Int J Earth Sci (Geol Rundsch) (2017) 106:1651–1663
DOI 10.1007/s00531-016-1379-z

ORIGINAL PAPER

3D geological modeling of the transboundary Berzdorf–Radomierzyce basin in Upper Lusatia (Germany/Poland)

Iwona Woloszyn[1] · **Broder Merkel**[1] · **Klaus Stanek**[2]

Received: 29 April 2015 / Accepted: 12 July 2016 / Published online: 22 August 2016

Abstract The management of natural resources has to follow the principles of sustainable development. Therefore, before starting new mining activities, it should be checked, whether existing deposits have been completely exploited. In this study, a three-dimensional (3D) cross-border geologic model was created to generalize the existing data of the Neogene Berzdorf–Radomierzyce basin, located in Upper Lusatia on the Polish–German border south of the city of Görlitz–Zgorzelec. The model based on boreholes and cross sections of abandoned and planned lignite fields was extended to the Bernstadt and Neisse-Ręczyn Graben, an important tectonic structure at the southern rim of the basin. The partly detailed stratigraphy of Neogene sequences was combined to five stratigraphic units, considering the lithological variations and the main tectonic structures. The model was used to check the ability of a further utilization of the Bernstadt and Neisse-Ręczyn Graben, containing lignite deposits. Moreover, it will serve as a basis for the construction of a 3D cross-border groundwater model, to investigate the groundwater flow and transport in the Miocene and Quaternary aquifer systems. The large amount of data and compatibility with other software favored the application of the 3D geo-modeling software Paradigm GOCAD. The results demonstrate a very good fit between model and real geological boundaries. This is particularly evident by matching the modeled surfaces to the implemented geological cross sections. The created model can be used for planning of full-scale mining operations in the eastern part of the basin (Radomierzyce).

Keywords Numerical modeling · Sedimentary rocks · Berzdorf subbasin (Germany) · Radomierzyce subbasin (Poland) · Upper Lusatia

Introduction

The study area is located on the Polish–German border to the south of the city of Görlitz–Zgorzelec (Fig. 1). The Berzdorf–Radomierzyce basin belongs to the northeastern element of the Eger Graben, which is an elongated tectonic depression running parallel to the southern slope of the Ore Mountains (Kasiński and Saternus 2002). The isolated terrestrial basin is filled by Miocene sediments containing lignite seams. Formation of the brown coal started 22 Ma ago in the Middle Miocene and lasted for over 7 Ma (Tietz and Czaja 2004). The basin is divided into the western Berzdorf subbasin—and the eastern Radomierzyce subbasin. The smaller Berzdorf subbasin is located in Germany and has a horizontal extension of 3 × 8 km (Bender 2004), whereas the bigger Radomierzyce subbasin on the Polish side has an extension of around 9 × 20 km (Hirsch et al. 1987).

The deposit in the Berzdorf area has been exploited from 1830 until 1997, whereas the Radomierzyce deposit has never been exploited. Nevertheless, the reconnaissance works in category C-2 were conducted from 1979 until 1980. The last attempt to restart the reconnaissance works was carried out in the context of the Foresight project in 2007. A simple geological model was developed, and the boundary of the economic viability of the deposit was set (Nowak 2007a). After the end of the rehabilitation of the open pit mine Berzdorf and its terminated flooding in 2010,

---

✉ Iwona Woloszyn
Iwona.Woloszyn@geo.tu-freiberg.de

[1] Chair of Hydrogeology, Institute of Geology, TU Bergakademie Freiberg, 09596 Freiberg, Germany

[2] Chair of Tectonophysics, Institute of Geology, TU Bergakademie Freiberg, 09596 Freiberg, Germany

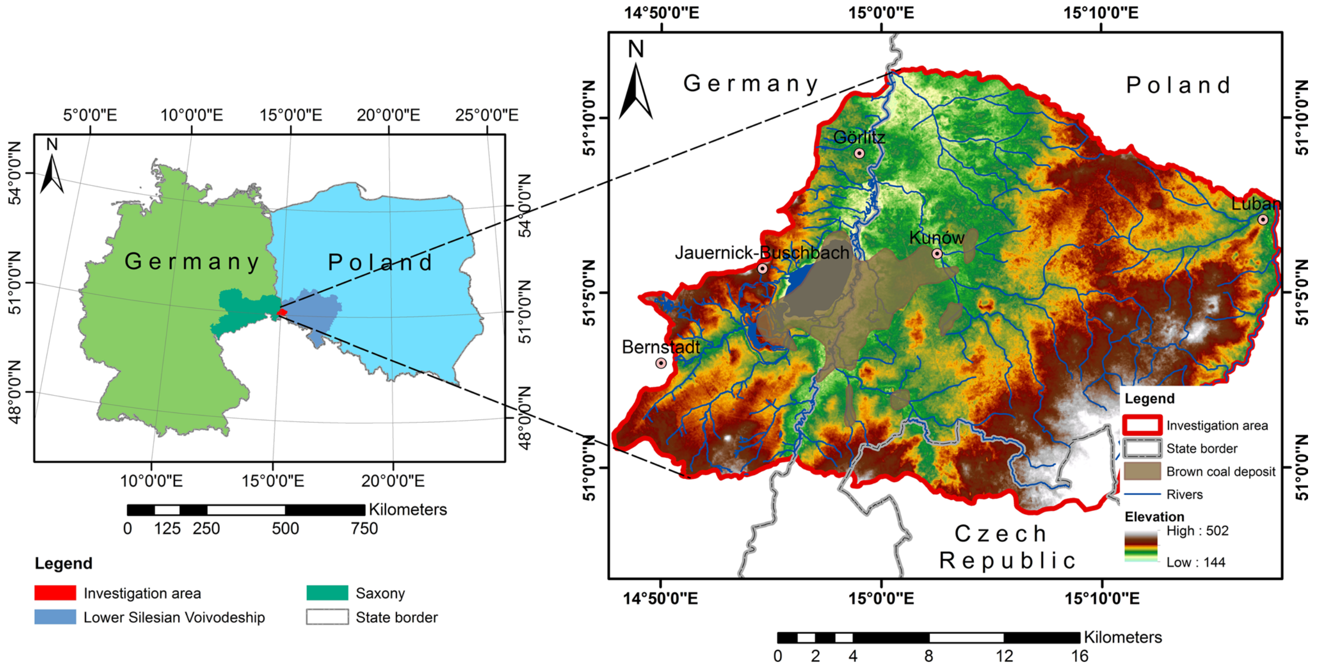

Fig. 1 Location of the Berzdorf–Radomierzyce basin [extension of the brown coal deposit after Kasiński and Saternus (2002)]

further reconnaissance works on Radomierzyce deposit were stopped. Nevertheless, the Radomierzyce deposit is still considered as a prospective deposit for the operating Turów coal mine, which is located only around 15 km from the deposit. On the German part, a hydrogeological model was created by the LMBV GmbH. However, this model has not been used further yet. So far, there is no model, neither geological nor hydrogeological, which covers both parts of the deposit. Any further investigation of the Polish part of the deposit requires comprehensive analysis of both sides of the deposit.

Geology of the study area

The pre-Tertiary base of the Berzdorf–Radomierzyce basin is built up almost entirely by East Lusatian Zawidów (Seidenberger) granodiorite, which belongs to the Lusatian granite massif (early Cambrian) (Krentz et al. 2000). The pre-Tertiary bedrock is covered by Paleogene and Neogene sediments of the Berzdorf–Radomierzyce formation. The sedimentary sequence varies from the eastern to the western part of the basin. The reason for this is an existing volcanic complex trending in the subsurface parallel to the national state boundary, so that the sedimentary exchange between the western (German—Berzdorf) and eastern (Polish—Radomierzyce) part of the basin was limited. The connection between both parts is the so-called lignite bridge breaking through the basaltic ridge (Bräutigam 1989).

The Berzdorf lignite complex consists of 13 seam beds and one seam bed "99" (Fig. 2), which from the stratigraphic point of view can be classified into any other group. The total thickness of the Berzdorf lignite complex is up to 140 m (Scholz et al. 2007). The Berzdorf lignite complex is underlain by the so-called Gaule Formation (higher/lower debris fans and volcanic complex) (Tietz and Czaja 2010). The Gaule Formation is created by Tertiary weathering products of the surrounding intrusive and volcanic rocks. The Tertiary weathering products are described as Tertiary rearrangement sediments or debris fans. The typical sedimentary sequence of the Berzdorf lignite complex (so-called Pließnitz Formation) begins with the "lower clay" (Table 1). The sedimentary sequences are usually very similar to each other in terms of their formation. At the bottom, there are coarse—and medium-grained sediments changing gradually upwards to silty-clayey sediments. On the top of the sequence, usually the brown coal can be found. The thickness of the particular sequences yields strong differences. The Berzdorf lignite complex is covered disconform by Quaternary sediments with a thickness ranging from few meters up to 70, 25 m in average (Tietz and Czaja 2004).

The sedimentary sequences of the Polish side are very similar to the German ones. Kasiński and Saternus (2002) distinguish four sedimentary sequences. Nevertheless, the geological exploration of the coal seams and aquifers of the Polish part of the basin was not performed intensively, so that more detailed information about the sequences is missing. Another division of the Radomierzyce lignite

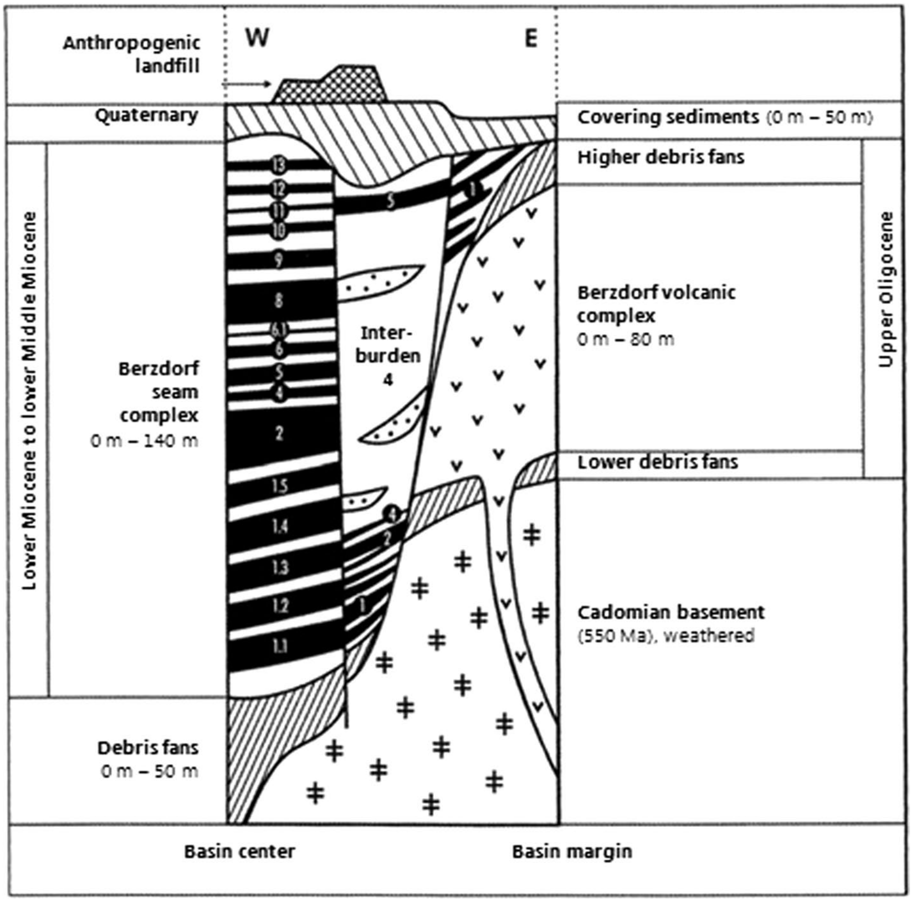

Fig. 2 Schematic profile of the formations in Berzdorf subbasin modified after Tietz and Czaja (2004)

complex was presented by Nowak (2007b), distinguishing between "upper" seam, coal seam and "lower" seam. The total thickness of the Radomierzyce lignite complex is up to 40.6 m (Kasiński and Saternus 2002). The covering Quaternary sediments reach a thickness from 0.3 to 49.9 m (on average 12.8 m) (Kasiński et al. 2010).

The Bernstadt and Neisse-Ręczyn Grabens are the southwestern and southern tectonic extensions of the Berzdorf–Radomierzyce basin, respectively. There are only few boreholes drilled in the range of both Grabens. The boreholes confirm the existence of Miocene sediments with various lignite seams. The thickness of brown coal is much less than in the range of the basin since the lignite seams wedge out in the rims of the basin. The lignite resources of Bernstadt and Neisse-Ręczyn Grabens have never been investigated in detail.

Materials and methods

An important point at the beginning of modeling is to define the specific objectives of the model. The size of the model and the degree of its simplification should be determined depending on the modeling target. Hence, models aiming exploration of deposit pay more attention on the very accurate reconstruction of particular seam beds. On the other hand, in models aiming the reconstruction of hydrogeological conditions, very high reconnaissance of particular seam beds is less important. All collected data needed for modeling were evaluated and converted to a uniform format and coordinate system (UTM) to enable efficient data management. Based on this, a conceptual model for hydrogeological interpretation and flow as well as transport models can be created. It is of great importance to understand the geological situation before creating the numerical model. The numerical model in this study should confirm the initial assumptions and contribute to a better understanding of the geology. It transforms spatially limited data in the form of boreholes, cross sections, etc., to regionalized data like geological surfaces, fault areas and spatial bodies. Additional hydrogeological rock properties were dedicated to all regionalized objects to include them in the corresponding hydrogeological flow model. Moreover, the regionalized data may help to estimate the brown coal resources in the Bernstad and Neisse-Ręczyn Graben.

Nowadays, several software packages are available for geological modeling: Paradigm GOCAD, Schlumberger Petrel, Surpac, RockWorks, Geomodeller3D, GSI3D,

Table 1 Stratigraphy of the Tertiary sediments of Berzdorf Radomierzyce basin according to Tietz and Czaja (2010), Nowak (2007a) and Brause et al. (1987)

Berzdorf subbasin / Berzdorf Group									Radomierzyce subbasin		
Formation	**Period**	**Epoch**	**Subformation**	**Seam**	**Seam bed / Subformation**		**Geological unit**		**Period**	**G.u.**	**Formation**
Pließnitz Subformation (Berzdorf Seam Complex)	Neogene	Lower Miocene	Higher Pließnitz Subformation	Upper seam	Seam bed 99		Geological unit 4	No correlation	Neogene	Geological unit 2-3-4	**Upper seam**
					Seam bed 13						
					Seam bed 12	Interburden 12 Seam bed 12					
					Seam bed 11	Interburden 11 Seam bed 11					
					Seam bed 10	Interburden 10 Seam bed 10					
					Seam bed 9	Interburden 9 Seam bed 9					
					Seam bed 8	Interburden 8 Seam bed 8					
					Seam bed 6	Interburden 6.1 Seam bed 6.2					
						Interburden 6.1 Seam bed 6.1					
					Seam bed 5	Interburden 5 Seam bed 5					
			Middle Pließnitz Subformation	Main seam	Interburden 4		Geological unit 3				
			Lower Pließnitz Subformation		Seam bed 4		Geological unit 2				
					Seam bed 3	Interburden 3 Seam bed 3					
					Seam bed 2	Interburden 2.4 Seam bed 2.4					**Coal seam**
						Interburden 2.3 Seam bed 2.3					
						Interburden 2.2 Seam bed 2.2					
						Interburden 2.1 Seam bed 2.1					
					Seam bed 1	Interburden 1.5 Seam bed 1.5					
						Interburden 1.4 Seam bed 1.4					
						Interburden 1.3 Seam bed 1.3					
						Interburden 1.2 Seam bed 1.2					
						Interburden 1.1 Seam bed 1.1, Lower clay					
Gaule Formation	Paleo-gene	Oligo-cene	Higher Gaule Subformation		Higher Debris Fans		Geological unit 1		Paleo-gene ?	Geo-logical unit1	**Lower seam**
			Middle Gaule Subformation		Volcanic Complex						
			Lower Gaule Subformation		Lower Debris Fans						

Vulcan etc. The choice of the modeling software for this study was dictated first of all by the possibility of comprehensive analysis of the input data (boreholes, geological maps and cross sections, faults etc.), compatibility with other softwares like ArcGIS and the simplicity of exporting data to another software, e.g., Visual Modflow FLEX. Besides fulfilling these requirements, the chosen software—Paradigm GOCAD—is very powerful, has a wide application in Saxony and is used by LfULG (Saxonian State Agency for Environment, Agriculture and Geology) and PGI Wroclaw (Polish Geological Institute Wroclaw), which simplifies data exchange with these institutions.

The whole modeling process consists of several steps, which at every stage require a plausibility test of the entered data. This enables to avoid the input of erroneous data for the modeling. Using different tools like ArcGIS, MS Access, WGEO, etc., the data can be selected and converted to different formats. All of the steps necessary to create the geological model are summarized in Fig. 3.

DEM, boreholes, cross sections, maps

To create the ground surface, the Global Digital Elevation Model (ASTER GDEM) with a resolution of 30 m was used (GDEM 2009–2014). In total, four raster datasets were necessary: ASTGTM2_N50E014, ASTGTM2_N50E015, ASTGTM2_N51E014 and ASTGTM2_N51E015. The raster data were imported to ArcGIS and converted to an ASCII file with UTM 33N coordinate system readable in Paradigm GOCAD. A total number of 10,671 boreholes were obtained from the Saxon State Agency for Environment, Agriculture and Geology and from the Polish Geological Institute–National Research Institute. By means of MS Access and ArcGIS, 8282 boreholes were selected, processed and converted into a uniform format and implemented into the model. Moreover, 33 and 27 geological cross sections were available on the German and Polish side, respectively. The cross sections on the German side based on geophysical correlations (borehole geophysics) were created within the framework of reconnaissance works of the mining field III in years 1987–1990. Since no geophysical investigations are available on the Polish side the geological cross sections base only on the drilling data and were created by their direct interpolation. The cross sections were available in analogous form. They were scanned and imported to Paradigm GOCAD (Fig. 4). During the implementation, special attention was paid to positioning the cross sections so that the geological layers match to each other. This task was satisfactory done in most of the cases. The biggest discrepancy was in the case of the

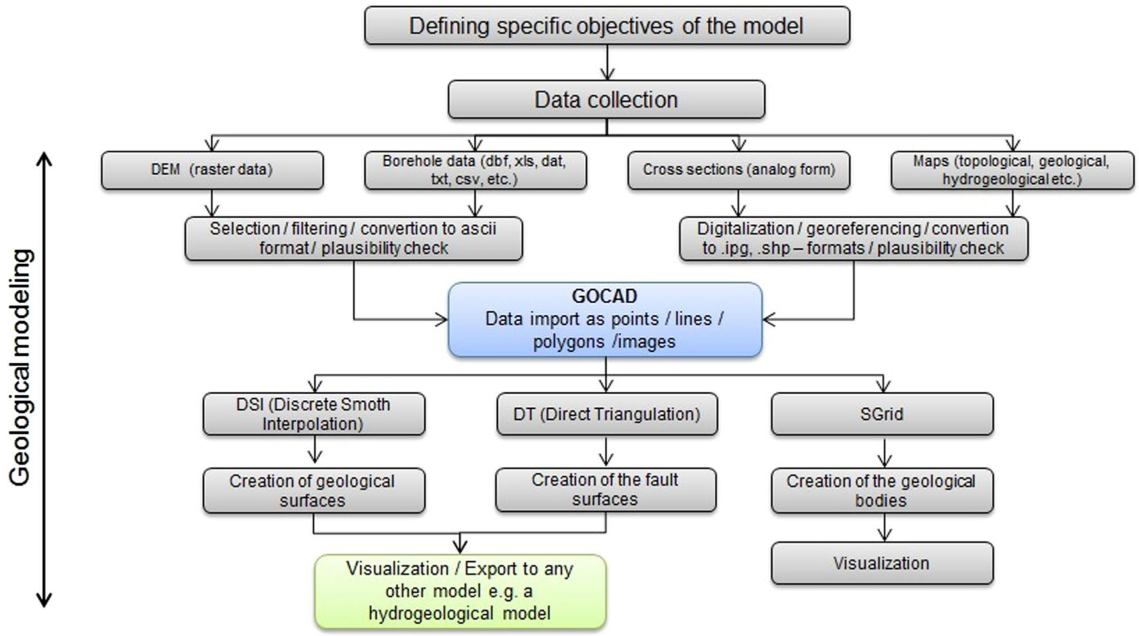

Fig. 3 Development process of the model

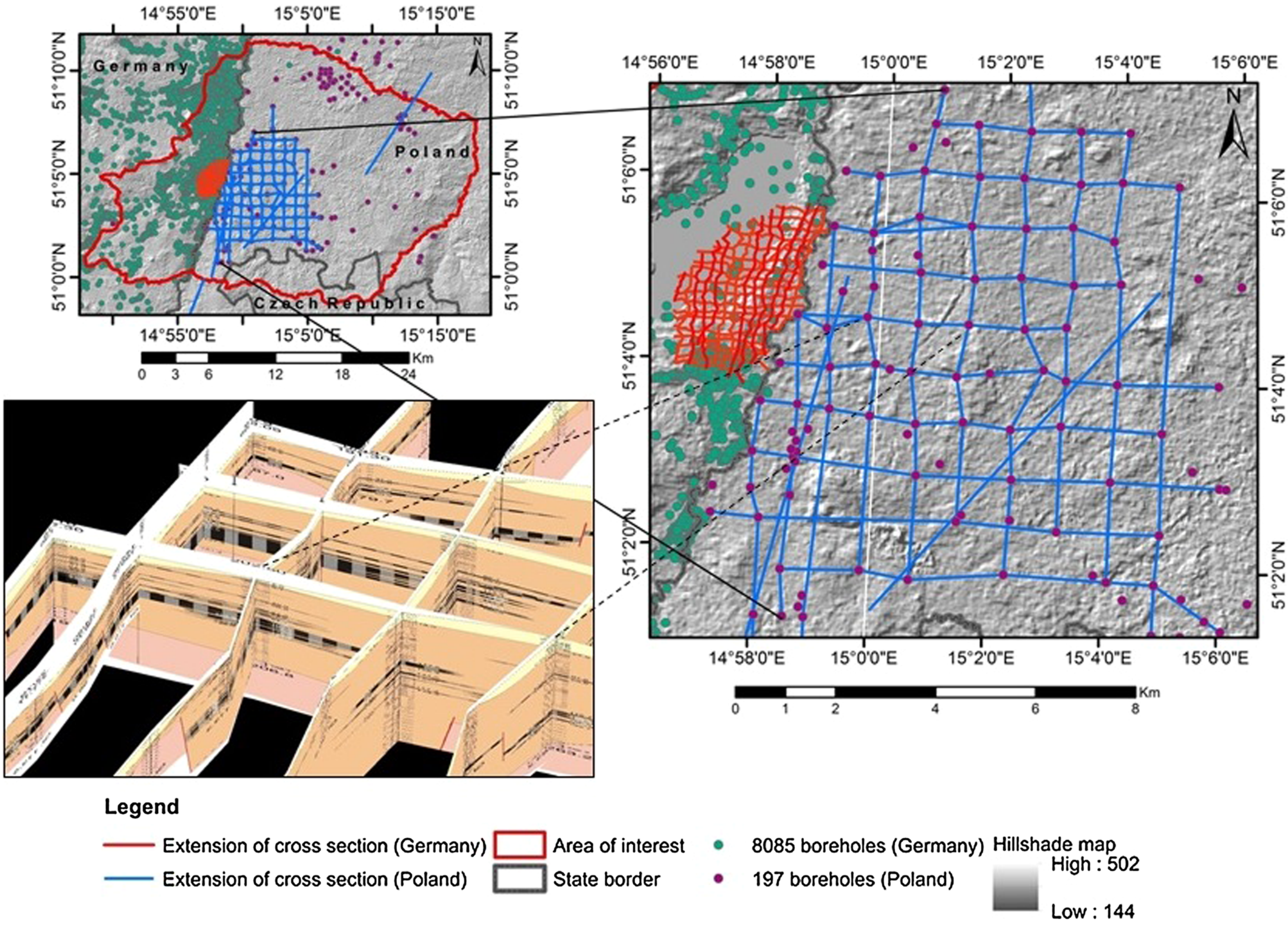

Fig. 4 Traces of geologic cross sections with visible boreholes and an exemplary cross sections implemented in Paradigm GOCAD

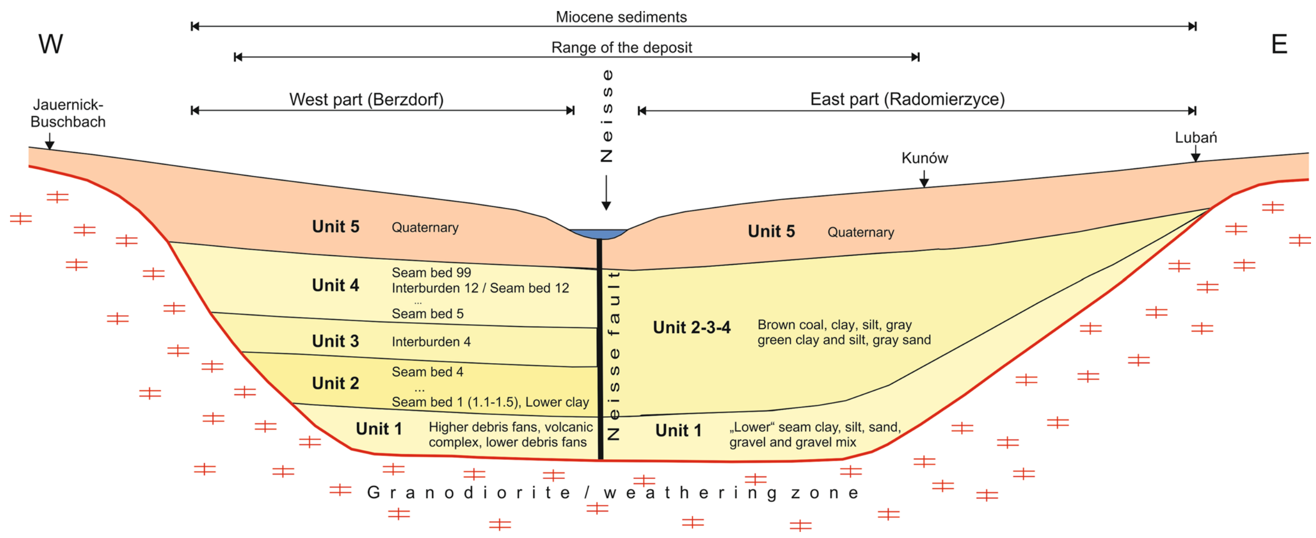

Fig. 5 Schematic representation of the modeled geological units (*red line*—bottom of the model)

N–S cross section No 17 (German side), where the height differences between the particular layers on two orthogonal cross sections reach even up to 26 m. In this case, the cross section was not considered in further modeling. In other cases where the difference was significantly smaller, the mean depth was taken as a reliable for the modeling. One part of the cross sections was used for the modeling, and second part was used for the validation of the model. Furthermore, the geological overview map without Quaternary for Saxony (1:400.000), the geological overview map without Quaternary and Tertiary for Saxony (1:400.000), the geological map at scale of the Lausitz–Jzera–Karkonosze area (Krentz et al. 2000) and the detailed geological maps of Sudetes (1:25.000) were used for the geological modeling. In addition to this, other maps showing the extension of the Miocene sediments and volcanics (Tietz and Czaja 2004) as well as an extension of the deposit (Kasiński and Saternus 2002) were included. The maps were georeferenced and processed by means of WGEO 5.0 and ArcGIS. The maps of the regional gravity anomalies done by Sedlák et al. (2007) were analyzed but not implemented to the modeling, because the regional gravity map focused mainly on the pre-Tertiary crystalline rock complex. The scale of these maps is 1: 100 000.

Modeled geological units and fault system

Geological layers with similar hydrogeological properties or with very small extensions or thickness could be merged and modeled as one geological unit. In this study, geological units are made up of different geological formations grouped according to their geohydraulic parameters. At later stage, it was possible to assign an average value of the hydrogeological parameters to the modeled geological units. The difference in data density in both parts of the basin as well as the separation through a volcanic threshold during sedimentation time resulted in the division into different numbers of modeled units. Both parts of the basin were connected through the "lignite bridge" (see "Geology of the study area" section), which led to different facies conditions during the accumulation of sediments. According to Tylikowski and Nemec (1990), the correlation between both parts of the deposit is only possible between the seam beds 1 and 2.

For the western part (Berzdorf), five geological units have been determined (Fig. 5). In the eastern part (Radomierzyce), only three geological units were differentiated due to the lack of geophysical borehole surveys and the almost uniform development of sandy and clayey sediments with thin brown coal lenses. The lower (1) and upper (3) geological unit can be directly correlated with the 1st and 5th unit on the German side, respectively. The 2nd geological unit on the Polish side corresponds to the German units No 2, 3 and 4.

The top of the pre-Tertiary rocks (granodiorite and weathering zone, respectively) was selected as base for the whole geological model. In the range of the Miocene sediments (Fig. 5), the base of the model was designated between the granodiorite (or its weathering zone) and the lower debris fans (Berzdorf) or the "lower" seam (Radomierzyce). Outside of the distribution area of the Miocene sediments, the base of the model was the border between granodiorite (or its weathering zone) and Quaternary sediments. The subdivision into the modeled geological units is depicted in Fig. 5.

Berzdorf–Radomierzyce basin is considered as a tectonic formation. Therefore, the faults and their age play a significant role and have to be considered in the model. The fault analysis was conducted on the basis of the available literature and maps. For further modeling, only the most important faults surrounding the basin were implemented in the model. The regional faults were analyzed by Bräutigam (1990), Kasiński et al. (2010) and Badura (1996). Moreover, two important faults in the German part surrounding a very big accumulation of interburden 4 were implemented. In the range of these faults, the thickness of interburden 4 reaches even up to 122 m and outside of it is similar to other interburdens and has a thickness between 1 and 2 m (Bräutigam 1989).

Modeling results

All of the preprocessed data described above were used to create the geological surfaces by the 3D modeling software Paradigm GOCAD. Two interpolation algorithms were used: Discrete Smooth Interpolation (DSI) and Direct Triangulation (DT). DSI algorithm was used to interpolate geological surfaces. This method is very efficient for interactive interpolation of the model geometry (Mallet 1989). In case of new data are available or some modifications on input data were done, only few iterations are required to update the interpolation. To create fault's surfaces, DT algorithm was used. It bases on triangular patches, so that no point (e.g., borehole) is inside of any triangle. Such created surface model reflects the boundaries of the delimited geological units. All inconsistencies of the input data and the modeling errors were eliminated during the modeling steps by a visual inspection and removal of non-plausible data. The modeling results represent an approximation of the geological situation based on the used data and adopted assumptions. According to them, the basin arose as a result of tectonic movements and is strictly related to the existing fault system with the distinct volcanic activity. As a result, a plausible model without artifacts was obtained, which can be updated in case of new data. The geological model was validated in terms of matching to the geological cross sections, which were implemented to the model but not used for the modeling itself. In total, 15 out of 30 and 16 out of 27 cross sections were used for the validation on the German and Polish part, respectively.

Analysis of the reliability of source materials as well as of the modeling results shows that the accuracy of the model is few meters, and locally, especially in areas with a low data density decrease to more than 10 m. The modeling result strongly depends on the input data like boreholes, geological maps and cross sections, which could be already affected by some uncertainties. At the points of borehole data, uncertainty is reduced to zero or to the level of measurement error (Freeze et al. 1990). The uncertainty in the result of the geological model could be reduced by improving the data density especially on the Polish part as well as by even coverage of borehole data over the domain of study. However, sparse and imprecise data which are not evenly distributed can lead to partly biased geological models. Such uncertainties have to be included in decision-making process (Mallet 2002). Only extensive geological knowledge about the investigation area itself does not eliminate the occurrence of uncertainty of model. To manage appropriately the uncertainty of structural geological models, several aspects have to be taken into account. First of all the involved parameters have to be identified and quantified on how much is unknown (Gringarten 2010). Second of all, additional constraints, such as fold shapes, constant thickness or stratigraphic relations, should be considered. This approach is closer to the real natural phenomenon than using geostatistical methods in case to reduce the uncertainty (Tacher et al. 2006). These constraints can be applied as rejection filters in uncertainty modeling, to obtain the best-guessed geological model (Wellmann et al. 2014). For models simulating physical processes like flow, heat transfer, wave propagation, etc., different approaches for assessing the uncertainties are presented, e.g., by Caumon (2010), Freeze et al. (1990) and Batu (2006).

Pre-Tertiary base of the model

The top of the granodiorite or its weathering zone builds the base of the model. Basically below the deposit and in the range of the non-lignite bearing Miocene sediments (on the Polish side from Kunów to Lubań), this is the base of geological unit No 1. Outside of the basin, it is the base of unit No 5, so that Quaternary sediments rest directly on the granodiorite or its weathering zone.

The rather high number of boreholes made it possible to reconstruct the bottom of the basin and its surroundings. As expected, the deepest depressions are inside the basin and stretch out from around 10 to 140 m a.s.l. in both parts of the basin (Fig. 6). Outside the basin, the elevation of the granodiorite or its weathering zone was determined by the model and is from 70 to 395 m a.s.l. on the German side and from 40 to 300 m a.s.l. on the Polish side. Because on the Polish side in the east of the deposit, no boreholes are available, the minimum values here are rather uncertain. The highest elevation of the model's base on the German side is Steinberg (335 m a.s.l.) and Knorrberg (330 m a.s.l.) and on the Polish side to the east of the city of Zawidów (300 m a.s.l.). The modeling results confirm the existence of the Bernstadt Graben to the southwest as well as the Neisse-Ręczyn Graben to the south of the basin (Fig. 6). By means of visual assessment, it can be seen that the grabens

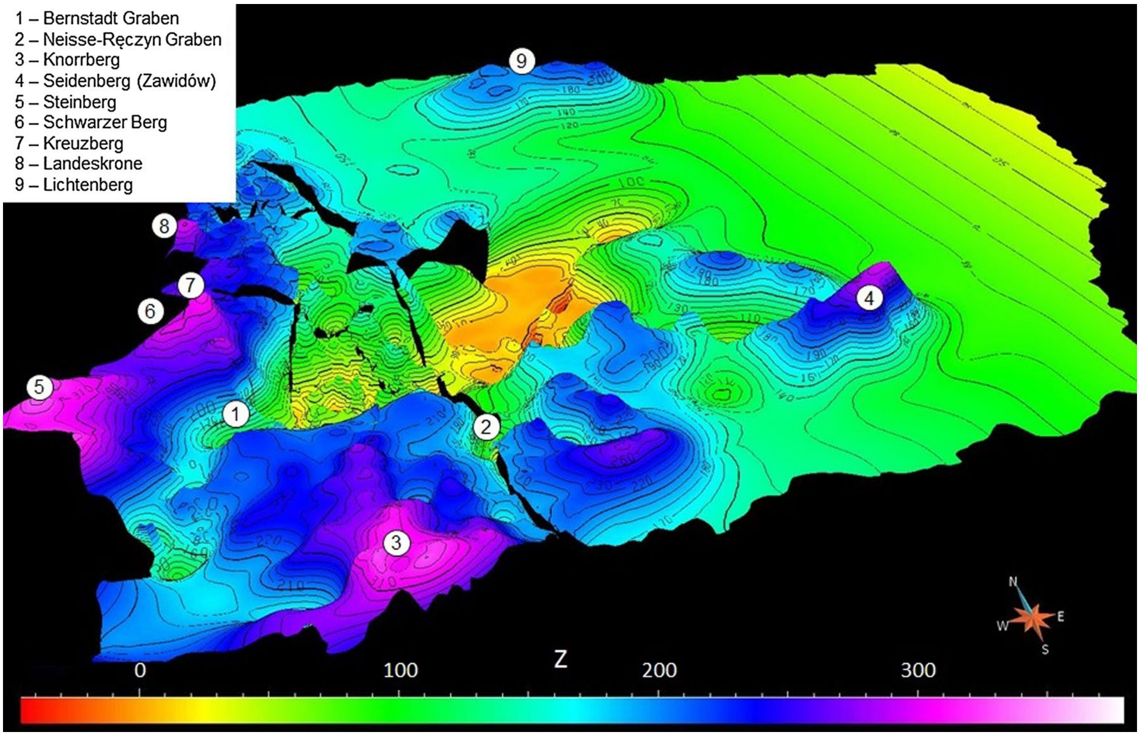

Fig. 6 Top of the pre-Tertiary base (*color bar* for elevation in meter a.s.l., 10 times vertical exaggeration)

lie higher than the basin itself. The deepest depressions are around 60 m and 80 m a.s.l. in Bernstadt and Neisse-Ręczyn Graben, respectively. Although they are characterized by a clear graben structure, the sedimentation conditions of brown coal were less favorable here. This resulted in less thickness of the brown coal, which is around 1 up to 17 m in the Neisse-Ręczyn Graben and increase toward the basin. The Bernstadt Graben is filled mostly with sandy and clayey sediments. The lack of the coal deposit in this part can be explained with the course of the ancient Neisse River, which is supposed to run directly through the Bernstadt Graben and has eroded big parts of the graben fill.

Geological unit No 1 (Berzdorf–Radomierzyce basin)

The geological unit No 1 is limited by two surfaces: the pre-Tertiary base of the model and the bottom of package No 2 (Berzdorf) and No 2–3–4 (Radomierzyce) (see Figs. 5, 7). The extension of geological unit No 1 was determined based on existing boreholes and previous investigations done by Hirsch et al. (1987) and modified by Tietz and Czaja (2004). The elevation of the top of geological unit No 1 is around 20 m a.s.l. in the range of the interburden 4 and up to 180 m a.s.l. toward the west of the Neisse fault. The rather big differences in elevation correspond to the volcanic complex, which is modeled "within" this unit. The location of the volcanic complex in the model is in agreement with the range of the volcanic complex estimated by Bräutigam (1990). The elevation of the top of unit No 1 on the Polish side is around 37 m a.s.l. in range of the deposit and up to 220 m a.s.l. in the range of the non-lignite bearing Tertiary sediments (from Kunów to Lubań). The fitting between the cross sections and modeled top of geological unit No 1 is depicted in Fig. 8.

Geological unit No 2 (Berzdorf subbasin)

Geological unit No 2 is bounded by the top layer of unit No 1 and bottom layer of unit No 3. The extension of the modeled geological unit No 2 is smaller than the extension of the unit No 1 (Fig. 7). It could be that the sediments are thinning out to the east. In some parts, package No 2 seems to have been eroded so that only geological unit No 1 exists. This is confirmed by drilling data. The modeled top of unit No 2 in the spread of the interburden 4 ranges from 10 to 70 m a.s.l. locally even up to 120 m a.s.l. Outside of the interburden 4, the top surface is from 20 to 160 m a.s.l.

Geological unit No 3 (Berzdorf subbasin)

The modeled interburden 4 as geological unit No 3 is limited by the top of unit No 2 and bottom of unit No 4. The extension of this package almost corresponds to the extension of the geological unit No 2 (Fig. 9). The deepest

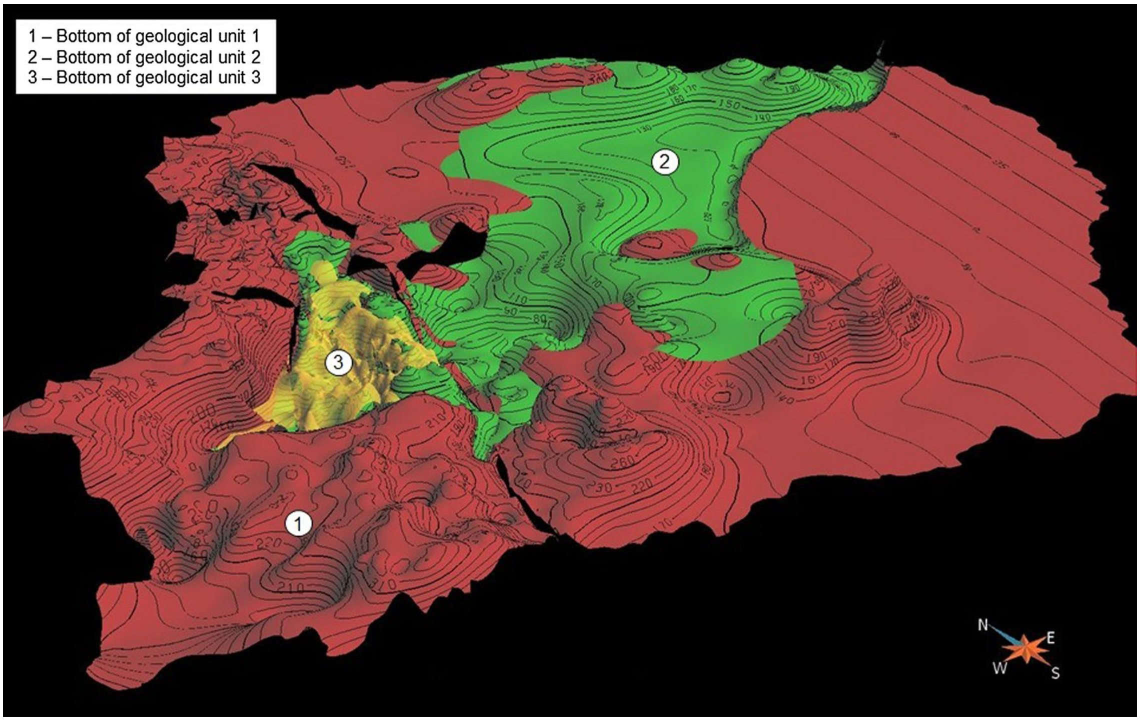

Fig. 7 Bottom of the modeled geological units 1 (*red*), 2 (*green*) and 3 (*yellow*) with visible fault system in the *lower right corner*. 10 times vertical exaggeration

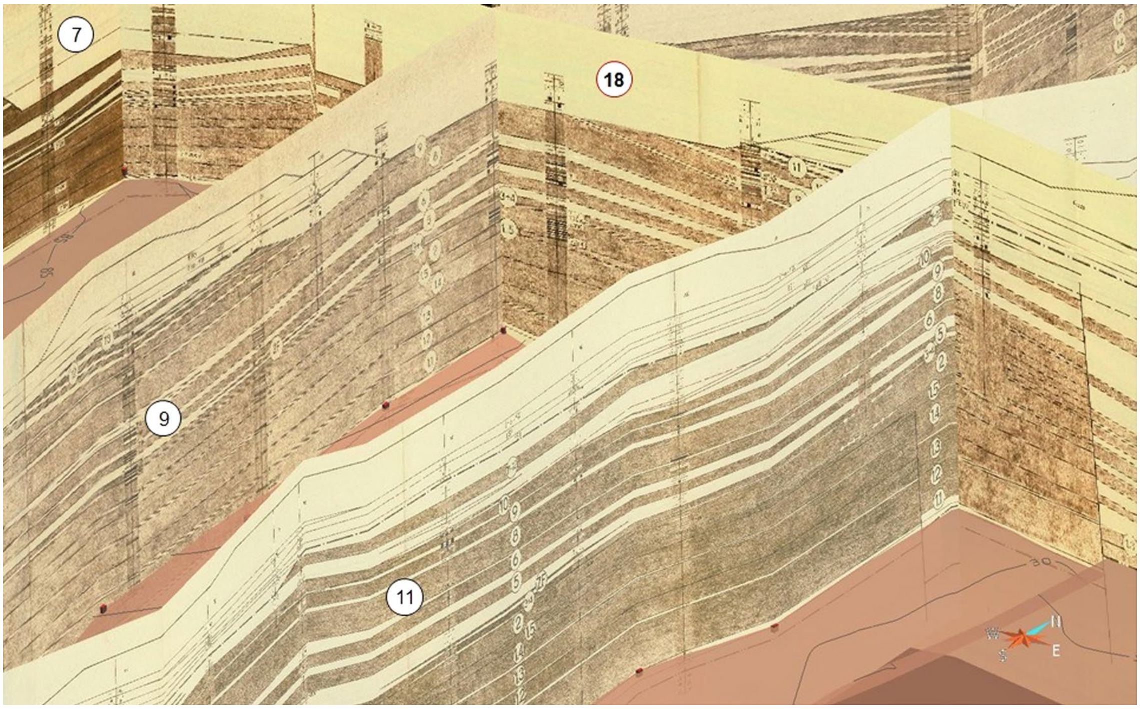

Fig. 8 Fitting between the cross sections No 18, 11, 9, 7 and top of package No 1 (German side). *Red points*—boreholes with the top of package No 1. Cross section 18 was used for modeling, and cross sections 11, 9, 7 were used for validation. 1 time vertical exaggeration

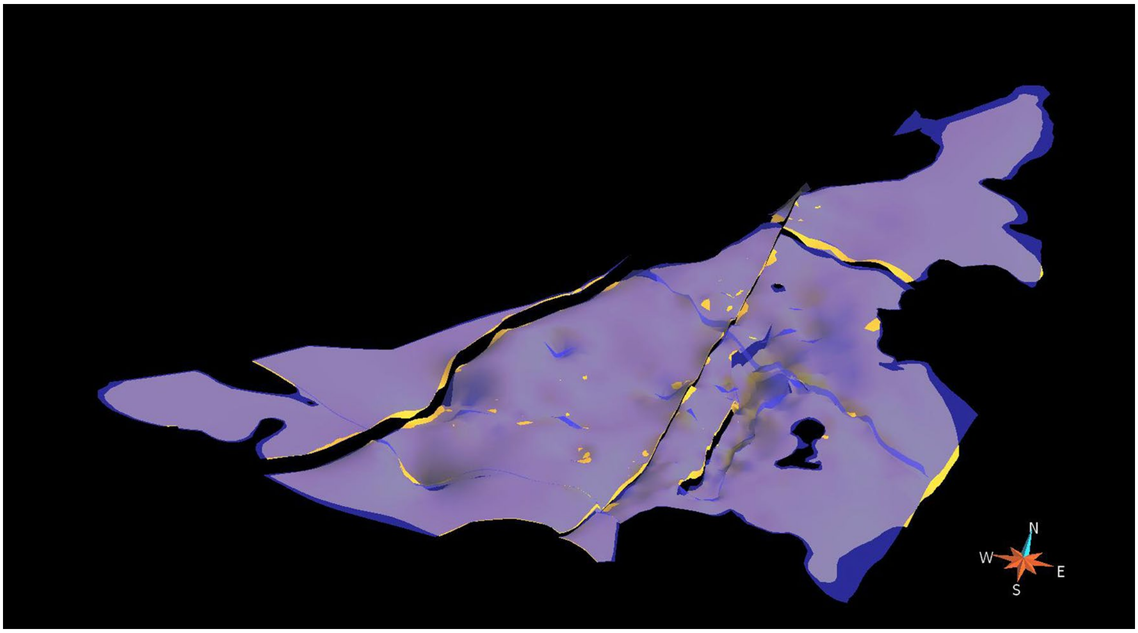

Fig. 9 Modeled top (*blue*) and bottom (*yellow*) layer of package No 3 (Berzdorf Basin). 3 times vertical exaggeration

depression detected in unit No 3 is related to two faults with north southern course and reaches down to 60–120 m a.s.l. The big accumulation of interburden 4 (even up to 120 m) surrounded by these faults can be explained as a syn-sedimentary river system (Brause et al. 1987). Outside of the fault-related structure, the altitude of the top surface ranges from around 80 up to more than 180 m a.s.l. As in the case of the 2nd geological unit, it comes to the partial erosion of the 3rd unit. In the northern part of the thickest accumulation of interburden 4, the modeled thickness is more than 100 m. In the southern part, it is around 10–30 m. The thickness west and east of the volcanic complex reaches around 50 m. Outside these areas, geological unit No 3 has a low thickness between 1 and 2 m. The modeled thicknesses are in high agreement with the thicknesses given by Bräutigam (1989).

Geological unit No 4 (Berzdorf subbasin) and No 2–3–4 (Radomierzyce subbasin)

On the German side, the geological unit No 4 is bounded by the top layer of unit No 3 and the bottom layer of unit No 5. Geological unit No 2–3–4 on the Polish side is limited by the top layer of unit No 1 and the bottom layer of unit No 5 (Fig. 5). The top layer of unit No 4 is more or less plane. Its elevation is around 130–220 m a.s.l. on the German side. The top layer of unit No 2–3–4 on the Polish side ranges between 95 and 280 m a.s.l. (Fig. 10). In some places, geological units No 4 or 2–3–4 are eroded so that the top layer of the underlying package crops out.

Geological unit No 5 (Berzdorf–Radomierzyce basin)

Geological unit No 5 is based on the Quaternary sediments and is limited by the top of unit No 4 (Berzdorf subbasin), the top of unit No 2–3–4 (Radomierzyce subbasin) and the ground surface. The ground surface based on the Digital Elevation Model (GDEM 2009–2014) and elevations is measured during drilling works. The top of the model shows an incision valley of the Neisse River with a base elevation of 170 m in the north and 190 m a.s.l. in the south. The surrounding hilly landscape is characterized by altitudes from 200 to 320 m a.s.l. (Fig. 11).

Discussion

The collected data were sufficient to obtain a plausible 3D geological model. The modeling results confirm the description of the deposit done by Brause et al. (1987), Bräutigam (1989) and Kasiński et al. (2010) and summarize all existing data. Nevertheless, the reconnaissance of the German part of the deposit is much higher than that on the Polish side. Due to the past exploitation of the deposit, a lot of investigations were done on the German side. On the Polish side, no geophysical investigations were done and no geophysical borehole data were available for this work. This was one of the reasons for division of the basin into different numbers of geological units in the model. The first and last geological units on the German and Polish part correspond to each other since they contain the same

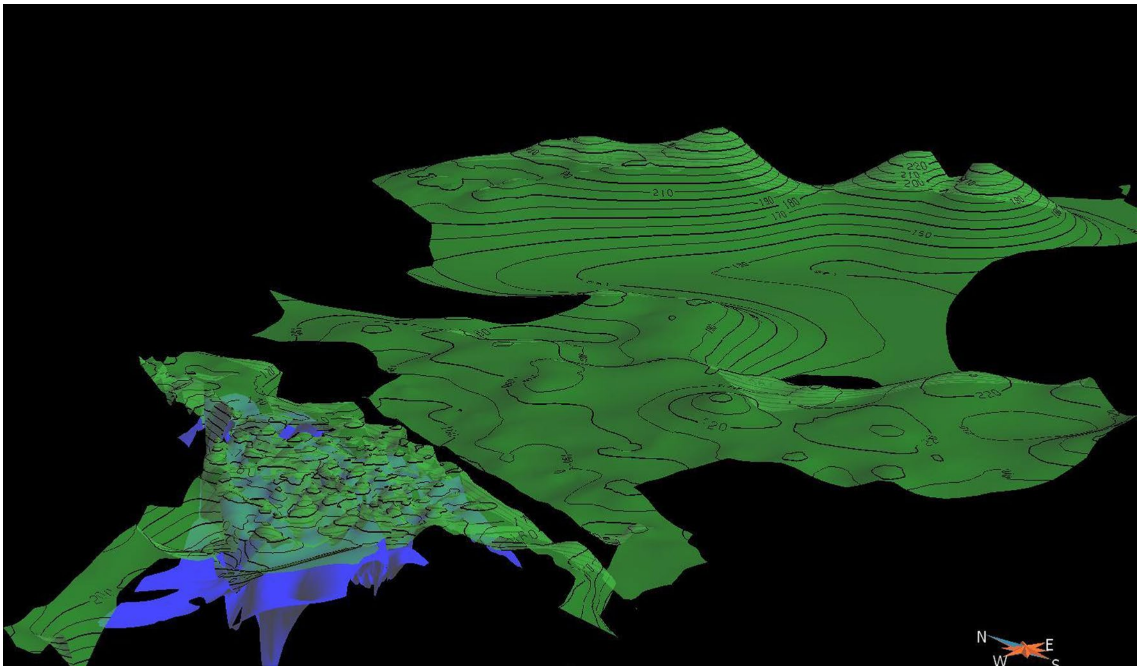

Fig. 10 Modeled top layer of package No 4 (Berzdorf basin) and No 2–3–4 (Radomierzyce basin)—*green*, and the bottom layer of package No 4 (Berzdorf basin)—*blue*. 10 times vertical exaggeration

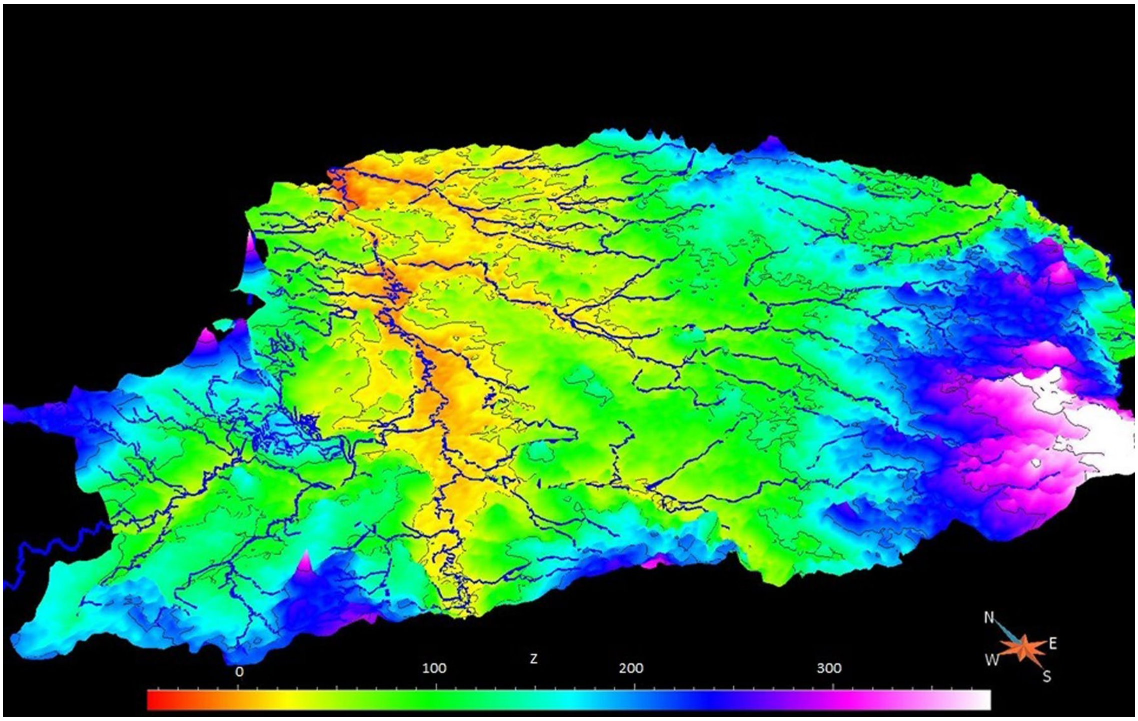

Fig. 11 Modeled top of the Quaternary layer. *Color bar* for elevation in meter a.s.l. 10 times vertical exaggeration

kind of sediments. On the German part, the Miocene lignite complex was divided into three modeled geological units (packages No 2, 3 and 4). On the Polish side, the division of the lignite complex in geological units turned out to be impossible at this stage of information. So, the whole lignite complex was modeled only as one unit (unit No

2–3–4). Hence, lithological and stratigraphical correlation of the particular seam beds and also units between both parts of the basin requires more investigations. Any attempt to correlate without additional data can result in misinterpretation of the geological data. On the other hand, the very high degree of reconnaissance should be maintained on the German part of the deposit. That is why the modeled geological units 2, 3 and 4 on the Polish side were merged into one unit and were compared with the higher number of geological units on the German side.

Conclusions

1. The collected borehole data, geological cross sections and geological maps allowed to build a 3D geological model of the Berzdorf–Radomierzyce basin. The modeling area is highly affected by faults especially in the range of basin. The seam complex is unsettled by volcanic processes and Neogene fluvial system, so that some of the seams were completely eroded. This is especially evident in the range of the interburden 4 (modeled unit 3) and Bernstadt Graben. The used software Paradigm GOCAD enables to depict these complex geological conditions. The 3D model reproduces the geological conditions of the investigated area before the mining operations in the vicinity of the city of Berzdorf have started.
2. The modeling results confirm the existence of the Bernstadt and Neisse-Ręczyn Graben to the south-west and south of the basin, respectively. The Bernstadt Graben does not contain significant accumulation of brown coal. This is due to the Neogene great-Neisse course, which was flowing through the Bernstadt Graben. The thickness of brown coal deposit in Neisse-Ręczyn Graben is from 1 up to 17 m and increase toward basin even up to more than 30 m. The rather low thickness and size of the modeled Neisse-Ręczyn Graben prevent an economically viable exploitation of the brown coal.
3. In total, 8282 boreholes and 33 cross sections on the German part and 27 cross sections on the Polish part were used for the modeling.
4. To simplify the geological model, a homogeneous sets of geological formations were created. The total number of the modeled geological units is 5 on the German side and 3 on the Polish side. The 2nd modeled geological units on the Polish side corresponds to the modeled units 2, 3 and 4 on the German side.
5. The modeling results, especially the course of the volcanic complex and the thickness of the modeled geological units, are in very high agreement with the description from Bräutigam (1989). Moreover, during the validation process the modeled surfaces have been compared with the geological cross sections, which were not used for the modeling itself. The modeled geological surfaces showed a high compatibility with the real data, which underlines the quality of the modeling results.
6. More accurate investigations are required to increase the degree of exploration and the number of the modelable geological units on the Polish side. Nevertheless, the 3D geological model will be used as a basis for 3D groundwater model to investigate groundwater flow in the aquifer system of this area. Moreover, in case that further lignite mining is considered for the operating Turów coal mine, the 3D geological model can be used for planning and full-scale mining operations.

Acknowledgments We would like to thank Mr. Bernd Bräutigam for his constructive comments and valuable discussions. The assistance of Jens Hofmann and Mandy Hoyer in preparing the manuscript is also gratefully acknowledged. Furthermore, we would like to thank the Polish Geological Institute–National Research Institute and the Saxon State Agency for Environment, Agriculture and Geology for the quick and smooth data transfer.

References

Badura J (1996) Morfotektonika Obniżenia Żytawsko–Zgorzeleckiego. Przegląd Geologiczny 44:1239–1243

Batu V (2006) Applied flow and solute transport modeling in aquifers: fundamental principles and analytical and numerical methods. Taylor & Francis Group, CRC Press, Boca Raton

Bender J (2004) Die Entwicklung der Natur in Bergbaufolgelandschaften der südöstlichen Oberlausitz. Rekultivierung und Renaturierung im Tagebau Berzdorf. Eigenverlag der Naturforschenden Gesellschaft der Oberlausitz e.V

Brause H, Tschernikl J, Raithel E, Richter A (1987) Kenntisstandanalyse Brk. Berzdorf—SO. Freiberg: VEB Geologische Forschung und Erkundung Freiberg

Bräutigam B (1989) VEB Geologische Forschung und Erkundung Freiberg. Berichtsteil I: Geologie. Freiberg

Bräutigam B (1990) VEB Geologische Forschung und Erkundung Freiberg. Braunkohle Berzdorf. Bohrriß und Strukturkarte. Freiberg

Caumon G (2010) Towards stochastic time-varying geological modelling. Math Geosci 42(5):555–569

Freeze RA, Massmann J, Smith L, Sperling T, James B (1990) Hydrogeological decision analysis: 1. A framework. Ground Water 28(5):738–766

GDEM A (2009–2014) ASTER GDEM. http://gdem.ersdac.jspacesystems.or.jp/. Accessed 12 Nov 2013

Gringarten E (2010) Uncertainty assessment in 3D reservoir modeling. Earth Decision Sciences. https://www.pdgm.com/resource-library/articles-and-papers/archive/uncertainty-assessment-in-3d-reservoir-modeling/. Accessed 29 May 2016

Hirsch D, Rascher J, Schulze H (1987) Die Braunkohlen–Lagerstätten der Oberlausitz (Tertiärbecken von Berzdorf und Zittau). Wiss.-Techn. Informationsdienst (WTI), Berlin, 30, Reihe A, 1:27–30

Kasiński J, Saternus A (2002) The Radomierzyce lignite deposite (Upper Lusatian coal basin) and potential significance of its resources. Krakow

Kasiński J, Saternus A, Sztromwasser E, Urbański P (2010) Dokumentacja geologiczna złoża węgla brunatnego Radomierzyce w kategorii C2. Warszawa

Krentz O, Walter H, Brause H, Hoth K, Kozdrój W, Cymerman Z et al (2000) Mapa Geologiczna Lausitz–Jizera–Karkonosze 1: 100 000 (bez osadów kenozoicznych). Freiberg, Warszawa, Praha

Mallet J-L (1989) Discrete smooth interpolation. ACM Trans Graph (TOG) 8(2):121–144

Mallet J-L (2002) Geomodeling. Applied geostatistics. Oxford University Press Inc, New York

Nowak A (2007a) Analysis and modeling of geological data and concept of Radomierzyce brown coal prospective deposit development with utilization of geological-mining design tools. Breslau

Nowak A (2007b) Analysis of the lithologic composition of Radomierzyce brown coal deposit overburden and assessment of deposition and exploitation conditions. Górnictwo Odkrywkowe

Scholz H, Tietz O, Büchner J (2007) Unionoid bivalves from the Miocene Berzdorf Basin (eastern Germany): taxonomic remarks and implications for palaeoecology and palaeoclimatology. Stuttgart N Jb Geol Paläont Abh 244(1):43–51

Sedlák J, Gnojek I, Zabadal S, Farbisz J, Cwojdzinski S, Scheibe R (2007) Geological interpretation of a gravity low in the central part of the Lugian Unit (Czech Republic, Germany and Poland). J Geosci 52(2007):181–197

Tacher L, Pomian-Srzednicki I, Parriaux A (2006) Geological uncertainties associated with 3-D subsurface models. Comput Geosci 32:212–221

Tietz O, Czaja A (2004) Die Braunkohlenlagerstätte Berzdorf-Geologie, geologische Substrate und Paläobotanik. Görlitz Ber Naturforschende Gesellschaft der Oberlausitz eV 11:57–76

Tietz O, Czaja A (2010) Die Stratigrafie des Berzdorfer Beckens in der Oberlausitz (Ostdeutschland)—eine Ergänzung zur Stratigraphischen Tabelle von Deutschland 2002 (STD 2002). Stuttgart Z dt Ges Geowiss 161:459–463

Tylikowski M, Nemec J (1990) Charakteristik der Braunkohlenlagerstätte “Radomierzyce”. Unpublished

Wellmann J, Lindsay M, Poh J, Jessell M (2014) Validating 3-D structural models with geological knowledge for improved uncertainty evaluations. Energy Procedia 59:374–381