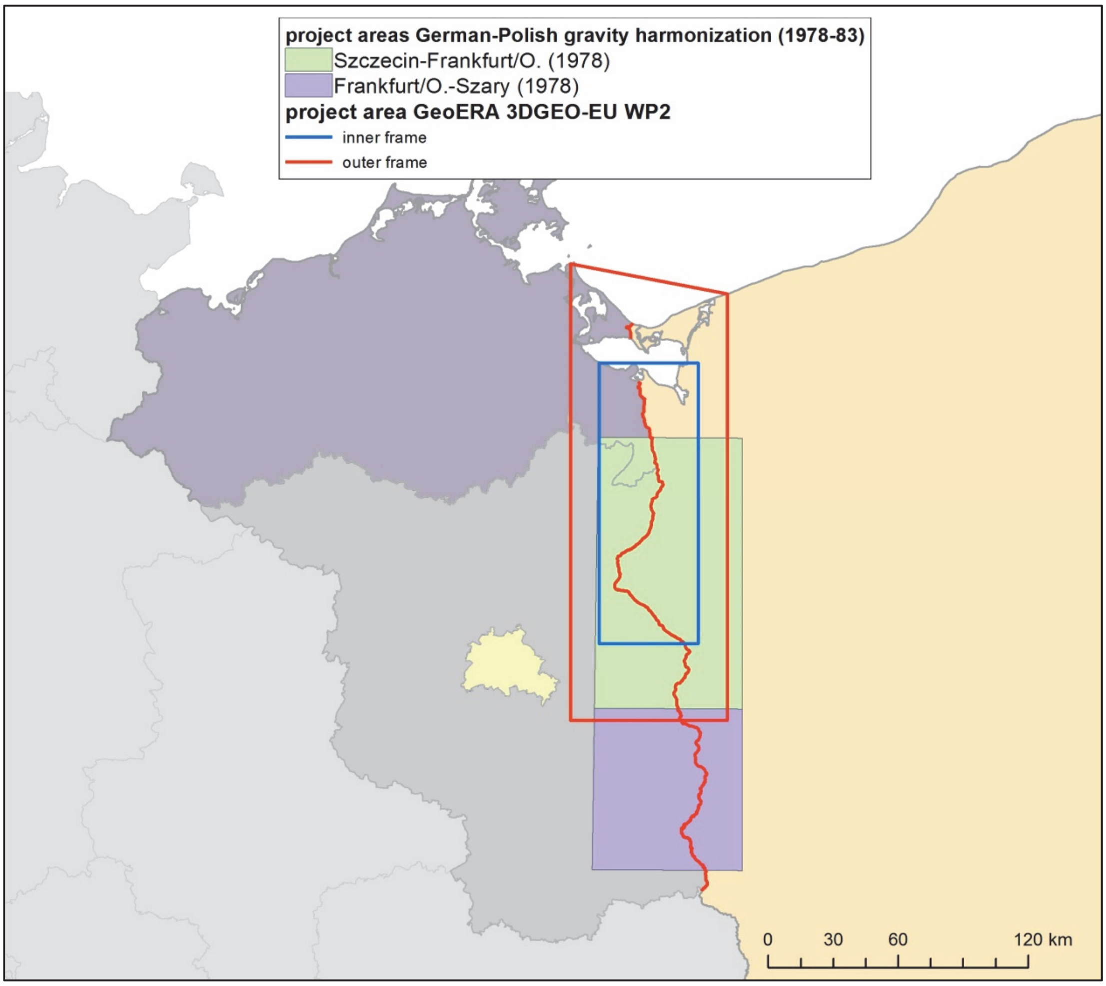

Figure 18: Areas of the joint Polish-German harmonization of gravity data (1978-83)

The reports include in addition an analysis of the existing density data and density models and calculated gravity profiles based on cross sections and density models (not cross-bordering).

3.2 Projects after 1990

3.2.1 Morphotectonic Map of the European Lowland Area (MELA-Project, 2004-2008)

The MELA project was coordinated by the PGI-NRI within the frame of the Maria Curie Host Scholarship Programme of 6th Framework Programme of EU (Kowalski et al. 2008). The project was prepared for the Transfer of Knowledge (ToK), and Development Host Scheme. Several partner institution from different European countries participated in the project, e.g. the Technical University of Berlin, the State Geological Surveys of Brandenburg (LBGR) and Mecklenburg-Western Pomerania (LUNG). The project faced following problems:

• Impact of the various tectonic structures on the glacial processes in Pleistocene, in connection with multiphase liquid flow in the basement,

• Correlation of the in situ and remote sensing methods (including interferometry), in the analysis of the young Alpine, glacitectonic and neotectonic structures to define zones with especially intensive disturbances, influencing hydrodynamic field and initiating mass movements,

• Assessment of the nuclear physics techniques utilized in direct of age dating as well as testing environmental pollution, and

• Applying of new prospecting geophysical and geochemical techniques.

The project made it possible to systematize the knowledge of a study area in the Lower Oder/Odra River region with reference to newly obtained geophysical, geothermal, geochemical, SAR interferometric and other data. The information were added to a GIS database and presented either as vector or raster data or as spatial digital models (**Figure 19**, **Figure 20**). Because of the very wide spectrum of phenomena and processes taking place at and beneath the terrain surface, it was decided to present the obtained results in two separate plates of the map in the scale of 1:250,000.

Plate I, compiled for specialized users, shows the recorded geological phenomena, elements of palaeorelief, tectonic features, geophysical and geothermal anomalies, hydrological and hydrogeological indices and other features. In turn, Plate II was designed for the users such as town-planners, land-use planners and local and regional administration so it shows the studied areas from the point of view of advantageous and disadvantageous conditions and constrains for habitation and location of new settlements and economic activities. The studies carried out within the frame of MELA Project also included comparative analyses of reference areas. The studies made it necessary to elaborate a methodology for compilation of the map and its explanatory note.

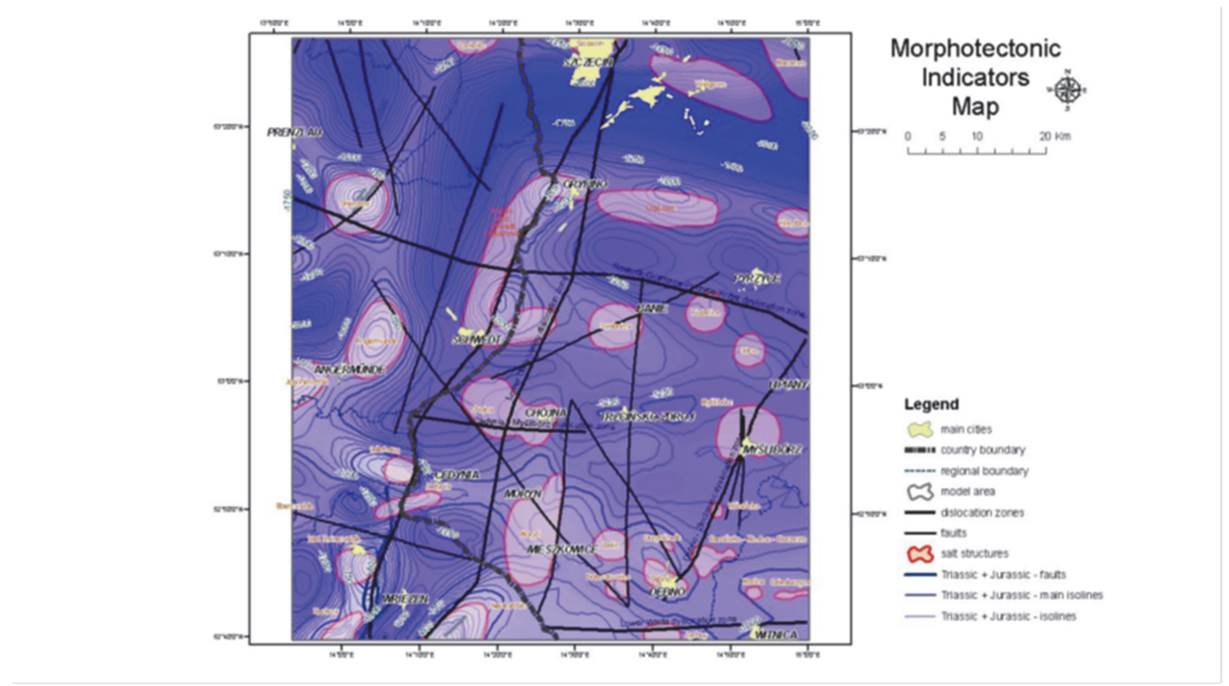

Figure 19: Map of the MELA project area between Germany and Poland showing the salt structures and faults (Project Report 2008, unpublished).

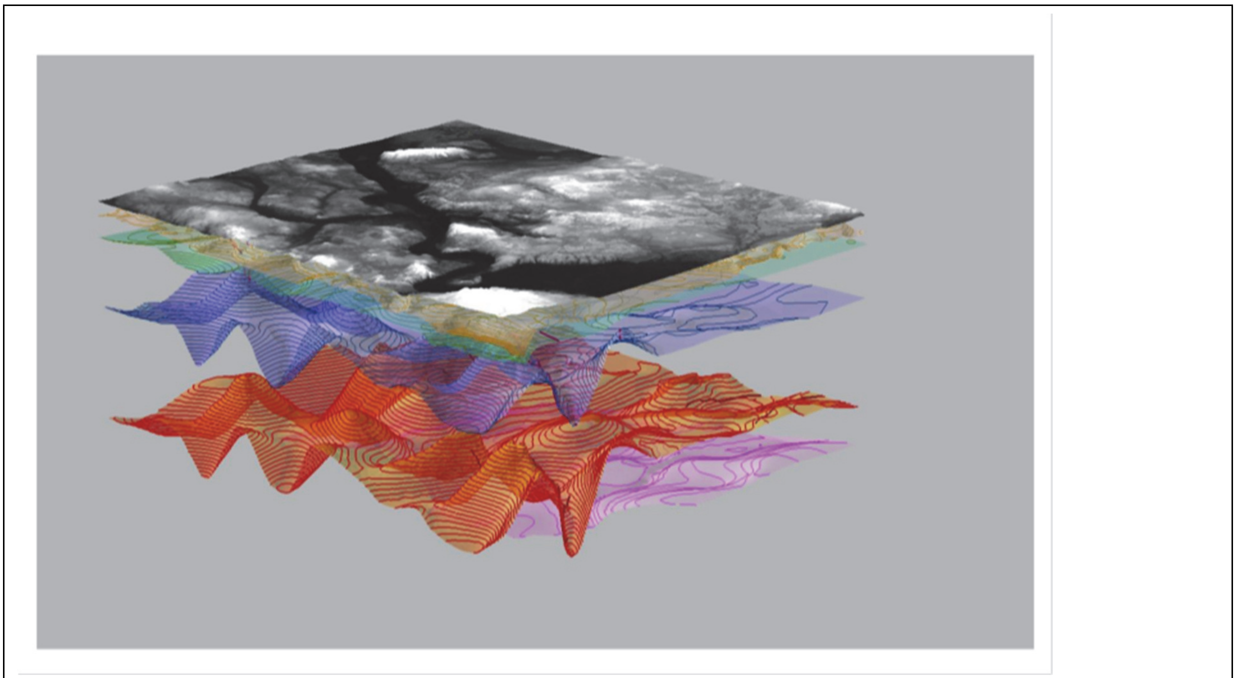

Figure 20: 3D model of the MELA project area between Germany and Poland with modelled stratigraphic horizons (Project Report 2008, unpublished).

3.2.2 Petroleum Geological Atlas of the Southern Permian Basin Area (SPBA–Project, 2010)

The SPBA project was a joint project of the Geological Surveys of the United Kingdom, Belgium, Denmark, the Netherlands, Germany and Poland initiated by Ken Glennie and coordinated by the TNO. The atlas was published in both paper and digital format. The project has been supported by a wide range of petroleum E&P companies, licensing authorities, research institutes and universities.

The atlas (Doornenbal and Stevenson 2010) aims to present a comprehensive and systematic overview of the results of over 150 years of petroleum exploration and research in the Southern Permian Basin area and stimulate the petroleum E&P industry to continue their activities in this mature basin. It contains a review of the entire Southern Permian Basin area. The atlas addresses the geological evolution and hydrocarbon potential per stratigraphic interval. The paleogeographic and tectonic evolution is covered within the framework of the principal stratigraphic intervals, from the pre-Cambrian basement to the Holocene. In addition, petroleum generation, migration, trapping and production as well as the history of exploration and licensing in the basin are covered, together with a summary of resource assessments and other potential options for use of the deep subsurface such as gas storage and geothermal energy (https://www.nlog.nl/southern-permian-basin-atlas). The project database comprises various types of spatial data: well and seismic data, oil and gasfield attributes, geochemical and gas composition data. GIS Maps, which are presented in the Atlas can be imported in Petrel and ArcGIS.

An important aspect is the stratigraphic correlation on a European scale that includes of course the local lithostratigraphic units of Germany and Poland (see Figure 21, example for the Triassic) and large scale depth and thickness maps.

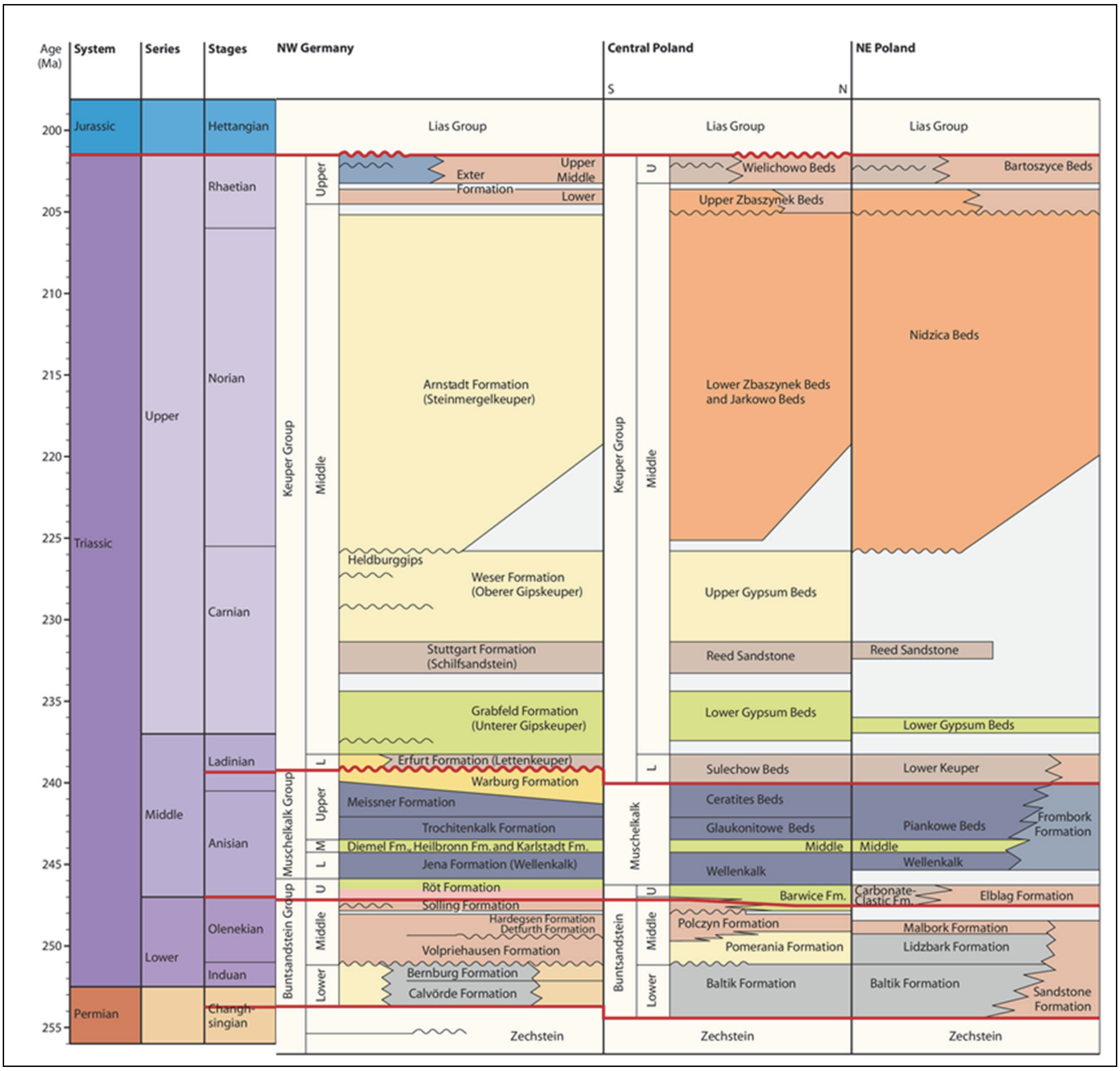

Figure 21: Southern Permian Basin Atlas (Doornenbal and Stevenson 2010), Chapter 9 Triassic, Figure 9.1, Triassic correlation chart.

3.2.3 Cross-border Geology between Poland and Germany (GEOPOLD-Project, 2010-2017)

The GEOPOLD project was initiated and coordinated by the BGR. It was supported by the Polish Geological Institute (PGI-NRI), the State Geological Surveys of Mecklenburg-Vorpommern (LUNG) and Brandenburg (LBGR). The aim was to harmonize selected reservoir and barrier formations across the Polish-German border. The work includes a detailed examination of litho-stratigraphic units especially of the Mesozoic, incorporating sequence-stratigraphic aspects and interpretation of borehole measurements. The results of project, which can be integrated in a regional geological 3D model, are documented in unpublished reports (Barth and Kuhlmann 2018; Kuhlmann 2018).

4 DEVELOPMENT OF GEOLOGICAL 3D-MODELS – CURRENT NATIONAL STATUS

4.1 Brandenburg - State Office for Mining, Geology and Raw Materials Brandenburg (LGBR)

Within in the project "Brandenburg 3D" (B3D, duration 2013-2014) the Geological Survey of Brandenburg started digitizing its predominantly analog archive inventory and developing a geological 3D model as well as an infrastructure node to integrate all geological and spatial data within the Spatial Data Infrastructure Brandenburg and provide it to the public through an interactive 2D/3D web application. The geological 3D model of Brandenburg includes surfaces of the 12 most important seismic reflector horizons from the base of Cenozoic to the Lower Permian, along with a large-scale fault-network and a detailed Zechstein-salt surface basing on well data and depth contour maps in a scale of 1:100.000 (Reinhardt 1965, 1993).

All data are stored in a data infrastructure build of Free and Open Source Software, including databases and customized interfaces. A publishing tool allows the publication of approved 2D and 3D data sets to a web server that in turn provides it through OGC services to the web. To make the results of B3D available to external users, the web portal "Brandenburg 3D" provides a 2D- and a 3D-viewer (based on WebGL) with components typical of a WebGIS like an overview-map and a layer tree (http://www.geo.brandenburg.de/Brandenburg_3D/, Figure 22).

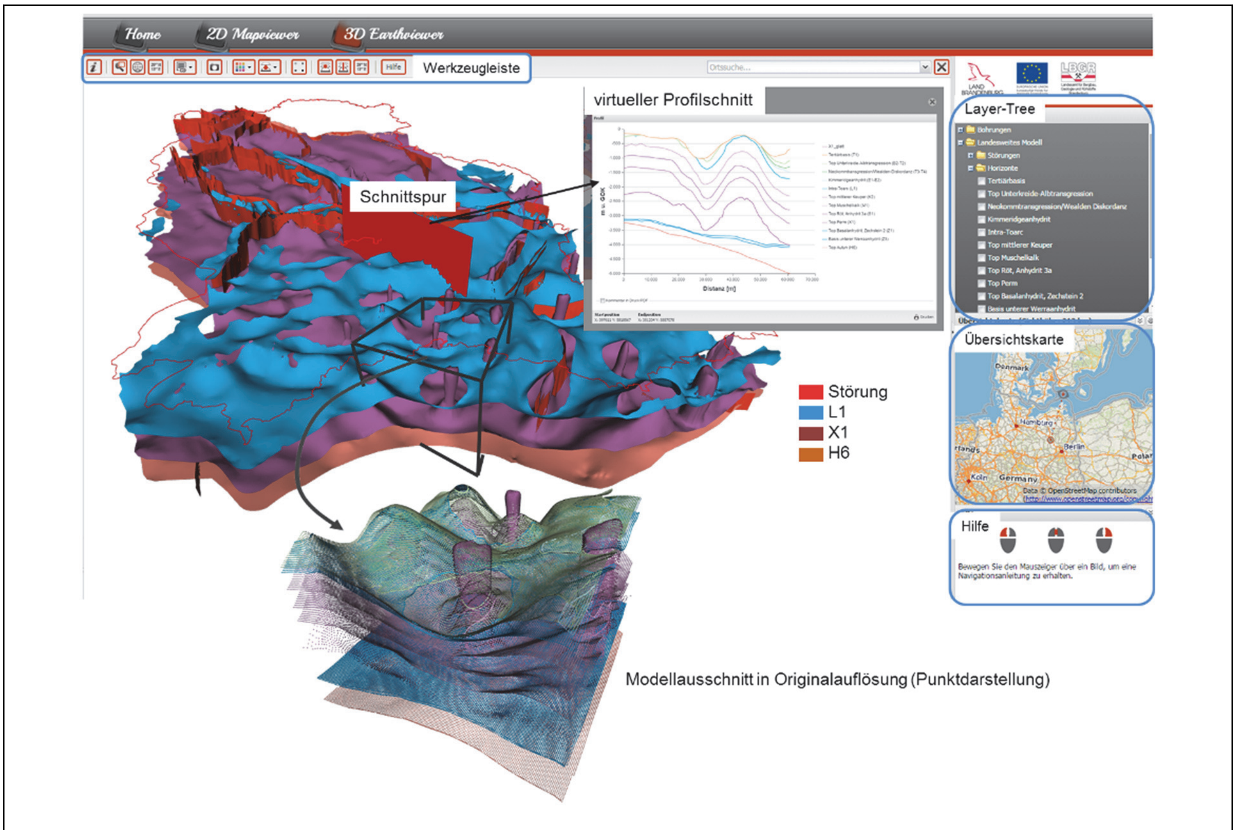

Figure 22: 3D-modell of the subsurface of Brandenburg, web portal: 3D Viewer, representation of some functionalities of the viewer, e.g. creating virtual cross sections and request for model data with original resolution

Within the ongoing project "Subsurface potentials for storage and economic use in the North German Basin" (TUNB) (duration 2014-2021) the subsurface model of Brandenburg B3D is enhanced at the time. In a close cooperation of the Federal Institute for Geosciences and Natural Resources (BGR) and the Northern Federal States of Germany a consistent basin-wide 3D model of the subsurface in the North German Basin including the German North Sea is developed. The subsurface model of Brandenburg is completed in the framework of this project with the major lithostratigraphic groups and boundaries of the Mesozoic an Upper Permian and a more detailed fault network. The model has a working scale of 1:100.000 to 1:50.000 depending on the resolution of the primary data and covers a region of nearly 30.000 km². The work is performed with the software SKUA/GoCAD® basing on boreholes, depth migrated seismic and interpreted structural maps.

4.2 Mecklenburg-Western Pomerania – State Authority for Environment, Nature Conservation and Geology (LUNG)

Since 2014, the Geological Survey of Mecklenburg-Western Pomerania is developing a 3D model of the subsurface of the northeastern German federal State Mecklenburg-Western Pomerania (Figure 23) as part of the government-funded TUNB project (also named Subsurface potentials for storage and economic use in the North German Basin). The model, which comprises an area of about 25,000 km^2 is based on well data and 2D seismics – mainly obtained from hydrocarbon exploration between 1960 and 1990. The model represents 13 stratigraphic horizons ranges from the base Zechstein to Ruplian base. Furthermore, important Mesozoic fault systems as well as faults of the base of Zechstein are modeled. As agreed with all project partners, the model is created with SKUA/GoCAD®.

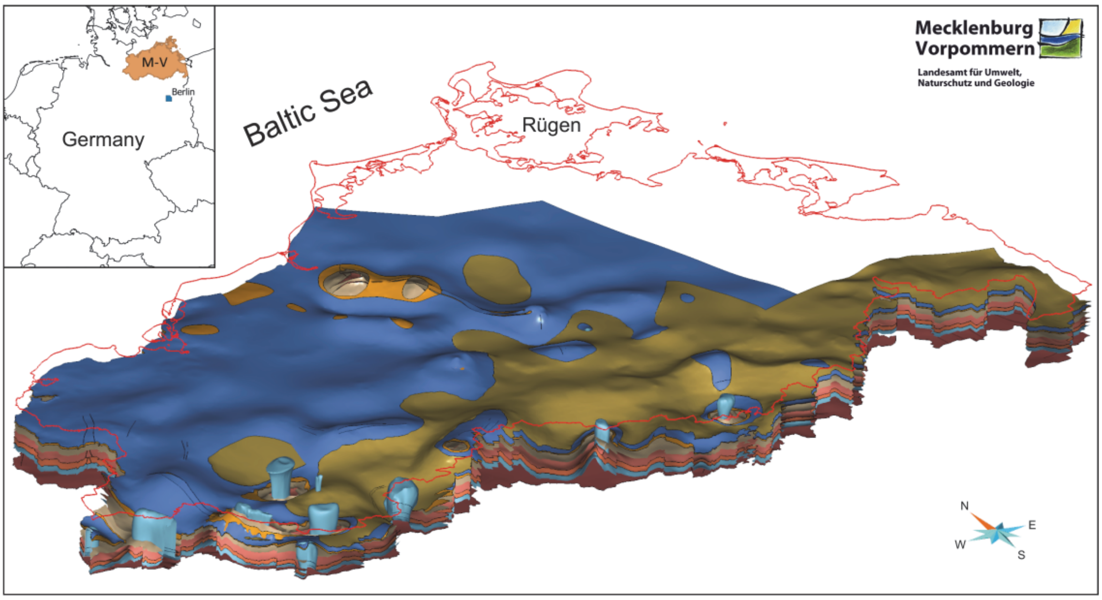

Figure 23: 3D model of Mecklenburg-Western Pomerania with horizons from base Zechstein to base Middle Jurassic (Obst et al. 2019).

4.3 Poland – Polish Geological Institute (PGI-NRI)

Current 3D modeling activities in Poland (PGI-NRI) follow three scale-dependent, interrelated paths: country-scale framework geological modelling, basin-scale (or major tectonic unit) modelling, and local-scale, for-purpose modelling (hydrocarbons, geothermal, mineral deposit etc.). This strategy was described in several reports and papers (Jarosiński et al. 2014; Małolepszy et al. 2015; Małolepszy and Szynkaruk 2018) and is being consequently applied in the PGI-NRI.

The country-wide modeling will start in mid-2019 and will include construction of greatly improved (as compared to the 2005 version) "Framework 3D Model of the Geology of Poland". This model will incorporate much more data, will be an opportunity to verify and upgrade the content of the Institute's Central Geological Database and will serve as a reference for all other models we produce.

The basin-scale models are of the most interest to the 3DGEO-EU project as two of those models overlap with our study area: the Gorzów block model and the Szczecin Through model (see Figure 1, Figure 24. These models will be used as input for harmonization with the Northern German basin model within the present project. The models on Polish side of the study area are being developed within the framework of Polish geological survey long-term activities aiming at construction of 3D regional-scale models for all sedimentary basins of Poland. These models are based on all seismic and deep well data available. They reach depths of several km, analyzing entire stratigraphic pile from the topographic surface down to at least the depth of reliable (well) information. They comprise several stratigraphic horizons, major and medium-scale faults and geologic grids showing distribution of several key parameters such as lithology, shale ratio, porosities, permeabilities, temperatures etc.

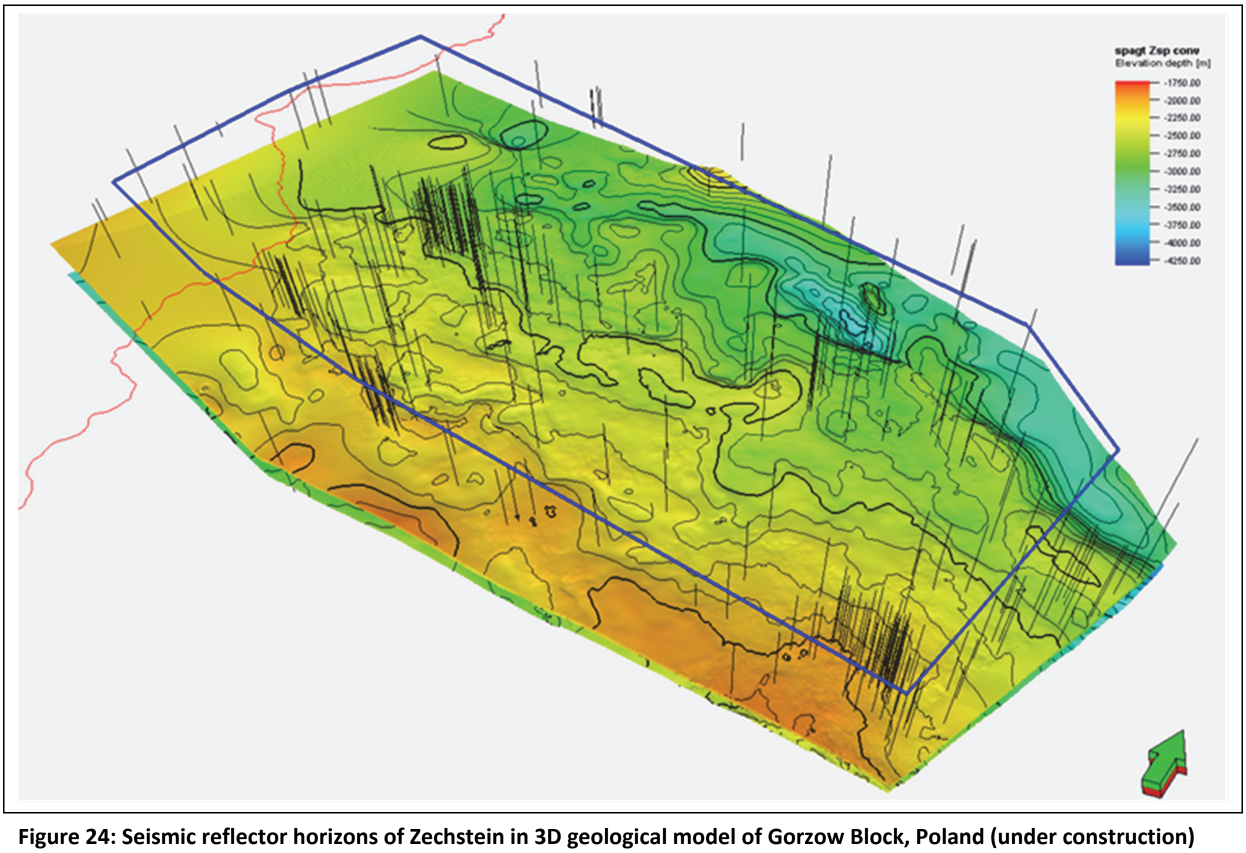

Figure 24: Seismic reflector horizons of Zechstein in 3D geological model of Gorzow Block, Poland (under construction)

5 CONCLUSIONS AND OUTLOOK

The chapter 2 shows that the national data bases are comparable in quantity and quality on the Polish and German side in the field of drillings, seismic and gravity. Challenges are the existing data gaps in wellbore and seismic exploration in the central study area (surround Chojna and in the region Szczecin Lagoon - Stargard-Szczecinski - Gryfino) and the different age and processing state of the investigations from the 1960s to recent data. In order to close the data gaps in seismic and well exploration at the Polish-German border region the use of gravity data is planned. Gravity data cover the whole project area (except for the water areas of the Baltic Sea and the Szczecin lagoon).

Because of legal restrictions only a part of the data can be shared in the project and published (public research and national investigation wells, gravity data). The non-public data can only be used in the internal work of the partners (but will be used in the development of the models).

The cooperation between Germany and Poland in the 1970s was focused on the geophysical investigation (harmonization of seismic velocities, correlation of seismic reflectors, adjustment of gravity networks). Unfortunately this cooperation stopped in the beginning of the 1980s, but basic knowledge was developed that can be used for the ongoing work.

The cooperation after 1990 was focused on greater European scales (Southern Permian Basin Area, SPBA Atlas) or to individual aspects (projects MELA, GEOPOLD).

The work package 2 (WP2) of the project 3DGEO-EU will continue these earlier works and will incorporate and combine several aspects of it to a consistent 3D-model, that will be an opportunity to verify and upgrade the content of the national data bases.

The work will show on the example of a cross-border pilot area how harmonization across the borders can be established and maintained with the progress of the national models. The methodologic advantages (agreements on best practices, optimized workflows, etc.) and the gain in experience on cross-border 3D harmonization work will be a keystone for further transnational harmonization projects.

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