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METHODOLOGY AND RESULTS OF DIGITAL MAPPING AND 3D MODELLING OF THE LOWER PALAEOZOIC STRATA ON THE EAST EUROPEAN CRATON, POLAND

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Abstract: The paper presents a multi-phase and multi-stage methodology of 3D structural-parametric modelling and mapping that has been applied during implementation of the GAZGEOLMOD project. The core of the applied processing workflows is a 3D geological model constructed in Petrel, which functions as a spatial database for all kinds of geological models. The first phase of the workflow comprised an extended process of database project building that was very intensive at the beginning of the project and continued to its end.
The second phase of processing consisted of a complex process of mapping and structural modelling that is performed in 8 stages, allowing for iterative improvements of model resolution. During the realization of stages 1 to 7, processing was run independently for the Baltic (BB), Podlasie (PB) and Lublin Basins (LB). The workflow included the following stages: (1) unification and digitization of published and on file analogue and digital, structural maps; (2) preliminary reinterpretation, including adjustment to stratigraphy data acquired from archives; (3) adjusting the maps to the primary results of seismic interpretation, mainly from archival data; (4) digitization and gridding of pre-existing palaeothickness maps and updates of them with data from boreholes completed after 2009; the reinterpretation of the palaeothickness maps into contemporary thickness maps; (5) elaboration of the primary structural 3D models for the three basins; (6) increasing of the stratigraphic resolution of models up to the rank of the geological epoch for Ordovician–Silurian strata; (7) conversion of basin-scale structural models into a 2D grid, and their merging into platform-scale surfaces, resulting in 45 structural and thickness maps; finally, they were adjusted to the results of seismic interpretation and sedimentological studies, obtained in the project; and (8) completion of the resulting structural models for each of the basins and for the entire Polish part of the East European Craton in several different versions. In the third phase of processing, parametric models of vitrinite reflectance (R_o) and Total Organic Carbon (TOC) were estimated.

Key words: 3D structural models, parametric models, digital mapping, data integration, shale gas, Lower Palaeozoic, East European Platform.

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INTRODUCTION

One of the main goals of the GAZGEOLMOD Project was the construction of a complete set of 3D structural models and 2D grid-based structural and thickness maps of the Lower Palaeozoic complexes (Michna *et al*., 2017; Papiernik, 2017a, b). The methodology selected to obtain these objectives comprised a multistage set of procedures, based on the direct efforts of a team with approximately 10 members and indirect collaboration with practically all scientific participants of the project, in fact with dozens of scientists. The main phases of the procedure included the completion of an exhaustive database project in Petrel™, completion of several generations of intermediate structural and thickness maps and composed of them 3D structural models, separately for the Baltic Basin, the Podlasie Basin and the Lublin Basin, then the integration of partial maps into the digital maps (2D grids) and 3D models for the onshore part of the East European Craton (EEC), and finally the construction of parametric models of selected basic components of the Silurian–Ordovician petroleum system (Papiernik *et al*., 2017b, 2019), such as total organic carbon content (TOC), vitrinite reflectance (Ro) and porosity. Preliminary, regional models of velocity for the Lublin Basin, the Narol Zone (NZ) and the Radom-Kraśnik Zone (RKZ) were also developed. The main scope of the work comprised Lower Palaeozoic strata. However, to give some support to other teams engaged in the project, mapping and modelling activities involved also the Upper Palaeozoic, Mesozoic and Cainozoic complexes, with the last-mentioned being prepared with lower stratigraphic and spatial resolution (Barmuta *et al.*, 2017, 2019).

The present paper is focused on methodological aspects, presenting a short description of the iterative procedure of spatial modelling performed during the completion of the GAZGEOLMOD Project. The methodology described is based on essential assumptions of petroleum structural-parametric modelling workflows (Zakrevsky, 2011; Wygrala, 2014), but owing to the specific aims of the research, i.e., mapping and 3D modelling solutions, stratigraphic studies and preliminary prospecting conclusions, only directly applicable components of that procedure were selected. The process of spatial mapping and 3D modelling in the project can be divided into three main phases of work. Furthermore, the most time-consuming and complex phase of mapping and structural modelling consisted of eight additional stages, necessary to achieve the planned goals.

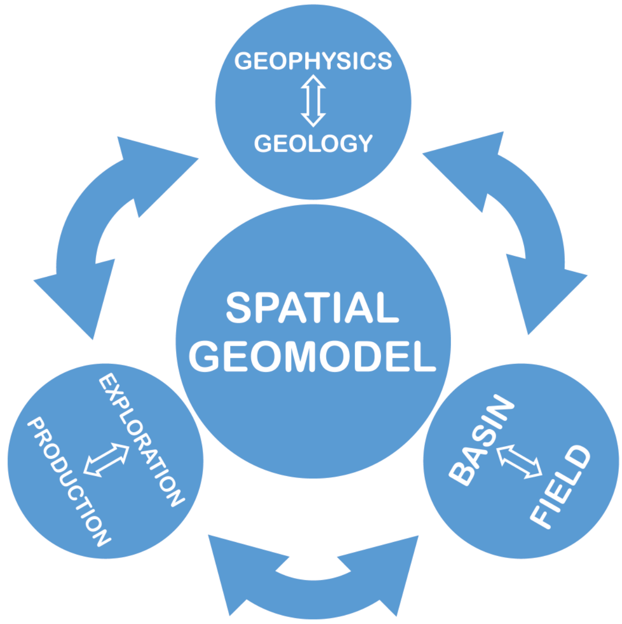

Fig. 1. The role of digital 3D geological models in the process of interpretation, prospection, exploration and production from basin to field scale (based on Wygrala, 2014).

GENERAL OUTLINE OF METHODOLOGY

Mapping tasks during the research project were based on the utilization of Schlumberger's Petrel™ Software Platform. It allows for extensive integration of different kinds of data (geological, geophysical, cartographic, petrophysical, production, etc.), accurate quantitative digital mapping and structural modelling, and broadly understood parametric modelling (facies, temperatures, petrophysical or geomechanical parameters, etc.). In this philosophy of geological modelling the centre of all analyses performed is the digital geomodel (Petrel Project). First, it plays the role of the Spatial Database, integrating all digitally available data. Projects can incorporate these data into the common, spatial form of 2D and 3D structural and parametric grids. Interactive data integration enables analyses in various scales - from basin to field scale (upscaling or downscaling). The models can be transformed into different resolutions, providing expected solutions that are suitable for exploration, appraisal, development, and finally production phases. These models gradually can be converted from static 3D into 4D dynamic models with simulations through geologic time to model generation and migration processes, geomechanical parameter changes or petroleum production and enhancements of hydrocarbon recovery (Fig. 1; e.g., Dubrule, 2003; Zakrevsky, 2011; Orlic *et al.*, 2013; Wygrala, 2014; Klimkowski *et al.*, 2015; Papiernik *et al.*, 2015).

3D modelling utilised in petroleum prospecting is a complex process, encompassing a wide range of procedures and processing methods, from data acquisition, structural and tectonic interpretations of seismic, through structural and thickness mapping, sedimentological analyses, seismic attribute analyses, velocity modelling and time-depth conversion to modelling the variability of lithology and petrophysical parameters, resources / reserves assessments and uncertainty analysis (e.g., Deutsch and Journel, 1992; Dubrule, 1998, 2003; Cosentino, 2001; Mallet, 2002, 2008; Coburn *et al.*, 2006; Zakrevsky, 2011; Chatellier and Jarvie, 2013; Sowiżdżał, 2013; Vernik, 2016).

In general, digital processing workflows in petroleum prospecting can be divided into six phases (Fig. 2) covering complete workflows, including model-centred procedures that assure optimum quality of the end result. The first phase (phase 1) is to create the optimum input database that covers geological, geophysical, cartographic, drilling, production and other data, which then is used for interpretation and modelling tasks. In the case presented, the database is a Petrel project, which is subjected to iterative enhancements and verification throughout the research project. The second phase (phase 2) consists of developing sets of input maps

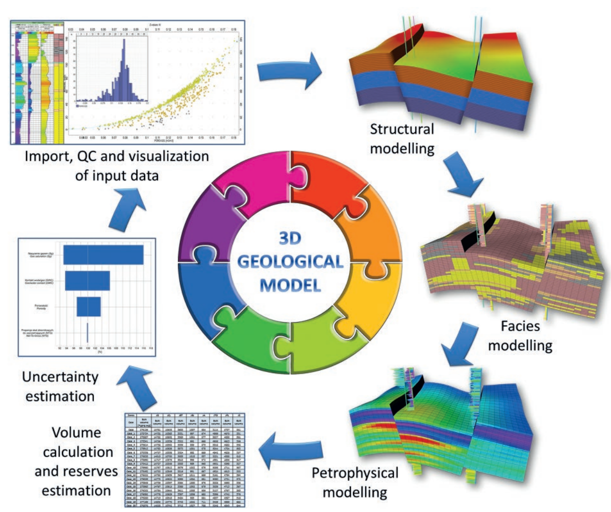

Fig. 2. Main phases of static modelling (from Wachowicz *et al.*, 2016).

and a structural model. In the case of the regional model, this is a complex and time-consuming task, but it is essential for the development of a solid foundation for the play- and prospect-scale analyses that follow.

The software used in the research enables structural models to be created with three methods, starting with the basic *Simple Grid* (SG) through the universal *Corner Point Gridding* (CPG) method, to a geometrically complex *Structural Framework* (SF). SG is a regular 3D grid, which cannot include faults. *Corner Point Gridding* is a method that allows most universal irregular 3D grids to be deployed and these then are used in further parametric modelling and dynamic simulations (e.g., Zakrevsky, 2011; Klimkowski *et al*., 2015). The CPG procedure also enables flexible increases in the stratigraphic resolution of the model. Structural Framework is the geometrically most advanced method, as it enables complex fault models to be included, including many generations of faults, constructed with triangular meshes. On the other hand, SF has limitations on increasing the stratigraphic resolution of the model, using well tops as stratigraphic markers. Structural Framework models also cannot be directly used for parametric modelling.

The development of the fault model (FM) is the first stage of structural modelling (Structural Modelling -> Fault Modelling). Interactive modelling of fault geometries using CPG enables flexible unifications of faults, drawn as lines on archival maps in 2D projections, their transformation into a spatial dimension (Papiernik *et al*., 2010), as well as faults interpreted spatially with the use of seismic interpretations (Fig. 3).

The main limitation of CPG is the ability to include only one generation of faults in the model. Therefore, it can be used successfully only in the Baltic and Podlasie basins. In the case of the Lublin Basin, the Narol Zone and the Radom-Kraśnik Zone, where complex fault and thrust tectonics are developed, the FM was built using the Structural Framework (SF) method (Fig. 4).

Fault model building is followed by the procedure of introducing structural surfaces within the Structural Framework of the 3D model, also called *horizon modelling*. Normally regular 2D grids, seismic interpretations or point data are treated as the main input for horizon modelling. *Horizons* in a 3D grid are the equivalents of *Surfaces* (2D Grids), but in 3D grids built with the SF or CPG method are converted to irregular numerical models, termed *Horizons*. In contrast to 2D grids, they are discontinuous at fault intersections. The geological complexes of the model, bounded by horizons, are called the *Zone* (Papiernik, 2017a)

Corner Point Gridding methods enable further increase of the model stratigraphic resolution by means of *Zone Modelling* procedures. This enables the stratigraphic resolution of the model to be improved, compared to the resolution of the seismic horizons (Papiernik, 2010a; Papiernik *et al*., 2015). Commonly the inputs for the procedure are

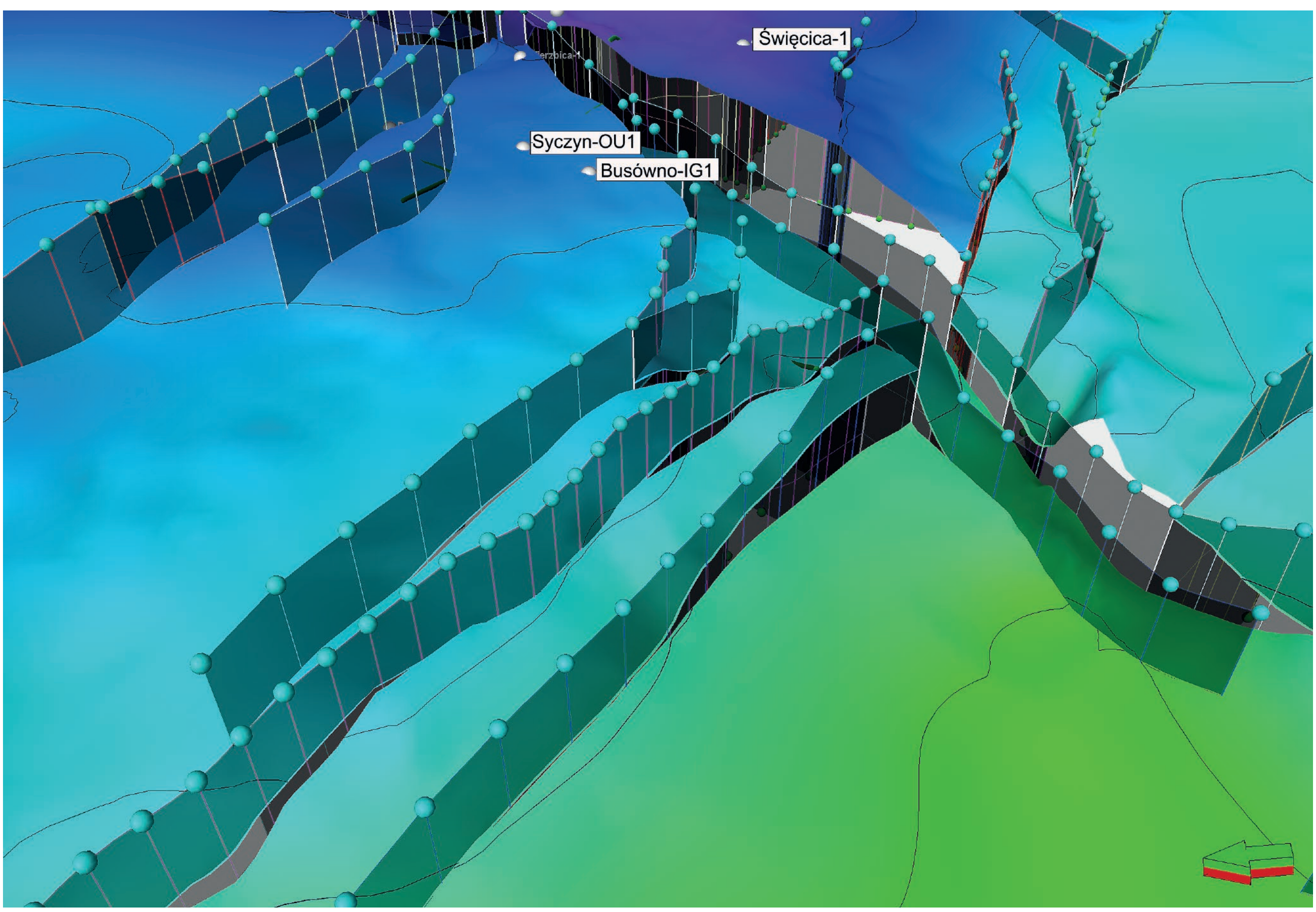

Fig. 3. Interactive editing of the fault network using the Fault Modelling procedure in the Corner Point Gridding structural modelling method.

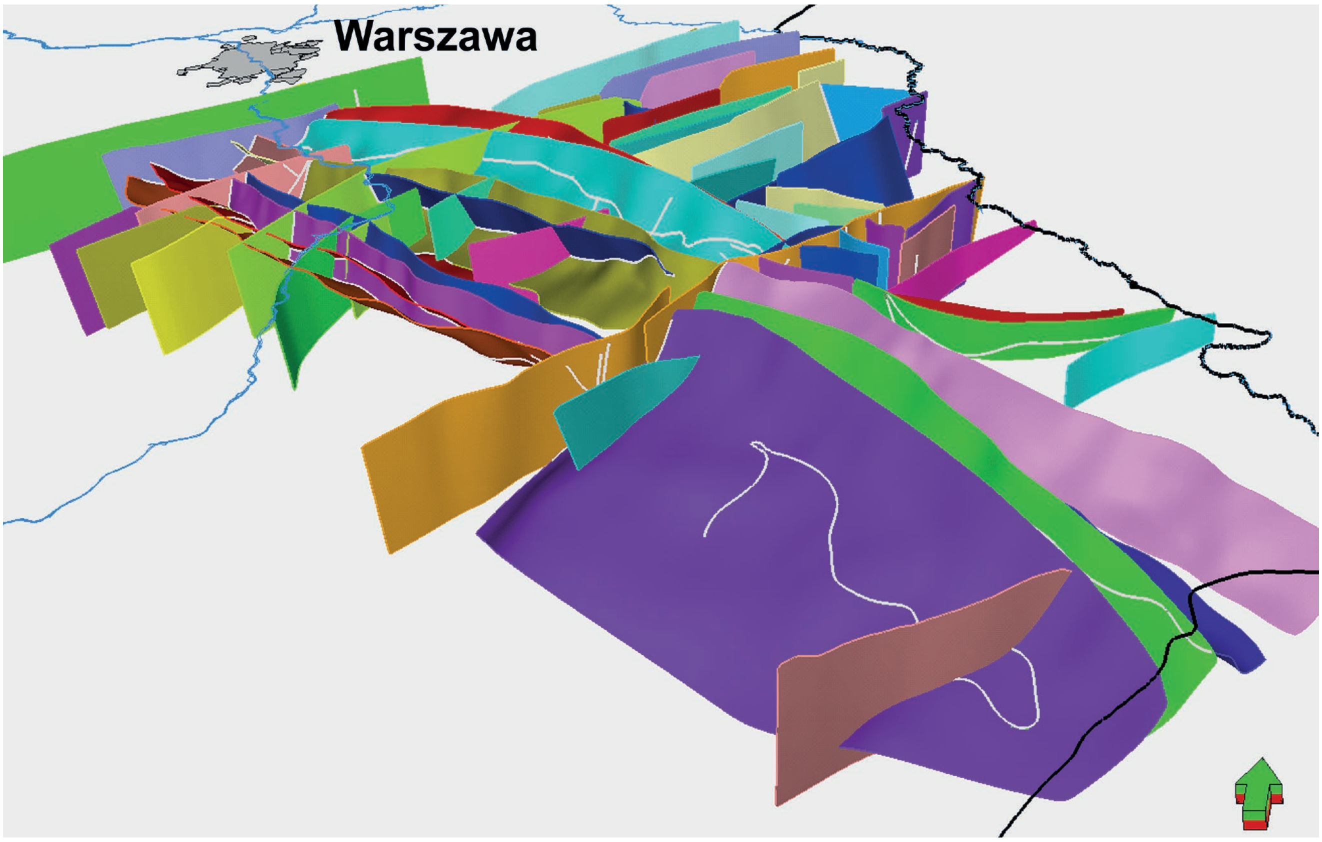

Fig. 4. Fault model in the area of the Lublin Basin and the Radom-Kraśnik Zone built using the Structural Framework method.

isochore maps or Well Top markers. As a result of the Make Zone procedure, lower-rank complexes are created within existing model Zones. They are referred to as sub-zones.

The third stage (phase 3) of the process is the development of a deterministic or stochastic model of lithology-facies variability (e.g., Dubrule, 1998, 2003; Zakrevsky, 2011). The results of that modelling phase allow for improvement of the overall quality of further estimates; however in cases where data on lithology or facies are scarce, the phase 3 procedures often are omitted. This situation also applies to the GAZGEOLMOD project.

The next step of the 3D modelling (phase 4) procedure is the development of parametric models. This is an extremely broad concept, because as petrophysical parameters can be understood not only the percentage of lithological compositions, porosities, permeabilities, average or interval velocities, and geomechanical parameters, but also temperatures, hydrocarbon compositions, thermal conductivities, vitrinite reflectance, and geochemical parameters of rocks or organic matter, etc. Input data for the completion of such models can be laboratory measurements, geophysical logs and 3D cubes of seismic attributes (Dubrule, 2003; Mallet, 2008; Herwanger and Koutsabeloulis, 2011; Vernik, 2016).

The GAZGEOLMOD research was not focused on parametric modelling. However, these model types were implemented either for the purpose of time-to-depth conversion of seismic interpretations or for the preliminary spatial delineation of sweet-spot areas (Papiernik *et al*., 2010, 2017b; Papiernik, 2017b, c).

In the case of modelling for the needs of the oil and gas industry in the next stage (phase 5) of the work, the previously constructed computer models are used for prospective resource/reserve assessments, using deterministic and/or stochastic methods (Fig. 2). In a typical petroleum exploration/development/production scheme, the culmination of the work cycle is the estimation of the sensitivity and uncertainty of individual, geological components that control the resources calculated (phase 6). From the point of view of the economics of exploration and production, this is an extremely important work package. It concerns the prospecting phase (e.g. depth recognition errors, due to limited accuracy of seismic interpretation, low precision of the velocity model, or lack of accuracy of mapping in the zones weakly controlled by data), recognition phases as well as production periods (reservoir properties, location of the Oil/Gas Water Contact O(G)WC, pressure maintenance, etc. (see Chilès and Delfiner, 1999; Abrahamsen *et al*., 2000; Coburn *et al*., 2006; Papiernik, 2010b; Papiernik and Michna, 2010; Ma and La Pointe, 2011; Klimkowski *et al*., 2015; Arnold *et al*., 2016). Tasks typical for phases 5 and 6 were not undertaken, as economic topics were not the goal of the research.

DATA, RESULTS AND DISCUSSION

In this paper, a synthesized review of the work and results obtained in the GAZGEOLMOD project is carried out in the context of the phases of the digital modelling procedure described above. In the research, mapping and structural modelling issues belong to the most important goals. In the context of the prospecting scheme presented above, the research tasks can be included in phases 1, 2 and 4 of general workflow.

Petrel database project creation (phase 1)

For all good-quality software used for computer-aided geological interpretations, the key element is the database. The research presented was carried out using Petrel™ software, which in typical installations does not support classical databases. Instead, a comprehensive Petrel database project (PDBP) can be created. The PDBP enables a huge amount of input data that is available to many users to be organized, grouped and indexed. The PDBP not only acts as a repository, but also as an interactive spatial data browser. Functionality, ease of use and intuitive access to catalogued and spatially embedded data make this solution easy to use for a wide group of geoscientists. Database creation and operational activities lasted throughout the project implementation period and tasks included the import, unification, supplementation and verification of input data, such as geophysical logs, seismic surveys or stratigraphic information in wells, as well as the referencing of digital and analogue cartographic materials. The most important data stored in the PDBP are described in following paragraphs.

The borehole database contains 1,853 wells in which Total Depth (TD) exceeds 400 m. 504 wells are in the Baltic Basin, including offshore wells, 196 in the Podlasie Basin, and 1,153 in the Lublin Basin. Of the huge quantity of wells in the LB, most reach the Carboniferous series, as they were coal exploration wells in the Lublin Coal Basin (LCB). The southern margin dataset also contains wells from the Carpathian Foredeep. Borehole inclination logs were available for 118 of the boreholes. All recent wells include inclination data. The presence of well path deviations enables the proper spatial XYZ location of markers and well logs in the basins.

An important element of the data quality assessment was the evaluation of the correctness of the stratigraphy in boreholes. Among many data sources, the latest stratigraphic data obtained from CBDG were of key importance, together with the recent data obtained from industrial partners. The authors of the mapping task also independently verified the stratigraphy, comparing the location of stratigraphic horizons in boreholes with geophysical logs, such as gamma-ray, shale content, sand content or carbonate content logs. In practice, this work was realized during the entire project time. In the final periods of project implementation, the results of stratigraphic (chrono-, bio-, litho-) studies conducted by teams, dealing with sedimentological and stratigraphic studies (Dziadzio *et al*., 2017; Kędzior *et al*., 2017; Podhalańska, 2017; Porębski and Podhalańska, 2017; Stadnik 2017; Wendorff, 2017) were introduced to the final well tops collection.

The XYZ location of the stratigraphic surfaces (well tops) is stored in the stratigraphic folders of the *Database Project*. Typically, they include chronostratigraphic or lithostratigraphic units. However, there can be other kinds of subdivision, such as biostratigraphy, etc. In the research project, the mapping task focused on the chrono- and lithostratigraphic complexes of the Lower Palaeozoic and this type of data was collected. The chronostratigraphic data for the Lower Palaeozoic series were prepared with a resolution of up to the stage and in some cases to the sub-stage. Stratigraphic data in younger complexes were corrected with accuracy not higher than the system. The top markers were collected in 693 boreholes from the EEC, covering in total over 25,950 unique stratigraphic well tops. The information came from 294 wells (12,368 markers) in the Baltic Basin, from 116 wells (4,733) in the Podlasie Basin, and from 283 wells (8,866 unique well tops) in the Lublin Basin.

Lithostratigraphic complexes were interpreted only for Silurian and Ordovician strata, and only in 187 boreholes, located on the EEC. This collection was based on markers available in the Central Geological Database (CBDG) of the Polish Geological Institute – National Research Institute (PGI-NRI), 17 well documentations of Polish Oil and Gas Company (PGNiG) boreholes. The new interpretation, based on geophysical logs, documentations, and cores, also was prepared by the research authors A. Kędzior (12 wells), S. Porębski (34 wells), P. Dziadzio (30 wells) and T. Podhalańska (17 wells). In the Baltic Basin area, the lithostratigraphy was determined in 110 boreholes, in Podlasie Basin in 44 wells and in Lublin Basin in 28 wells (Fig. 5).

The *Well folder* contains *Global well logs* subfolders, in which different types of measurement and well log data can be stored. Typically, this folder contains continuous or discrete raw geophysical logs, interpreted logs, discrete lithological, facies or stratigraphic logs, curves with information about dip angle and dip azimuths of structural elements, or so-called logic curves. The database project contains 5,450 geophysical logs which were mainly interpretations, less frequently geophysical measurements, laboratory data and core photos. They were assigned to 763 unique groups and these in turn to thematic folders of petrophysical continuous logs, petrophysical laboratory data, geomechanical logs, geochemical laboratory data, geochemical logs, XRD data, RTG_CEC data, NMR data, desorption laboratory data, etc. The preparatory work involved combining the sectional curves, supplementing the missing measuring profiles, removing artefacts, assignment of appropriate units and their unification, and finally, quality control of geophysical well log data. These data were used in the research tasks for stratigraphic studies as well as for parametric modelling (Fig. 5).

The seismic datasets used in the project comprised over 200 2D seismic lines in the time and/or depth domain, and three 3D seismic surveys. These data were supplied by PGNiG (for the Lublin, Podlasie and Baltic Basins) and Orlen Upstream (LB, PB). Only a limited collection of seismic lines was made available by industrial partners for research purposes. Profiles imported to PDBP were part of the following 2D surveys: Czernic-Ryki 2D (5 lines), Dobre 2D (9 lines), Grabowiec 2D (21 lines), Kock 2D (5 lines), Koczmin 2D (7 lines), Lublin Shale 2D (2 lines), Radawiec 2D (15 lines), Stężyca 2D (27 lines), Wilga 2D (1 line), Zamość 2D (27 lines), Kosakowo 2D (21 lines), Kościerzyna-Gdańsk 2D (34 lines), Opalino-Lubocino 2D (28 lines), 2D Surveys (Żelazna Góra 2D 3C, Górowo Iławieckie) in the eastern part of the Baltic Basin (49 lines). The authors also had access to three

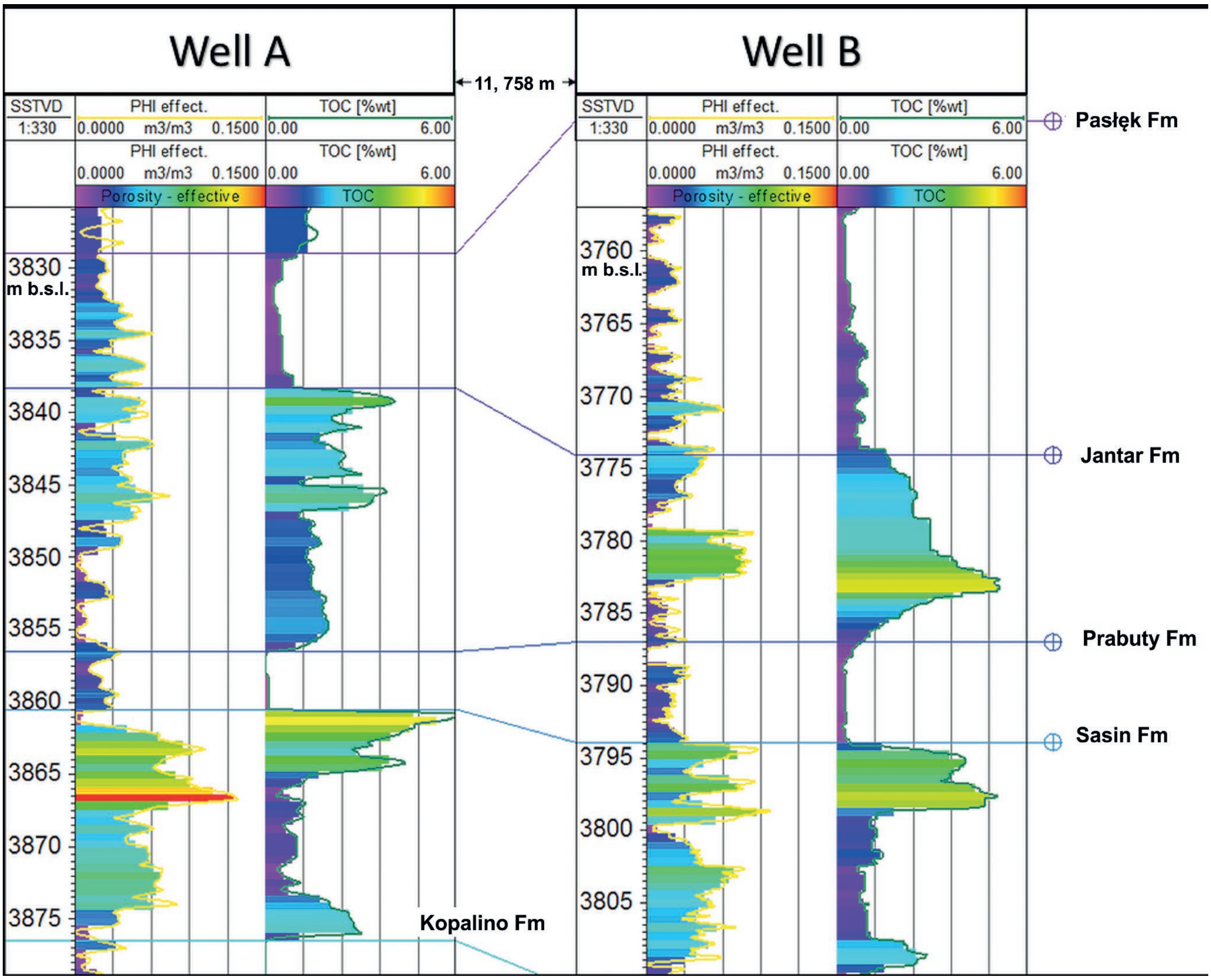

Fig. 5. An example of reinterpretation of stratigraphy in wells based on variability of curves and interpretations of geophysical logging (from Papiernik *et al.*, 2017b, modified).

3D surveys Zubów 3D, Opalino 3D, and Lubocino 3D. Along with seismic profiles, interpretations of horizons and faults were collected. These included imported 'industrial' data and the results interpreted during the project.

Published archival maps were digitized in the form of raster formats (Fig. 6). They were crucial for qualitative and, to some extent, quantitative mapping in the first period of the research. Several dozens of geological maps, quantitative maps, geological cross-sections and seismic profiles converted to raster were georeferenced and imported to the 1992 Coordinate reference system (ETRS1989). The database project contains published materials (Pożaryski and Dembowski, 1983; Żelichowski and Kozłowski, 1983; Pożaryski and Karnkowski, 1992; Królikowski and Petecki, 1995; Kotański, 1997; Wybraniec, 1999; Antonowicz *et al*., 2003; Stolarczyk *et al*., 2004; Buła and Habryn, 2008; Karnkowski, 2008; Modliński, 2010; Żelaźniewicz *et al*., 2011; Prugar, 2013; Mazur *et al*., 2015, 2016; Krzywiec *et al*., 2016). In addition, maps and cross-sections were imported from unpublished, archival materials.

The database project also includes Web Map Services (WMS). WMS is a standard created by the Open Geospatial Consortium (OGC) for providing raster maps using the HTTP interface. The connection to the map service takes place after entering the URL (Uniform Resource Locator) of a local or external map source. Over 50 different types of services have been introduced, mainly satellite images, road maps, topographic maps, maps of gravimetric measurements, maps of magnetotelluric measurements, geological maps of horizontal cuts, geological maps at various scales, subcrop maps, services with the location of boreholes, location of 2D and 3D seismic, geothermal WMS services, and hydrogeological WMS services.

The database project also contains Shape files from different sources. Crucial files were acquired from:

– the Central Geodetic and Cartographic Documentation Centre (CODGiK) - the borders of the State, provinces;
– CBDG, such as hydrocarbon license blocks, location of geoelectric, gravimetric and magnetotelluric surveys, 2D and 3D seismic data, boreholes;
– the physical and geographical regions of Poland (Kondracki, 2002);
– PGNiG and Orlen Upstream - concession blocks, location of the boreholes and lines of 2D seismic.

An important element of the project's input data set was also digital 2D grids. It included grids developed between

1995 and 2010 in the Department of Fossil Fuels AGH; grids of local seismic maps provided by the oil industry or interpreted by the seismic team as part of the project. The most important ones are described in detail later in the text.

Development of regional mapping and structural modelling (phase 2)

To create the digital maps within the framework of the project, a complex processing workflow was applied. It included both a conventional preparation of quantitative maps in the form of 2D grids, and the development of 3D structural models. The latter enable mutual spatial verifications of the correctness of digital maps and other input data, as well as the construction of structural maps for Lower Palaeozoic complexes with the rank of up to geological stage/epoch. This procedure included eight essential stages:

1. Structural mapping of the main geological boundaries, based on archival data (SM_1);
2. Adjustment of updated stratigraphy to trend maps (SM_2);
3. Adjustment of the MS_2 maps to initial results of seismic interpretation (SM_3);
4. Development of digital palaeo-thickness maps (PTM) and contemporary isochore thickness maps for stratigraphic stages and epochs of Lower Palaeozoic complexes (CTM);
5. Development of the preliminary structural model (PSTM);
6. Increase of the stratigraphic resolution of the initial structural model (PSTM) with the use of well-tops-based stratigraphy and CTM thickness maps (*Make Zones* procedure). The result of the work was the initial version of the resultant model, termed the Secondary Structural Model, (SSM = PSTM + CTM);
7. Final update of structural maps (FSM) and contemporary thickness maps (CTM), using the latest borehole data, seismic interpretation results and spatially calibrated public domain data (e.g., Mazur *et al*., 2015, 2016; Krzywiec *et al*., 2016);
8. Development of the Resultant Structural 3D model (R3DM) based on the results of stages 1–7.

The stages of modelling listed were repeated independently in the areas of the three Basins. Slightly different methodologies were applied in the area to carry out extension works in the Radom-Kraśnik zone and in the Narol Zone.

Stage 1. Structural mapping of the main geological boundaries, based on archival data (SM_1)

In the first stage of modelling, the unification of available input materials was carried out. Analogue data were subject to spatial calibration and digitalization to XYZ input files, compliant with the Petrel program formats (Fig. 6). The data processed in this way included the above-described maps, seismic and geological sections. However, the most important source of data for structural-parametric mapping at this stage was partial numerical models (2D grid), developed from archival maps, seismic and borehole data by the KSE-AGH team in years 1990–2012. The original data and models in digital formats were adapted to formats compatible with the Petrel[tm] program and converted to the ETRS1989 cartographic reference system (Papiernik, 2014). The most important, partial, digital data used in the project include:

- atlas of geothermal energy resources in the Polish Lowlands (Górecki *et al.*, 1995);
- assessment of oil potential and the possibility of discovering hydrocarbon deposits in the Mesozoic sediments in selected zones of the Polish Lowlands in relation to the North Sea Basin – analysis and interpretation in the Landmark system, (Górecki *et al*., 1998);
- atlases of geothermal resources of Mesozoic and Palaeozoic formations in the Polish Lowlands - geological, hydrogeological, geothermal and resource analysis of geothermal waters and energy in the Polish Lowlands (Górecki *et al*., 2006 a, b);
- in the case of modelling of Permian complexes, the basic input data were digital thickness and structure maps, elaborated by Kiersnowski and Papiernik (Peryt, 2008; Górecki, 2008);
- for the development of models of the thickness of Palaeozoic formations, a part of the thickness-structural models, developed by Papiernik for the Lublin and Podlasie region, was used as input material (Paczešna *et al*., 2005);
- for the older Palaeozoic strata in the rank of the epoch – from the Precambrian top to the Palaeozoic top – unpublished trend maps of thicknesses, developed by the authors in the form of regional 2D grids, were also used;
- an important set of input data was interim materials, created by Papiernik and the team as part of the implementation of the Atlas of the South Permian basin (Górecki, 2008; Peryt, 2008; Doornenbal *et al.*, 2010);
- geothermal atlas of the Carpathian Foredeep (Górecki *et al.*, 2012).

The dislocations and outlines of mapped stratigraphic units are a critical element of the cartographic studies being prepared. Preliminary versions of the outlines of individual Palaeozoic units and fault lines were compiled from the analogue and digital input materials described above. To achieve a satisfactory quality of the numerical 2D grids, these elements had to be edited to obtain local compliance. An important part of the data preparation was also the ability to accurately combine data from different sources. Preliminary versions of the outlines and fault lines of Palaeozoic complexes on the EEC were obtained from published analogue maps (Wierzchowska-Kicułowa, 1971; Pożaryski and Dembowski, 1983; Pożaryski and Karnkowski, 1992; Stolarczyk *et al*., 2004; Górecki *et al*., 2006b; Modliński, 2010). Editing work covered stratigraphic information on well tops, collected by the authors in the Database Project. The fault framework was reconstructed (Michna, 2017) at this stage independently for the Early Palaeozoic and Mesozoic. It required the connection of many partial sources. The dislocations, presented on maps of the Zechstein base, originated from a digital map, developed by Papiernik and the team (Papiernik *et al*., 2000) as well as Kudrewicz and Papiernik (2006), Papiernik and Machowski (2008).

In turn, faults on the Upper Permian and Carboniferous maps are modified and unified versions of fault networks, interpreted by Kudrewicz (2006), Kiersnowski (2008a, b, c), and supplemented by dislocations from the studies

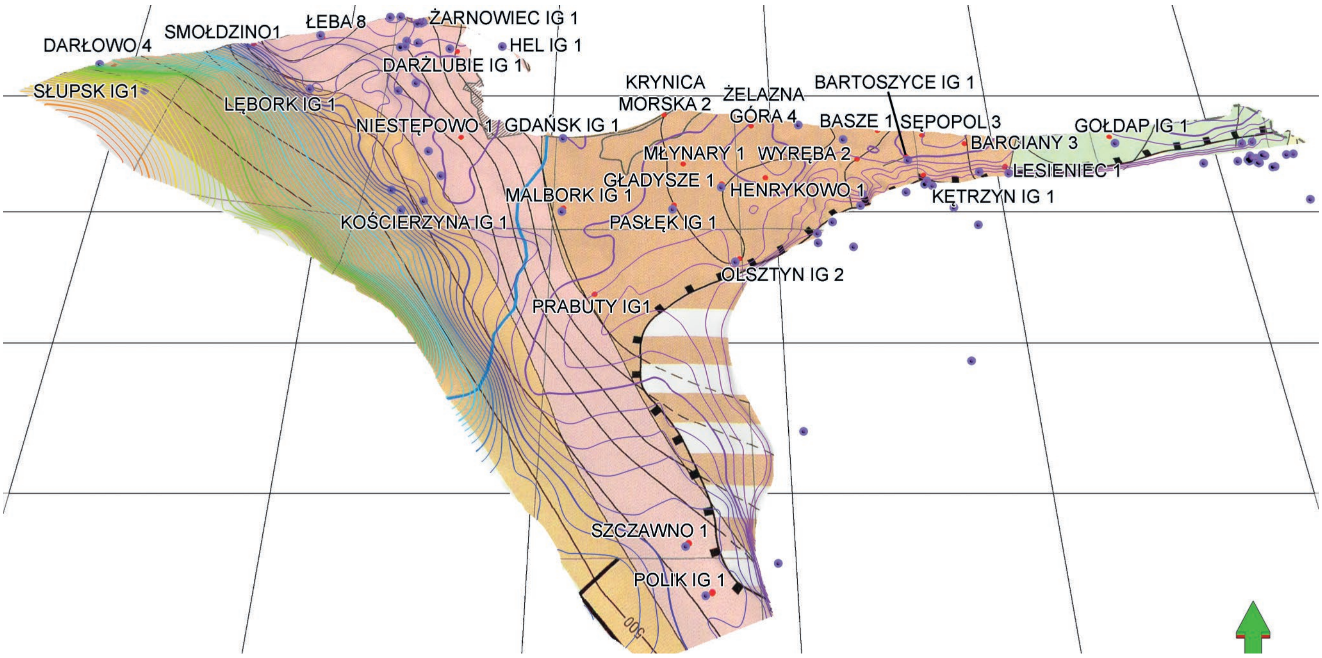

Fig. 6. An example of mutual checking of the accuracy of the location of well data and calibration of the scanned archive map.

by Pożaryski and Dembowski (1983), Żelichowski and Kozłowski (1983), and Modliński (2010).

In the southeastern part of the area, a network of dislocations for the Palaeozoic strata was adapted from Buła and Habryn (2008).

The process of unification of the input data to the form of 2D grids in stage 1 was carried out using modern interpretation procedures based on Petrel software. These procedures allow to more precisely define the spatial relations between the mapped surfaces (complexes) and enable better integration of various input data and partial numerical models (Papiernik and Machowski, 2008; Papiernik *et al*., 2009; Papiernik, 2010a). Their great advantage is the possibility of an easy interactive re-editing, allowing for:

– better integration of heterogeneous cartographic data;
– a local re-edition of digitized contours in order to correctly integrate partial input and precisely match models to input data;
– simplification of tectonics and its integration;
– consolidation and unification of the range lines of stratigraphic complexes, digitized from legacy maps, developed by various authors;

The end result of the work during this stage was the development for the Baltic, Podlasie and Lublin Basins of the map sets in the form of numerical regular interpolation grids (2D grid) in ranks erathems, systems, series, British Epochs. This set comprised 15 surfaces, representing from the Precambrian Top to the Cainozoic base (Tab. 1). Depending on the basin and stratigraphy, the number of maps could differ.

The development of maps at this stage of work was also accompanied by adjustments of their extent and the faults. Surfaces over the Silurian top were mapped with a lower horizontal resolution, as in the presented case they are only a structural closure of spatial models required only for tectonic modelling (Barmuta *et al*., 2019).

Table 1

List of preliminary structural maps (SM_1) created during realization phase 2, stage 1.

Mapped surface
1. Precambrian top (SM_1)
2. lower Cambrian top (SM_1)
3. middle Cambrian top (SM_1)
4. upper Cambrian top (SM_1)
5. Ordovician top (SM_1)
6. lower Silurian (Llandovery) top (SM_1)
7. middle Silurian (Wenlock) top (SM_1)
8. Silurian top (SM_1)
9. Devonian top (only in LB and PB) (SM_1)
10. Carboniferous (only in LN and PB) (SM_1)
11. Rotliegend top (SM_1)
12. Zechstein top (SM_1)
13. Triassic top (SM_1)
14. Jurassic top (SM_1)
15. Cainozoic base (SM 1)

Stage 2. Adjustment of updated stratigraphy to trend maps (SM_2)

The next step, after the unification of the structural archival maps was their adjustment to the stratigraphic data set collected and interpreted during the first period of the project. The resulting maps formed a group of SM_2 solutions that were the input material for further work (Fig. 7A). Well adjustment realized at this stage was based on legacy

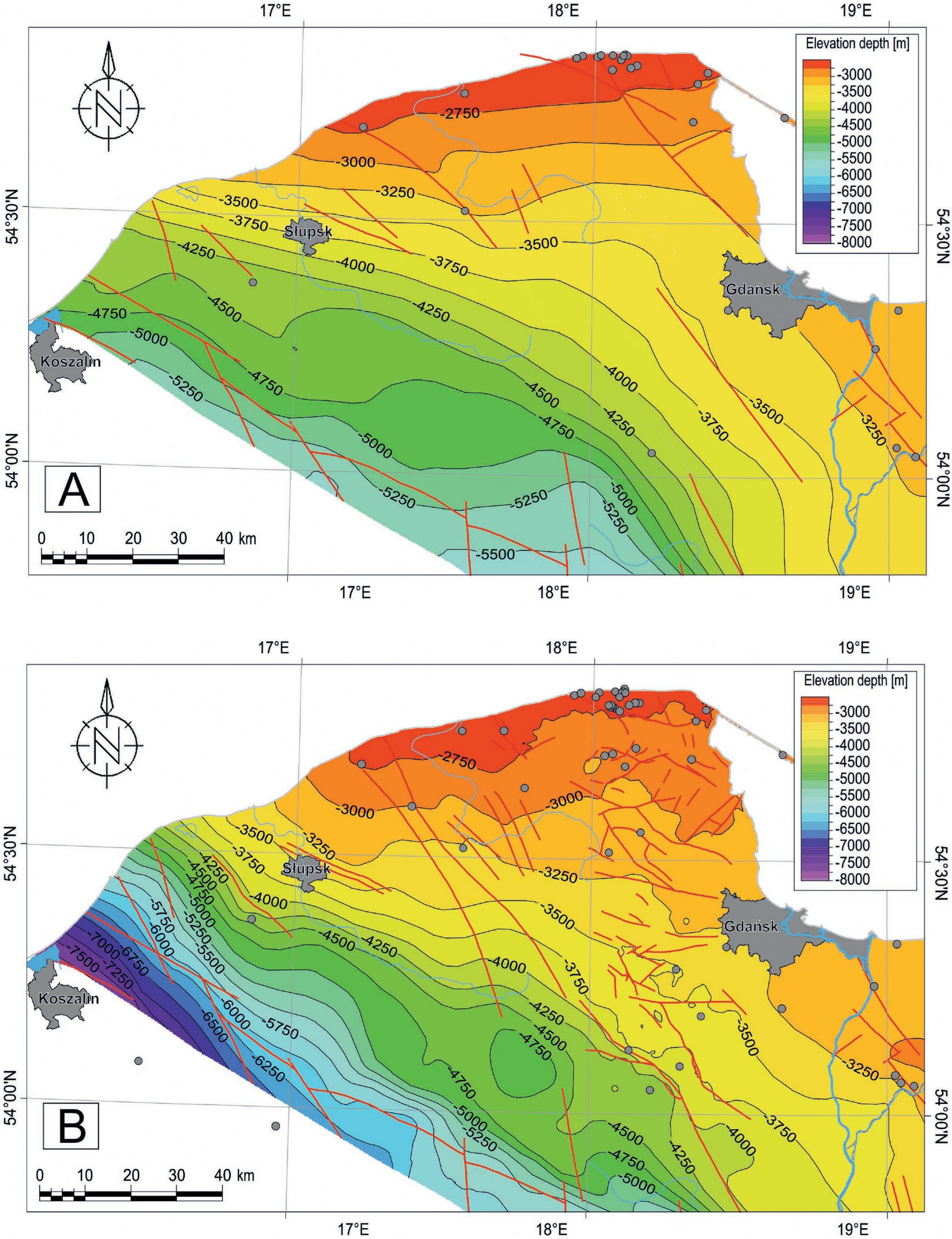

Fig. 7. Results of reinterpretation of structural maps illustrated with the maps of the Ordovician top in the central part of the Baltic Basin. **A.** Original trend map (MS_2 map set). **B.** Resulting map updated with the results of initial seismic interpretation (MS_3 map set).

data and some geophysical-log-based stratigraphy reinterpretations, which was completed by a mapping team. Maps created at this stage of work underwent locally significant modifications, as the adjustment included all wells drilled up to 2012. The tasks covered all the 15 maps mentioned above (group SM_1; Tab. 1), in each of the three sedimentary basins. This procedure was repeated in the next stages, as the teams running stratigraphic and sedimentology studies supplied novel interpretation work.

Stage 3. Adjustment of the SM_2 maps to initial results of seismic interpretation (SM_3)

At this stage of the work, trend maps adjusted to wells (group of SM_2 maps) were temporary modified with the use of preliminary, mainly legacy, results of seismic interpretation. The structural map modifications included a sharp, mechanical linking of the results of the applied seismic interpretation. (Fig. 7B). As a result, the seismically modified parts of maps differ drastically from the other areas of the map. The reinterpretation covered maps of the tops of ten stratigraphic surfaces (Tab. 2).

Table 2

List of intermediate maps (SM_3) locally updated with legacy seismic interpretations phase 2/stage 3.

Mapped top surface
1. Precambrian (SM_3)
2. middle Cambrian (SM_3)
3. Ordovician (Fig. 8) (SM_3)
4. Silurian (SM_3)
5. Devonian (only in LPB) (SM_3)
6. Carboniferous (only in LPB) (SM_3)
7. Rotliegend (SM_3)
8. Zechstein (SM_3)
9. Triassic (SM_3)
10. Jurassic (SM_3)

Simplified, the maps created at this stage are equivalent to the primary seismic horizons observed in basin scale and they are the basic surfaces that define the framework of the structural models. For detailed mapping and stratigraphic studies, the model must be filled with additional geologic information that is much more precise than the seismic resolution. It is also necessary for the precise, spatial delineation of important elements of the Silurian–Ordovician petroleum system.

Figure 7 enables a comparison of the SM_2 (Fig. 7A) and SM_3 (Fig.7B) generations of maps. It clearly shows that in areas where seismic interpretations and new well data were available, the structural and tectonic framework becomes much more complex.

Stage 4. Development of digital palaeothickness maps (PTM) and contemporary isochore thickness maps for stratigraphic stages and epochs of Lower Palaeozoic complexes (CTM)

Preliminary mapping of palaeothickness and contemporary thickness is a stage that can be performed out of the proposed sequence. The first task of this stage was the elaboration of primary palaeothickness maps *via* scanning, digitization and gridding of maps, published in Modliński (2010). It comprised a set of twelve 2D grids constructed with a horizontal resolution of 500 m:

1. Lithofacies-palaeothickness of the pre-Holmia lower Cambrian (Platysolenites antiquissimus and Schmidtiellus mickwitzi zones) (Paczeŝna, 2010a) (PTM);
2. Lithofacies-palaeothickness of the Holmia lower Cambrian (Holmia and Protolenus zones) (Paczeŝna, 2010b) (PTM);
3. Lithofacies-palaeothickness of the middle Cambrian (Paczeŝna, 2010c) (PTM);
4. Lithofacies-palaeothickness of the upper Cambrian (Szymański and Paczeŝna, 2010c) (PTM);
5. Lithofacies-palaeothickness of the Arenig (Modliński and Szymański, 2010a) (PTM);
6. Lithofacies-palaeothickness of the Llanvirn (Modliński and Szymański, 2010b) (PTM);
7. Lithofacies-palaeothickness of the Caradoc (Modliński and Szymański, 2010c) (PTM) (Fig. 8A)
8. Lithofacies-palaeothickness of the Ashgill (Modliński and Szymański 2010d) (PTM);
9. Lithofacies-palaeothickness of the Llandovery (Modliński *et al.*, 2010a) (PTM);
10. Lithofacies-palaeothickness of the Wenlock (Modliński *et al.*, 2010b) (PTM);
11. Lithofacies-palaeothickness of the Ludlow (Modliński *et al.*, 2010c) (PTM);
12. Lithofacies-palaeothickness of the Pridoli (Modliński *et al.*, 2010d) (PTM).

The maps were then modified, using legacy thickness data and the stratigraphy from wells completed after 2009, mainly as a part of shale gas exploration. Authors had no access to all data created in this time, as the exploration companies in most cases still own the data. Hence, final corrections were made using the new stratigraphy from 34 vertical wells that did not exist during the preparation of the input maps (Modliński, 2010).

Updated palaeothickness maps were then processed into the contemporary thickness maps (CTM). To meet this objective, the new and the reinterpreted archival well tops were applied to create isochore maps, using results of the work from stages 1–4 of phase 2, as well as the maps from Modliński (2010). The updated extent lines and fault lines also were applied in this task. Then, taking into account the character of the pinch-outs, palaeothickness maps were converted into the CTMs. In faulted zones, abrupt thickness reduction was interpreted, while in erosional zones, a gradational decrease of thickness was assumed (Fig. 8B). The final stage of this work was eleven isochore maps (CPT), created separately for the Baltic, Podlasie and Lublin basins.

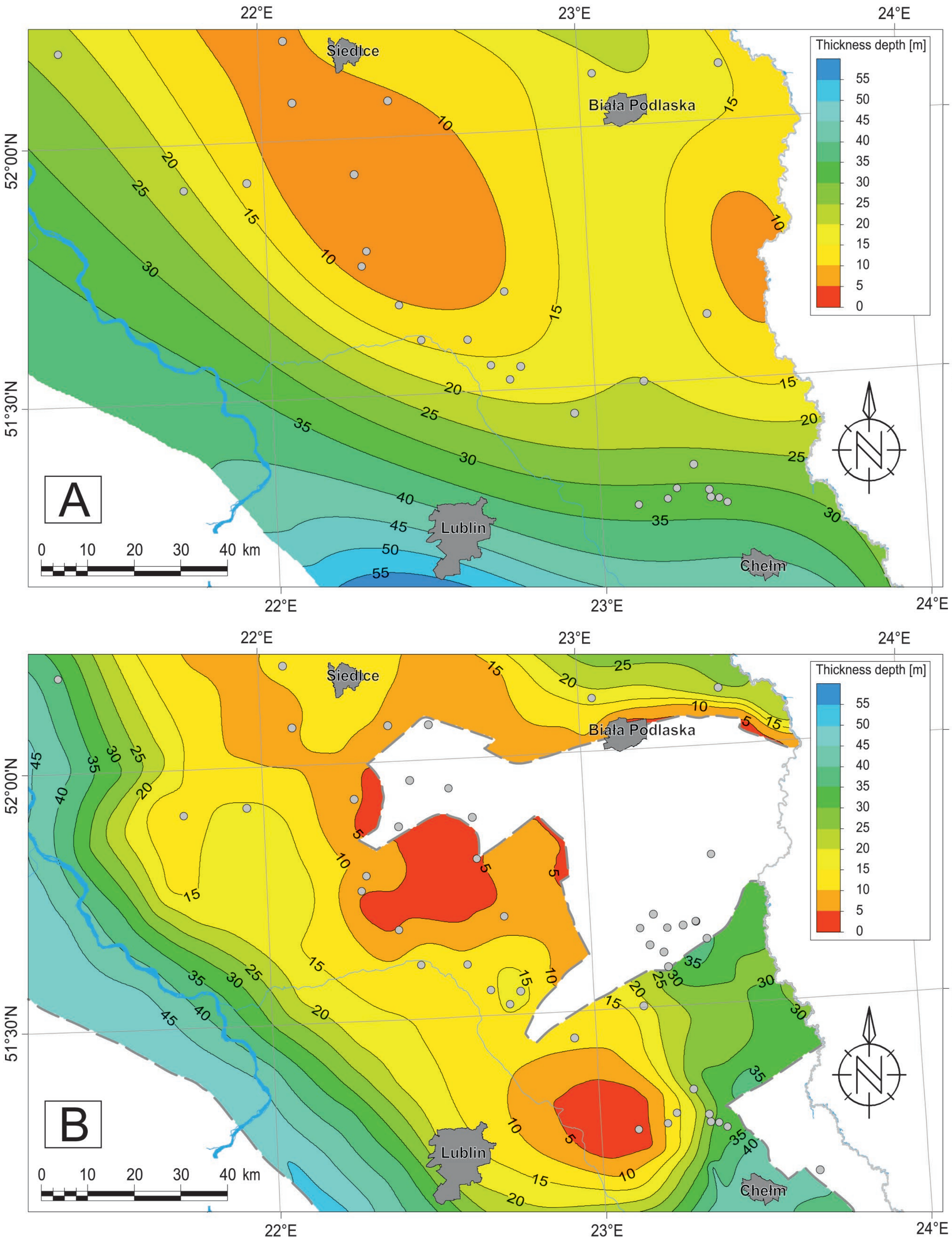

Fig. 8. Development of digital palaeothickness maps and contemporary isochore thickness maps for stratigraphic stages and epochs of Lower Palaeozoic complexes illustrated with the maps of Caradoc deposit in the central part of the Lublin Basin. **A.** Paleothickness map (PTM – map set). **B.** Resulting contemporary thickness map (CTM map set).

Table 3

List of intermediate contemporary thickness maps (CTM) updated with the legacy well data. Phase 2, stage 4.

Mapped surface
Thickness of the lower Cambrian
Thickness of the middle Cambrian
Thickness of the upper Cambrian
Thickness of the Arenig
Thickness of the Llanvirnian
Thickness of the Caradocian
Thickness of the Ashgill
Thickness of the Llandovery
Thickness of the Wenlock
Thickness of the Ludlow
Thickness of the Pridoli

Again, a comparison of the primary palaeothickness maps (Fig. 8A), with contemporary thickness maps, CTM (Fig. 8B), modified with the well data obtained after the year 2010, shows a much more complex thickness variability than had been assumed in the past.

Stage 5. Development of the preliminary structural model (PSTM)

Initial structural models were created independently for Baltic Basin (Fig. 9), LB and PB, the modelled surfaces were created using the procedure *Make Horizons* as irregular, digital surface models that can be discontinuous surfaces. In modelling procedures, they are called *Horizons*. The input data for these models were products of stages 2 and 3 structural maps MS_2 or MS_3 (Tab. 4).

The resulting model contained up to 15 horizons, creating 14 complexes in the rank of geological System to Series. These complexes are called the Zones in modelling jargon. Their stratigraphic rank depends on the specific stratigraphy of the input surfaces.

Stage 6. Increase in the stratigraphic resolution of the initial structural model (PSTM) with the use of well-tops-based stratigraphy and CTM thickness maps (Make Zones procedure)

The result of the stage 6 Secondary Structural Model, (SSM=PSTM+CTM). Source rocks at the EEC are a very small part of the monotonous complexes of Silurian and Ordovician, dominated by shales and mudstones. The almost uniform lithology renders seismic useless in attempting to image geological complexes in rank of series, stage, British Epochs, formation or member. To increase the stratigraphic resolution of the well-based stratigraphy and thickness map, the procedure *Make Zones* within the CPG method can be applied to enable the structural representation of potential source rocks (complexes).

At this stage of the modelling, the preliminary 3D framework, based on maps adjusted to seismic horizons (PSTM), is transformed into a detailed, structural model with sub-seismic stratigraphic resolution. In Petrel workflows, this operation is performed using the *Corner Point Gridding*

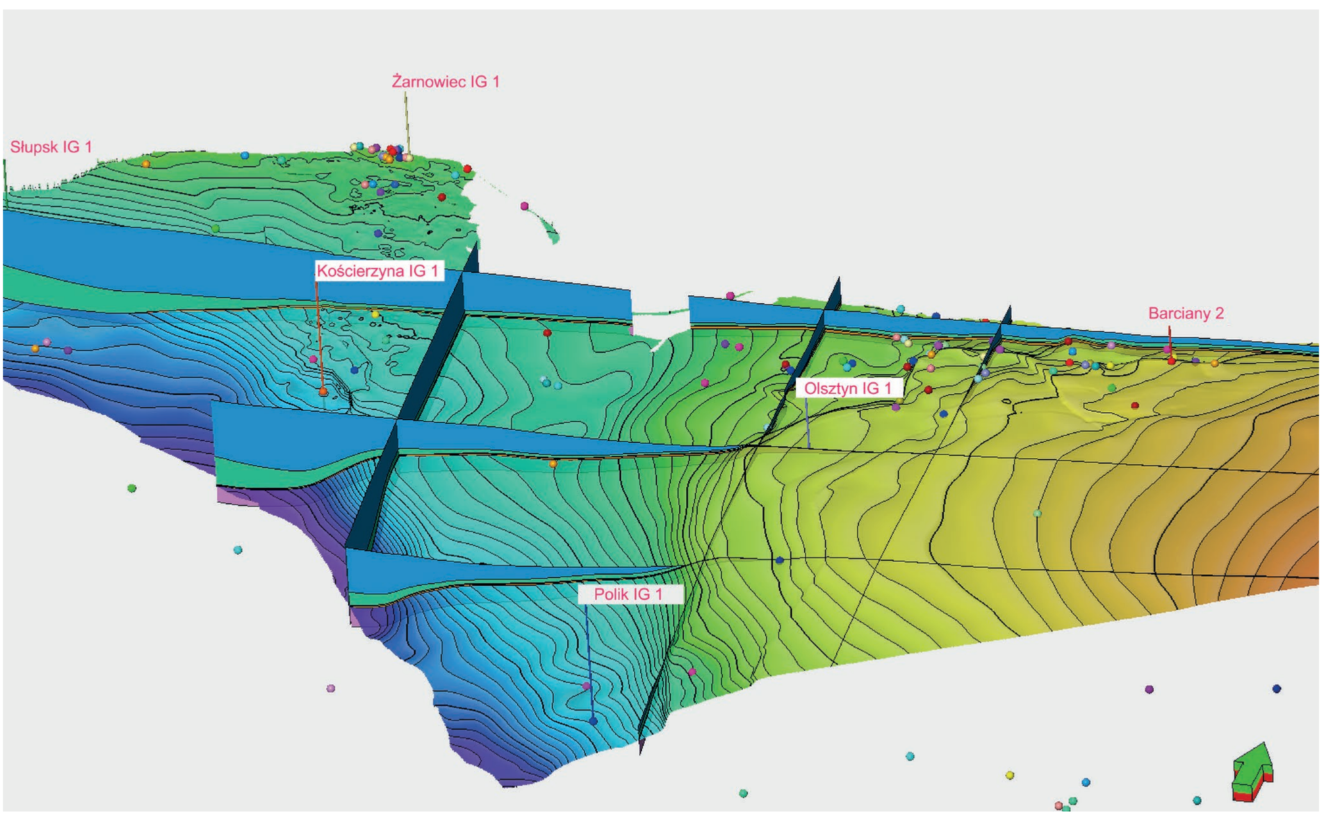

Fig. 9. Preliminary structural model (PSTM): An example: Baltic Basin, part of the profile: pre-Cambrian top – Silurian top (from Papiernik, 2017b, modified).

Table 4

List of intermediate structural surfaces used to build horizons (MS_2 or MS_3) of the preliminary structural model. Phase 2, stage 5.

Mapped surface
1. Precambrian top (MS_3)
2. lower Cambrian-top (MS_2)
3. middle Cambrian top (MS_3)
4. upper Cambrian top (MS_2)
5. Ordovician top (MS_3)
6. lower Silurian (Llandovery) top (MS_2)
7. middle Silurian (Wenlock) top (MS_2)
8. Silurian top (MS_3)
9. Devonian top (only in LB and PB) (MS_3)
10. Carboniferous (only in LN and PB) (MS_3)
11. Rotliegend top (MS_2)
12. Zechstein top (MS_2)
13. Triassic top (MS_3)
14. Jurassic top (MS_3)
15. Cainozoic base (MS_2)

Table 5

List of structural horizons creating the Secondary Structural Model (SSM). Phase 2, stage 6.

Mapped surface
1. Precambrian top
2. lower Cambrian top
3. middle Cambrian top
4. upper Cambrian top
5. Tremadocian
6. Arenig
7. Llanvirnian
8. Caradocian
9. Ashgill
10. Ordovician top
11. Llandovery
12. Wenlock
13. Ludlow
14. Silurian top

method, following the *Zone Modelling* procedure. This enables the introduction between the main structural horizons (MS_3) of additional surfaces that are controlled with well tops and/or thickness maps of chrono- / lithostratigraphic complexes (CMT; Fig. 10).

The procedure was repeated in the three basins investigated, enabling the construction of basin-scale models of Lower Palaeozoic strata with a stratigraphic resolution of system, series, and British epoch.

In the other group of models belonging to SSM, mixed lithostratigraphic and chronostratigraphic stratification was used, where Llanvirnian and Caradocian horizons were replaced by surfaces of the top and the base of the Sasino and Jantar formations. The top was introduced into the Llandovery complex (zone).

The surfaces obtained enable the structural representation of complexes not imaged directly by seismic methods, including potentially productive deposits of the Caradocian, Llandovery and Wenlock (e.g., Papiernik, 2017c; Papiernik *et al*, 2017a, b, 2019).

For the final update, structural horizons defining the structural models of the SSM group were converted to the form of Structured Surfaces and model complexes (zones) to thickness maps (isochore maps). Extracted from the SSM models, the thickness maps also allowed for additional reinterpretations in the context of the geometrical constraints, established by the geometry of horizons created within PSTM.

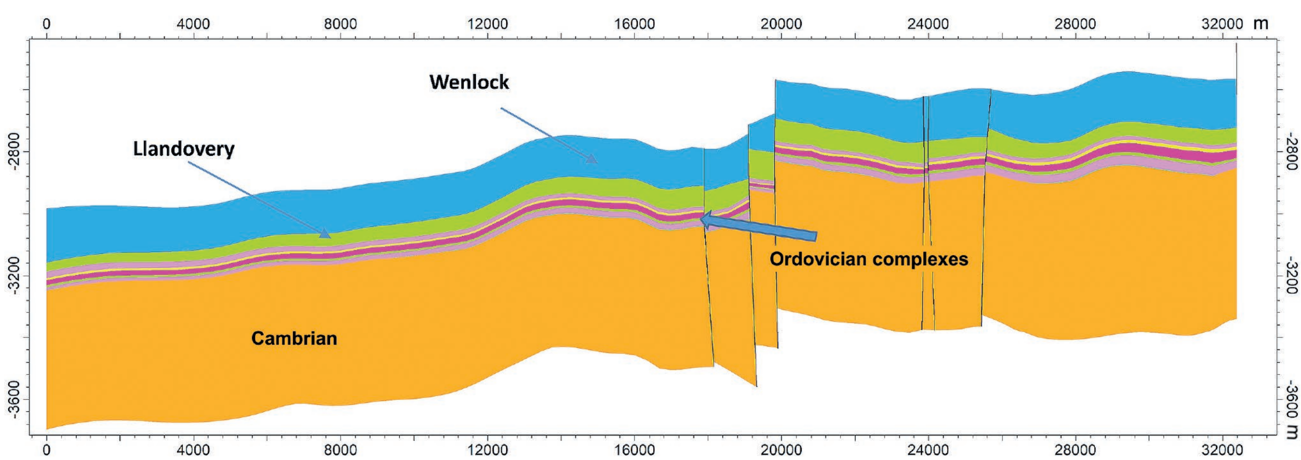

Fig. 10. Secondary Structural Model of the Lower Palaeozoic displayed as a cross-section in the central part of the Baltic Basin.

Stage 7. Final update of structural maps (FSM) and final thickness maps (FTM)

For the stage 7, the latest borehole data, seismic interpretation results and spatially calibrated public data (e.g., PolandSPAN) are used. In the last year of the project, a massive inflow of new interpretations occurred, comprising cartographic materials (e.g., Buniak *et al*., 2016) seismic interpretations and sedimentological, and stratigraphic studies (Dziadzio *et al*., 2017; Kędzior *et al*., 2017; Podhalańska, 2017; Porębski and Podhalańska, 2017; Stadnik 2017; Wendorff, 2017). In addition, the seismic team supplied new, local interpretations in the Baltic Basin (Cichostępski *et al*., 2019; Kasperska *et al*., 2019). The reinterpretation performed in the LB and southern part of Podlasie Basin was especially extensive. In the last phases of research, more than 70 seismic lines were interpreted in the Baltic Basin and on the SW edge of the Podlasie Basin. The interpretation of 32 of them was performed by the team from the Institute of Geophysics of Polish Academy of Science in Warszawa, and over 40 by the team from the Department of Fossil Fuels of UST-AGH in Kraków. The result of the work is over 20.000 km of seismic interpretation, in most cases performed in the time domain. To use it for the development of final maps, a regional 3D model of average velocity was developed and used for time-to-depth conversion.

At this stage of the work, regional interpretations, based on published ION cross-sections, were also used, including PL-5600 (Mazur *et al*., 2016) PL-5400, PL-5300 (Mazur *et al*., 2015), PL-5100, PL-5000, as well as a fragment of the profile PL-1100 (Krzywiec *et al*., 2016).

These results were used to modify *Structured Surfaces* and thickness maps (zones isochore), extracted from the SSM models. First, twelve seismically traced Palaeozoic and Mesozoic surfaces were corrected (Tab. 6). Surfaces shallower than top Silurian were used for tectonic modelling (Barmuta *et al*., 2019).

Table 6

List of resultant structural maps updated with seismic interpretation and updated well data (FSM). Phase 2, stage 7.

Mapped surface
Precambrian top
Cambrian top
Ordovician top
Lower Silurian (Llandovery)
Silurian top
Devonian top (only in LB and PB)
Carboniferous (only in LB and PB)
Palaeozoic top
Rotliegend top
Zechstein top
Triassic top
Jurassic top

Updating at this stage was also applied to the thickness and remaining 'subseismic" top maps of the Lower Palaeozoic complexes, extracted from the SSM model (Tab. 5). During stage 7, all the maps completed on the scale of basins (stage 5 and 6) were joined into platform-scale 2D grids. Their horizontal resolution equals 250 m x 250 m. Most of them are defined by 4 200 000 grid nodes.

Eventually, at this stage of processing the Lower Palaeozoic strata, 15 thickness maps (FTM) and 15 structural maps (FSM) were elaborated /updated (Tab. 7). They cover stratigraphic units, ranging from Erathem to Series in rank. Additionally, 14 trend maps of the thickness of lithostratigraphic complexes were created (Tab. 7). Their horizontal resolution is much lower than for the chronostratigraphic maps, as they utilised well tops information from only 187 boreholes, while chronostratigraphic markers were prepared in 693 wells. In practice, only the Jantar Fm, Sasino Fm and Ordovician Carbonate Complex represent a level of accuracy comparable to maps, based on chronostratigraphic divisions. It enabled the creation of three additional structural maps, covering Jantar Fm Top, Sasino Fm Top and Sasino Fm Base.

An important result of the work during this stage was also a significant modification of fault lines, defined for Lower Palaeozoic strata in all basins of the EEC. They were created as a result of export and unification of fault lines from 3D Fault models of the three basins.

Stage 8. Development of the Resultant Structural 3D model (R3DM) based on the results of stages 1–7

Owing to technical reasons, it turned out to be impossible to create platform-scale faulted structural models using solely the CPG method. The reason for this problem is the complex tectonics of the Lublin Basin, where both normal faults and overthrusts exist. This requires the application of the SF method in 3D modelling, while the size of the platform-scale model exceeded the maximum handling capability of the Petrel package. Eventually, owing to technical reasons, the authors developed resultant "faulted" structural models separately for the Baltic Basin (CPG 3D Grid; Fig. 13), the Podlasie Basin (CPG 3D Grid) and in the Lublin Basin (SF 3D Grid). Platform-scale models were elaborated in many versions for the Lower Palaeozoic strata as continuous 3D grids, constructed with the SG or CPG grids (Papiernik *et al*., 2017b, 2019). The input surfaces for horizon modelling in this case were structural surfaces of tops, estimated in stage 7 (Tab. 7).

The basic models of the workflow presented were created at a basin scale, then upscaled to platform-scale models and downscaled to local-scale, structural models (Fig. 13).

The special structural model was created for the Lublin Basin, the Narol Zone and the Radom-Kraśnik Zone in the time domain. Utilizing the results of seismic interpretation in this area, the authors developed, using the Simple Grid method, the structural model comprising the horizons 0 ms (flat), Jurassic top, Palaeozoic top, Silurian top, Cambrian top and Precambrian top. They created the structural framework of the average velocity model, used for time-to-depth conversion of the seismic interpretation in that area.

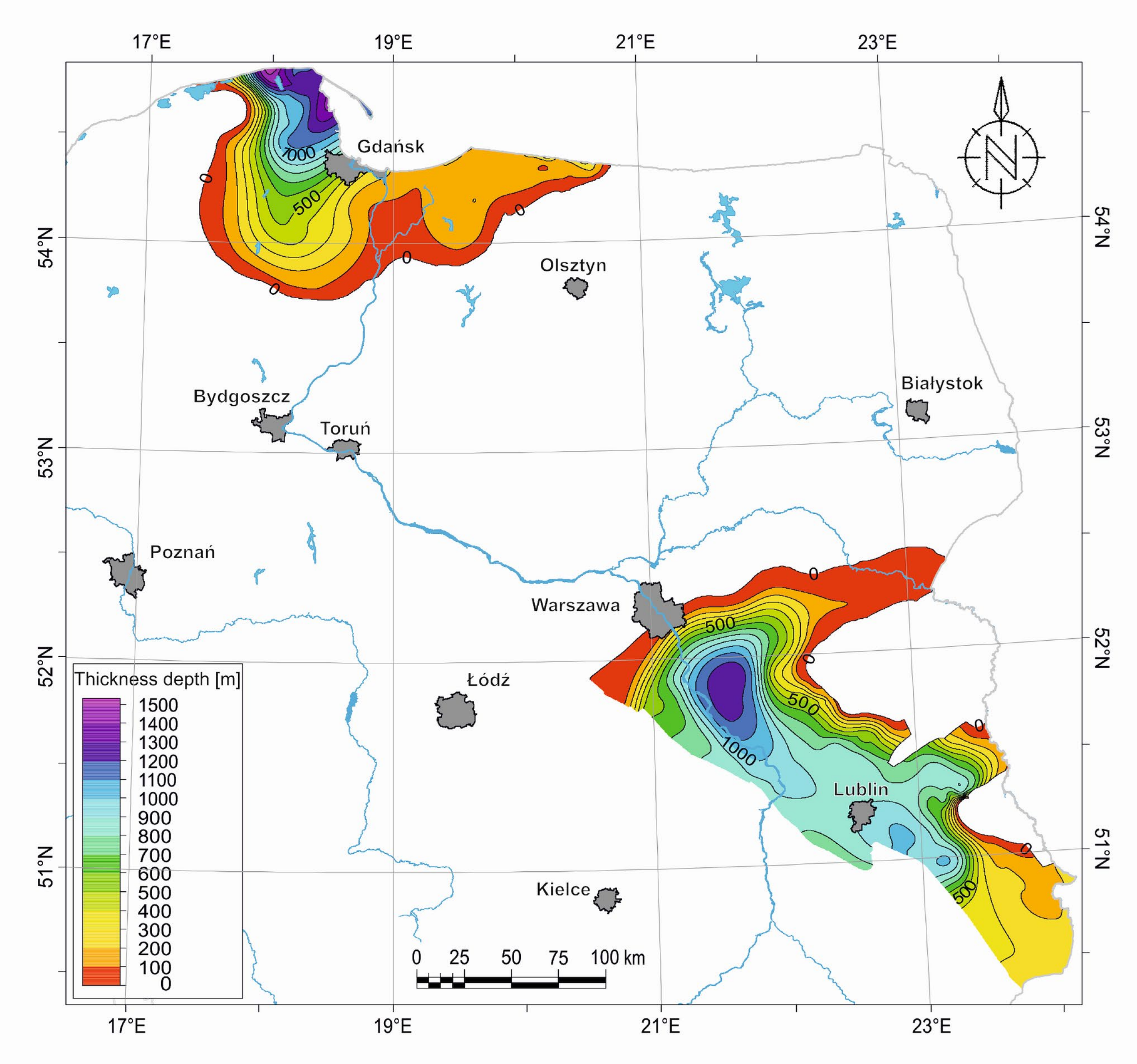

Fig. 11. Map of thickness of the Pridoli – derived from the regional 3D structural model SSM.

Development of parametric models and maps (phase 4)

The parametric modelling carried out in the GAZGEOLMOD project is marginal in scale. Important for its overall results were trend models and maps of the basic elements of the petroleum system, vitrinite reflectance, Ro (Fig. 14), and total organic carbon content (TOC), developed for Lower Palaeozoic strata (more: Papiernik *et al.*, 2017b, 2019).

Maps / models elaborated in this phase should be treated as preliminary solutions, owing to the diverse but generally low quality of archival parametric input data (the vast majority of the data set possessed) and their variable consistency with modern data acquired as part of the shale gas exploration campaign. The described models were developed on the platform-scale as 3D SG, based on resultant maps created during the completion of stage 7 of structural model construction (phase 2; Tab. 7). They do not include fault models directly, but owing to the accuracy of the input maps and the considerable horizontal resolution of the model (600 m x 600 m), the abrupt changes in structure that reflect faulting effects are honoured by the resultant structural-parametric model.

In addition to the parametric models mentioned above, a regional model of average velocity was completed (Fig. 15). Its geometrical framework was prepared in a time domain. It was required for the time-to-depth conversion of seismic data. These results were of great importance for the development of the resultant models, structural maps and thickness maps in the southern part of the Podlasie Basin and the entire Lublin Basin.

Parametric models must be supplemented and updated in the coming years, as data obtained by companies seeking shale gas are released. The authors had at their dispos-

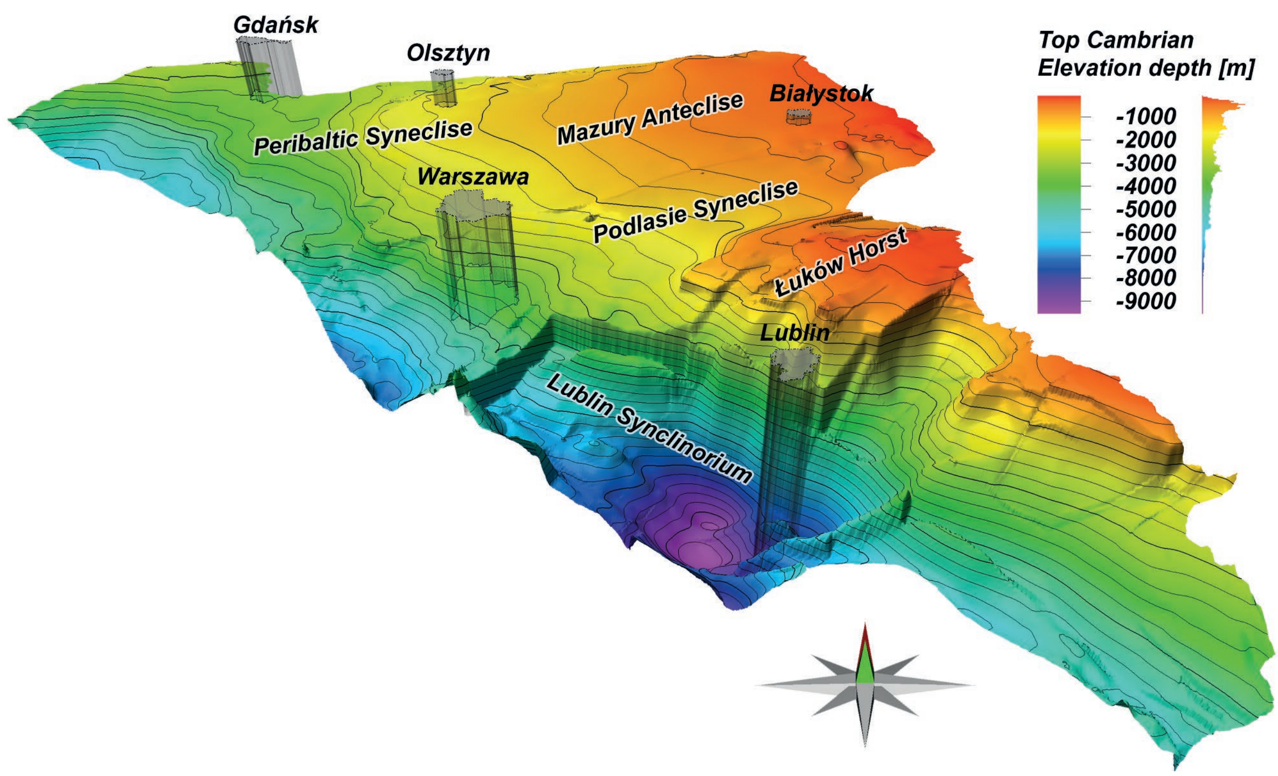

Fig. 12. Three-dimensional visualization of the Cambrian top – surface derived from the regional 3D structural model SSM (based on Golonka *et al*., 2017, modified).

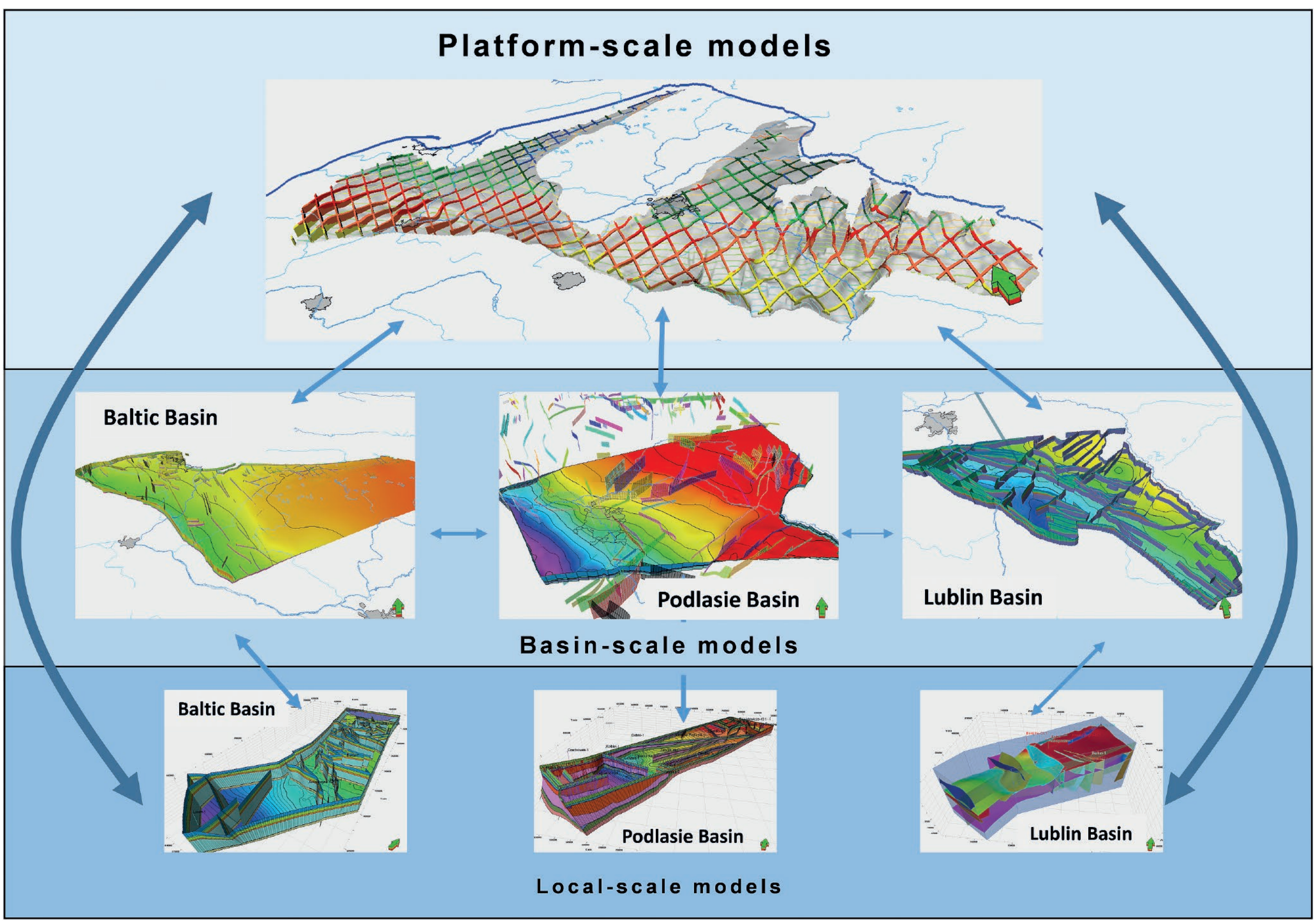

Fig. 13. Final structural modelling results of GAZGEOLMOD project.

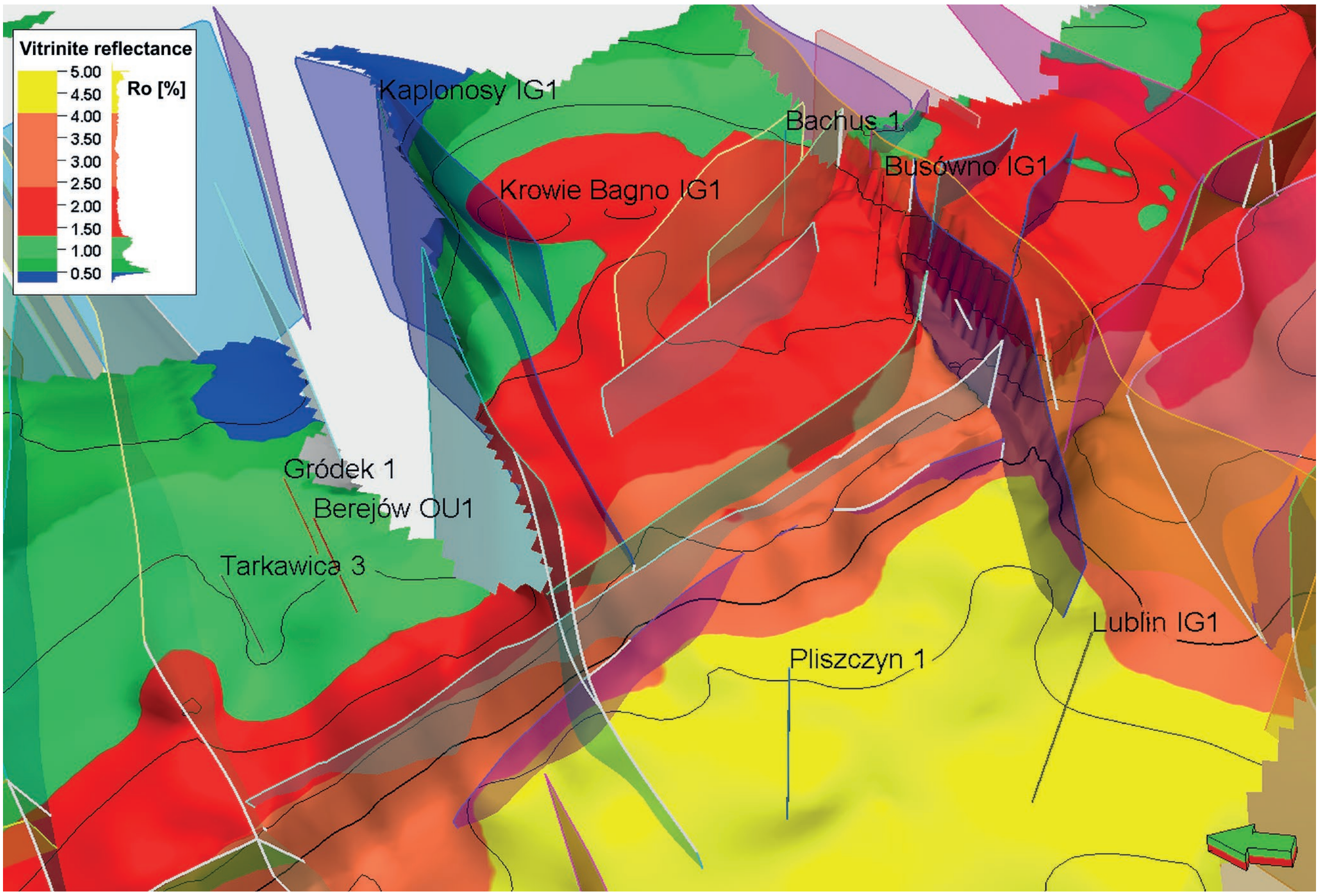

Fig. 14. Map of vitrinite reflectance (Ro) on the top of the Cambrian. Ro values derived from the 3D model on the Cambrian top.

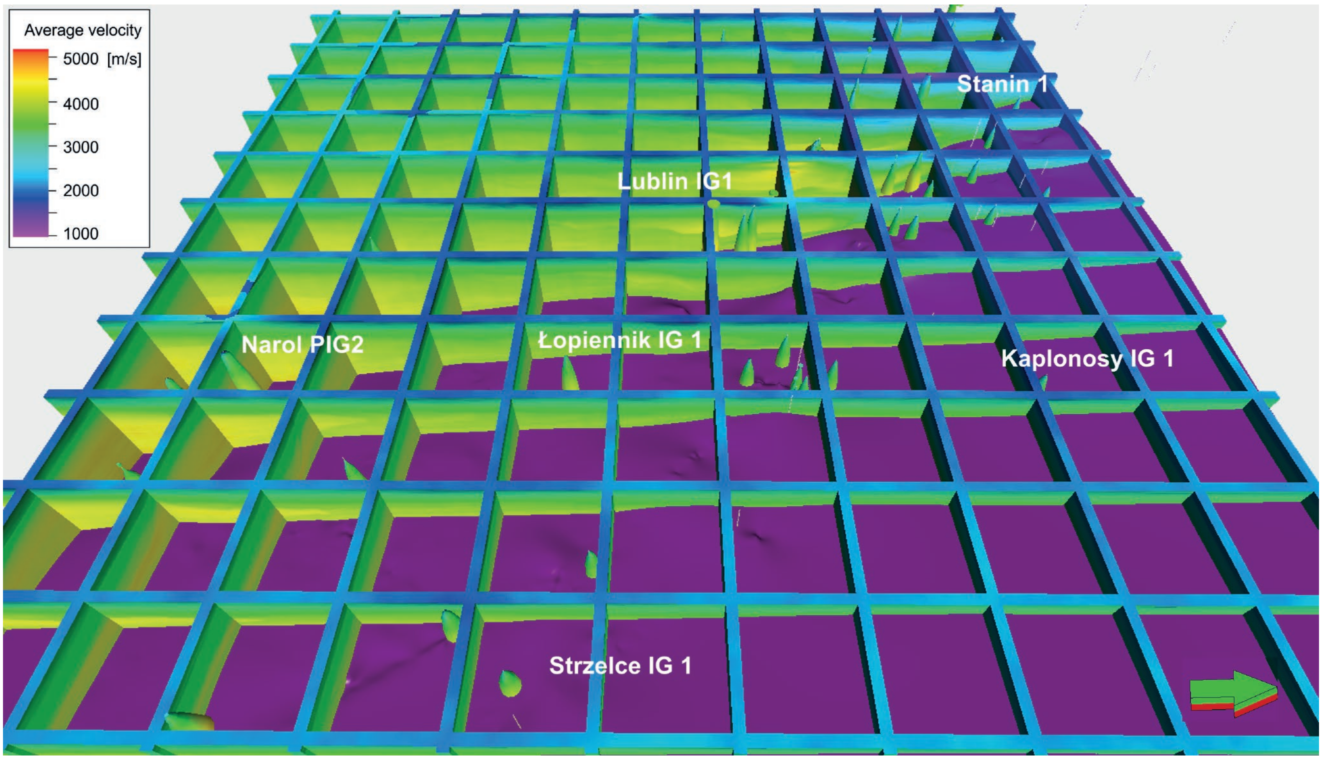

Fig. 15. Model of average velocity in the Lublin Basin area, southern part of Podlasie Basin, Narol Zone and Radom-Kraśnik Zone.

Table 7

Specification of resultant structural (FMT) maps of Lower Palaeozoic created within stage 7.

No	FSM structural map	FTM-Chronostratigraphic complexes thickness	FTM - Lithostratigraphic complexes thickness
1	Precambrian top	lower Cambrian	Sępopol Formation
2	lower Cambrian top	middle Cambrian	Rajsko Formation
3	middle Cambrian top	upper Cambrian	Słuchowo Formation (additionally Płonka Formation)
4	upper Cambrian top	Cambrian	Pieszków Formation, Widowo Formation, Uherka Formation, Narew Formation
5	Cambrian top (Fig.12)	Tremadocian	Ordovician Carbonate Complex
6	Tremadoc	Arenig	Sasino Formation* (additionally Włodawka Formation and Udal Member)
7	Arenig	Llanvirnian	Marly Carbonate Complex Of Ordovician
8	Llanvirnian	Caradocian	Barciany Formation
9	Caradocian	Ashgill	Jantar Formation*
10	Ashgill	Ordovician	Pasłęk Formation (Additional Wrotnowo Formation)
11	Ordovician top	lower Silurian (Llandovery)	Pelplin Formation
12	lower Silurian (Llandovery)	middle Silurian (Wenlock)	Kociewie Formation
13	middle Silurian (Wenlock)	Ludlow	Reda Member
14	Ludlow top	Pridoli (Fig. 11)	Puck Formation
15	Silurian top	Silurian	

* Sasino Fm top and base and Jantar Fm top surfaces were created additionally.

al only data from 14 modern wells from over 70 drilled in shale gas exploration (details are in Papiernik *et al*., 2017b, 2019). Extending the database will enable comprehensive modelling of lithological variables, the spatial reconstruction of sweet-spot locations and shape, and finally, risked resource assessment on a platform scale, using techniques developed at AGH for pilot areas during implementation of the ŁUPZAS project (e.g., Papiernik, 2017c).

CONCLUSIONS

The proposed project methodology of mapping and structural modelling uses and further develops the newest concepts and methodologies in the Exploration & Production industry. The spatial scale of these solutions can be compared only with some studies, implemented by the USGS and Schlumberger (Wygrala *et al.,* 2013; Wygrala, 2014), Geological Survey of the Netherlands –TNO (Den Dulk and Doornenbal*,* 2014) and the British Geological Survey- BGS (Mathers, 2014; Peach *et al.,* 2017), while the stratigraphic resolution of the completed maps/models seems to be much higher than those obtained for the Lower Palaeozoic strata with a stratigraphic resolution of geological series and stages.

The proposed model-cantered methodology enables the model to be utilized in many fields, starting from the database function, accompanied by interactive data import, unification, reinterpretation, and management, through structural mapping and modelling, and used later as a framework for parametric modelling (lithology, petrophysical parameters, etc.), and finally for resource assessments including risk analyses.

The proposed processing scheme is based on the use of multi-scale studies. Medium-scale models (basin-scale) are treated as a core component of the processing sequence and enable downscaling to local-scale models/maps and upscaling to platform scale (the EEC). The complex and considerably different tectonics of the Baltic Basin, the Podlasie Basin and especially the Lublin Basin influence the choice of modelling techniques The *Corner Point Gridding* method – more efficient and versatile in the further use of models cannot operate with the thrust-and-fault tectonics occurring in the Lublin Basin, while the geometrically more advanced *Structural Framework* method cannot be used on a platform scale, owing to technical limitations (too large grid size) of the method. In such a case, the most universal 3D models are designated on a basin scale, encompassing a uniform type of geology. The proposed hierarchy is due not only by geological reasons. In logistical terms, modelling and mapping carried out in this way enable a better organization of teamwork. Such a scheme also increases the detail of the solutions obtained, while optimizing the efficiency of computer processing.

The structural, thickness and palaeothickness maps described and the 3D models of the Lower Palaeozoic that have been developed during the course of the project for the onshore part of the EEC in Poland are the most detailed cartographic study of the region ever completed. However, they need to be updated in the coming years after declassifying information obtained by private operators during shale gas exploration. These updates should apply to both borehole and seismic data. The updated models then will be an excellent basis for the regional assessment of resources of shale gas prospects in the Silurian and Ordovician strata of the EEC.

The opinion of the authors is that the methodology presented should be used by petroleum companies as well as by geological surveys.

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