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RECONSTRUCTION OF INITIAL THICKNESS AND GEOMETRY OF THE LOWER PALAEOZOIC STRATA IN THE PODLASIE AND BALTIC BASINS, EAST EUROPEAN CRATON

Jan BARMUTA*, Maria BARMUTA, Jan GOLONKA & Bartosz PAPIERNIK

Faculty of Geology, Geophysics and Environmental Protection,
AGH University of Science and Technology, Mickiewicza 30 Avenue, Kraków, Poland;
e-mails: jbarmuta@agh.edu.pl, jgolonka@agh.edu.pl, maria.barmuta@gmail.com, papiern@geol.agh.edu.pl
** Corresponding author*

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Abstract: The aim of this study was to use the structural restoration technique to verify the correctness of the structural and palaeothickness maps created during the BLUE GAS Project. On the basis of well data as well as refined structural and palaeothickness maps of Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Permian, Triassic, Jurassic and Cretaceous horizons, a cross-section running across the Baltic Basin, the Mazury High and the Podlasie Basin was created. During the restoration process, the effects of compaction and fault activity were removed sequentially. The amount of erosion was estimated on the basis of the corrected palaeothickness maps. The resulting restoration is geologically reasonable and therefore both the structural and palaeothickness maps should be regarded as reliable. The reconstruction also allowed reproduction of the initial geometry and thickness of the Cambrian–Devonian strata and the recognition of three main episodes in the evolution of the sedimentary cover of this part of the East European Craton. The first episode was related to the deposition of the Lower Palaeozoic (up to the Lower Devonian) sedimentary complex on the relatively flat surface of the East European Craton edge. During the second episode, lasting most probably to the Permian, the Baltic and Podlasie Basins subsided significantly. The amount of subsidence was much higher in the Podlasie Basin. The third episode is related to the deposition of the almost flat-lying Mesozoic–Cainozoic complex.

Key words: Subsidence, decompaction, restoration, Podlasie Basin, Baltic Basin, Mazury High, shale gas.

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INTRODUCTION

One of the tasks carried out as a part of the Blue Gas Project was the construction of a consistent, regional, three-dimensional structural model of the Polish part of the East European Craton (EEC; Michna *et al.*, 2017; Papiernik, 2017a, b; Golonka *et al*., 2019; Papiernik *et al.,* 2019). As a result of this task, not only maps showing the present-day lateral extent and thickness of Cambrian-to-Cretaceous strata but also maps delineating the initial extent of sedimentation and palaeothickness were created (Fig. 1).

However, the model-building phase is a non-unique process, which strongly depends on geometrical assumptions (i.e., grid or voxel dimensions), mapping algorithms, data availability and quality as well as data distribution. The human impact, i.e., modeller knowledge, experience and skills, also is not without significance and sometimes might be of primary importance (Bond *et al*., 2007, 2015). As a consequence, the results of modelling are not necessarily valid geologically. One of the most commonly used technique to validate 2D or 3D models is a structural restoration method. This method assumes that if the geometries (i.e., undeformed) restored are geologically reasonable, the section (or model) is balanced, and therefore should be considered as correct, or at least possible (e.g., Gibbs, 1983; Clarke *et al*., 2006; Groshong, 2006).

Bearing in mind the uncertainties of the modelling, based on the maps created, an attempt was made to reconstruct the initial geometry of Cambrian–Devonian horizons along a regional 250 km-long transect comprising deep wells and crossing the Baltic Basin, Mazury High and Podlasie Basin (Fig. 2).

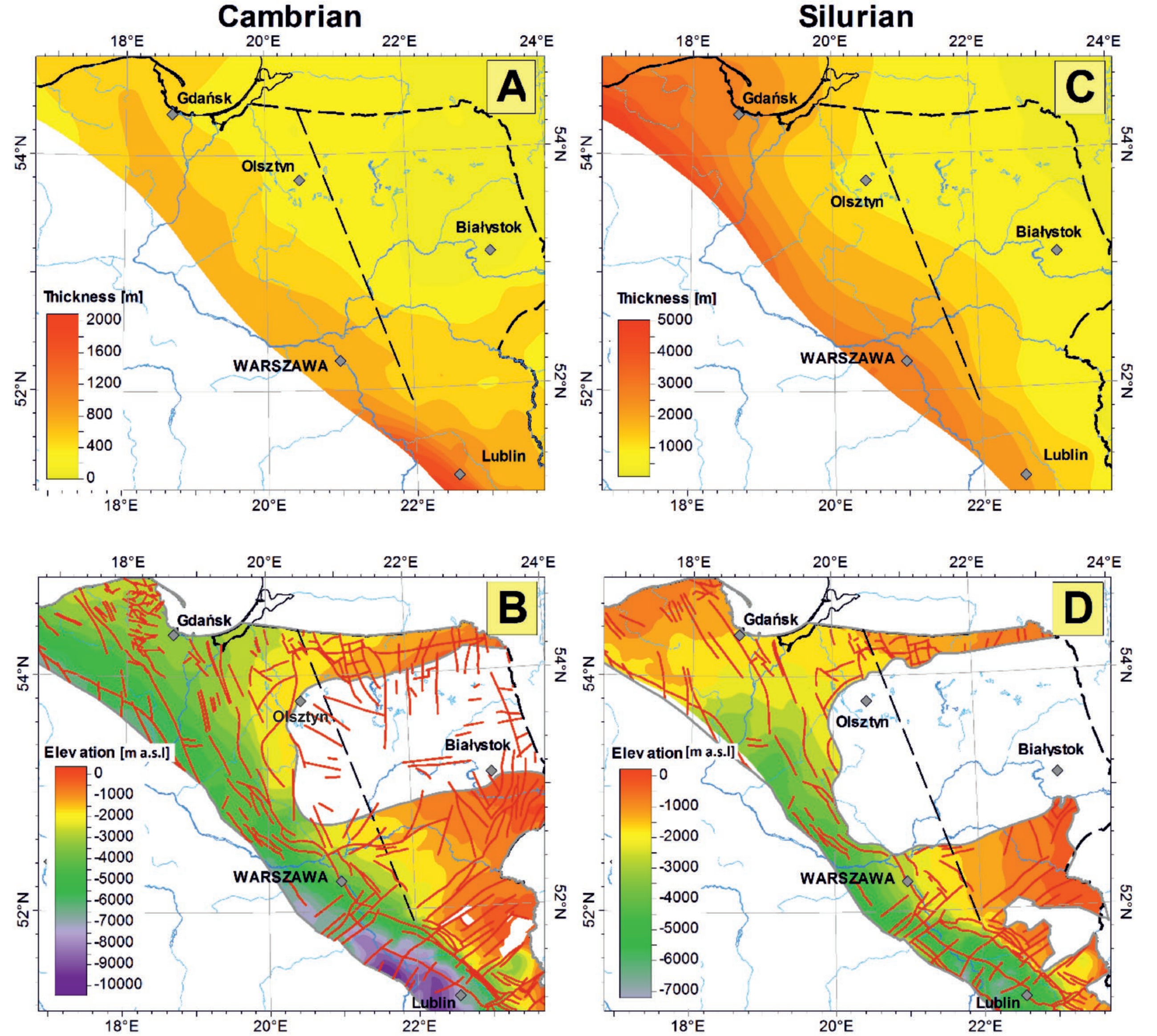

Fig. 1. Examples of palaeothickness maps (**A, C**) and present-day structural maps (**B, D**) of the Cambrian (left) and Silurian (right). More maps are presented in other papers in this volume (see text for more details).

The main aim of this study was to verify the reliability of the maps created during the modelling phase. For this purpose, cross-section restoration was supplemented with corrections for the effect of compaction. This technique permits checks on the admissibility of the interpretation in areas with poor data control.

Aspects of the subsidence history, Early Palaeozoic basins evolution and lithofacies distribution along the western edge of the East European Craton was investigated previously by numerous authors (e.g., Modliński, 1967, 1982; Modliński *et al*., 1994, 2010; Poprawa *et al*., 1999; Lazauskienė *et al*., 2002, 2003; Poprawa and Pacześna, 2002; Šliaupa *et al*., 2006). On the basis of the results of the authors mentioned above, during late Precambrian to Late Silurian time, three stages related to geotectonic events global in scale can be distinguished. The first event, encompassing the Late Vendian to Wuliuan time, was marked by significant subsidence related to the rifting and opening of the Tornquist Sea. On the other hand, the Late Drumian to Middle Ordovician interval was characterized by low subsidence rates govern by the thermal sag phase. The onset of the Avalonia-Baltica convergence is believed to have started during the Late Ordovician, while drastic acceleration of subsidence is observed for Late Silurian time. While the geotectonic environment for the first two stages are accepted, a simple load-related flexural bending seems to be an insufficient explanation for the formation of the Silurian basins, especially the Baltic Basin (Lazauskienė *et al*., 2003). In the model published by Lazauskienė *et al*. (2003), a flow of mantle material in a convection cell, located between the subducting Avalonian plate and the upper plate, i.e., the Baltica Craton, should be considered as an additional factor of the subsidence. However, this model implies a reversal in the polarity of the subduction zone from south-dipping to

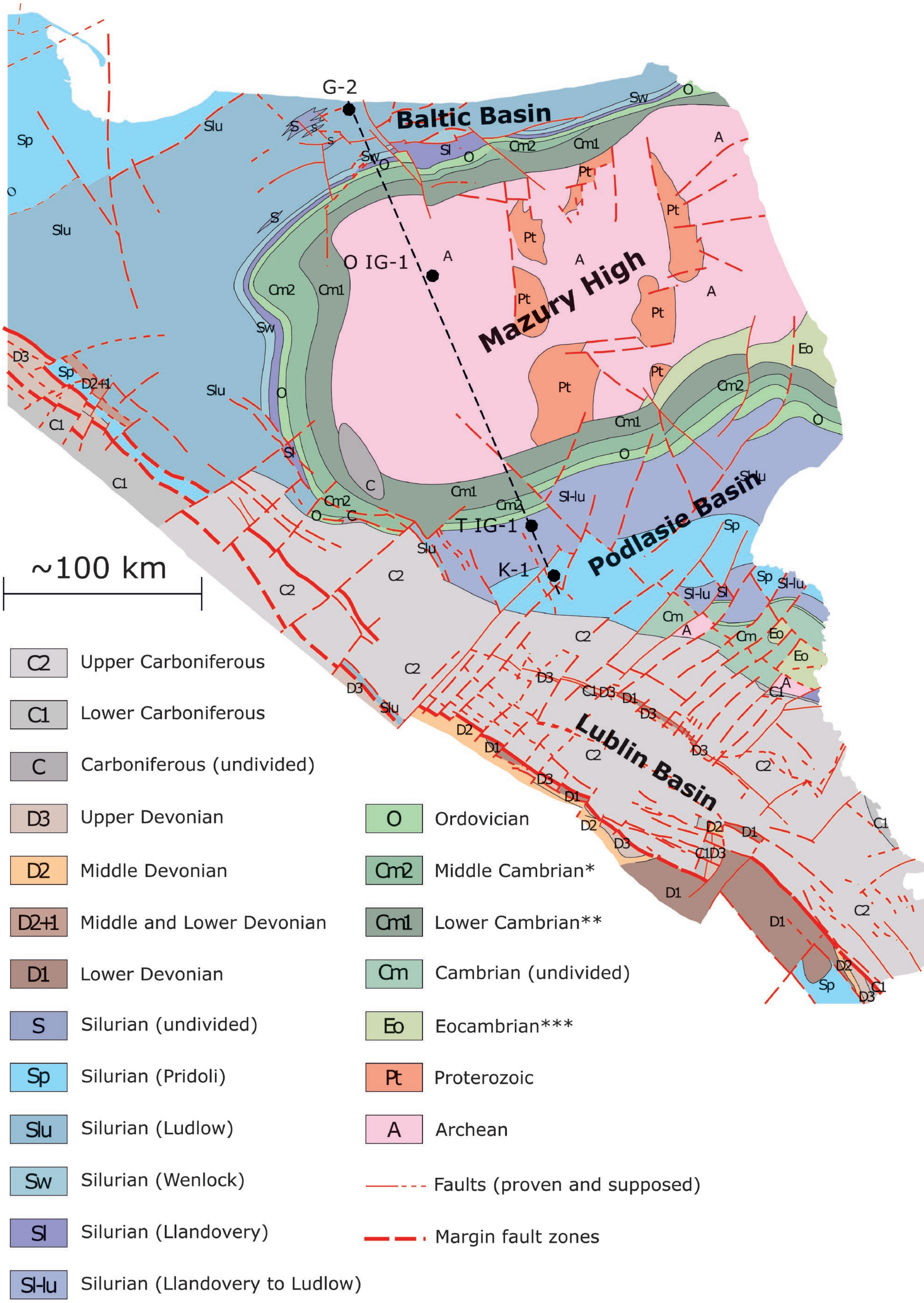

Fig. 2. Geological map of the pre-Permian unconformity of the Polish part of the East European Craton (after Stolarczyk *et al.*, 2004, modified). Location of the analysed cross - section is marked by a dashed line. Name abbreviations of wells: G-2 – Gałajny 2, O IG-1 – Olszyny IG-1, T IG-1 – Tłuszcz IG-1, K-1 – Kałuszyn 1.

north-dipping during the Silurian Period, which is disputable. This paper is an extended English version of a chapter, previously published in a Polish monograph (Barmuta *et al*., 2017).

GEOLOGICAL SETTING

The regional cross-section presented is located in the northern part of the Polish segment of the East European Craton (Figs 2, 3). The crystalline basement of this unit is composed of igneous and metamorphic rocks, consolidated during the Palaeoproterozoic suturing of Fennoscandia and Sarmatia (Krzemińska, 2010; Żelaźniewicz *et al.*, 2011; Bogdanova *et al.*, 2015 and references therein; Petecki and Rosowiecka, 2017). The broad anticlinal uplift of the basement rocks, i.e., the Mazury High, is flanked to the north and south by two Palaeozoic features, the Baltic Basin and the Podlasie Basin, respectively.

The Podlasie Basin is filled with a sedimentary sequence ranging in age from Neoproterozoic to Silurian and thickening to the south (Figs 2–3; e.g., Pacześna, 2006; Krzywiec *et al*., 2018). The deposition of the Neoproterozoic, siliciclastic rocks was restricted to small, fault-bounded basins. The origin of these basins was related to the break-up of the Pannotia supercontinent at the end of the Proterozoic. Then the area of the Podlasie Basin became part of the failed arm of a triple junction and thick Neoproterozoic sediments were deposited in rift-related grabens (Gorbatschev and Bogdanova, 1993; Pacześna, 2006; Poprawa, 2006a, b; Krzywiec *et al*., 2018). However, the Neoproterozoic sediments, known from the study area, are not present along the line of cross-section, where the Precambrian is represented by crystalline rocks. The Precambrian rocks are covered by Cambrian sandstones and mudstones. The preserved thickness of the Cambrian deposits reaches 507 m in the Tłuszcz-IG1 borehole (Fig. 4). The absence of Furongian sediments is a widely observed phenomenon within the Podlasie Basin (Poprawa, 2006b). Above the Cambrian succession, thin Ordovician carbonates and mudstones, which maintain a rather uniform thickness (ca. 40 m), are present. The Ordovician complex is covered by the thick Silurian shale complex. The present-day thickness of this complex gradually increases to the SW and attains up to 800 m in the study area (Kałuszyn-1 well; Figs 3, 4). The uppermost part of the Silurian strata in the Podlasie Basin is eroded and overlain by the Permo–Mesozoic sequence with an average thickness of 1,450 m.

The northern limb of the Mazury High is occupied by the southern part of the Baltic Basin. Its structure and stratigraphy in part resemble those of the Podlasie Basin. Two depocenters are distinguished within the Baltic Basin: The first one is related to the Peri-Tornquist Zone and is located close to the Trans European Suture Zone (TESZ), while the second one corresponds to the NE–SW trending Baltic Depression (Poprawa *et al*., 1999). As stated above, the formation of both basins probably was initiated during the rifting of the Pannotia supercontinent and the basins mentioned above should be treated as the failed arms of a triple junction (Gorbatschev and Bogdanova, 1993; Poprawa, 2006a, b). Along the line of cross-section, the thickness of the Cambrian rarely exceeds 200 m. In the Gałajny 2 borehole, located in the northernmost part of the study area, the thickness of Cambrian strata equals 224.5 m, while the thickness of the Ordovician and Silurian reaches 84 m and 629.5 m, respectively. The cumulative thickness of the Permo–Mesozoic and Cainozoic cover reaches 1,558 m (Fig. 3).

In the central part of the cross-section, the Mazury High (or the Mazury Anteclise), composed of igneous and metamorphosed sedimentary rocks of Palaeoproterozoic age, is present (Krzemińska, 2010; Żelaźniewicz *et al*., 2011; Figs 2, 3). The Palaeoproterozoic rocks are overlain by the Mesozoic and Cainozoic complex in the central part. The thickness of the sedimentary cover reaches 1,441.5 m in the Olszyny-IG1 well (Fig. 4). The sediments of early Palaeozoic age pinch out to the northern and southern slope of the Mazury High (Figs 2–3). On the basis of the cross-section presented, it may be noted that the post-Variscan complex, which in general might be treated as a "layer-cake" model, varies in thickness and reaches its maximum above the central part of the Mazury High.

On the basis of recent shale gas exploration and investigations carried out on the SW edge of the EEC, the Palaeo-

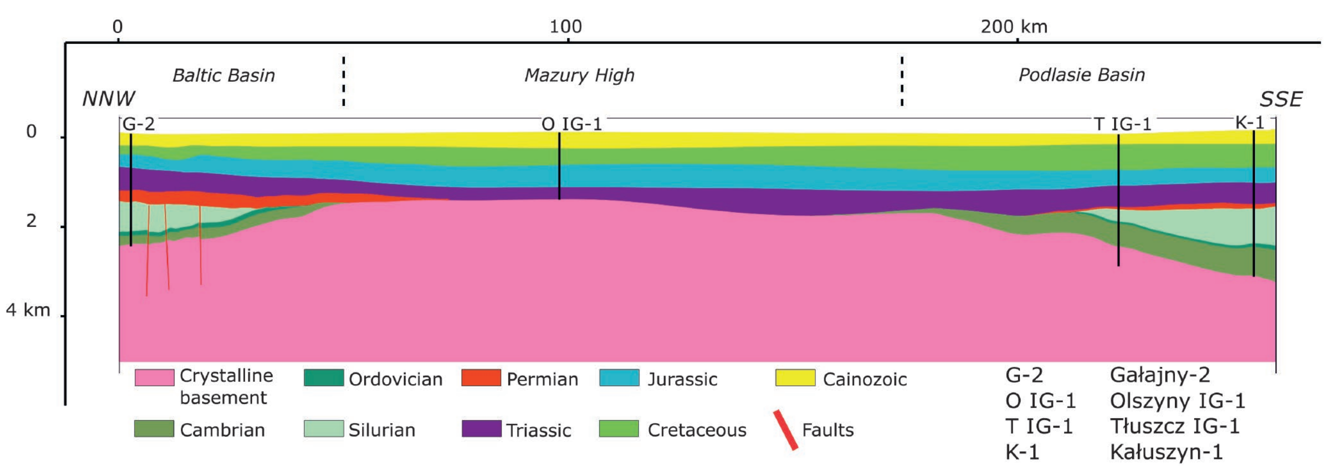

Fig. 3. Present-day geometry of main horizons along the cross-section analysed. All the cross-sections are presented with x10 vertical exaggeration. The colour coding is identical for all cross-sections.

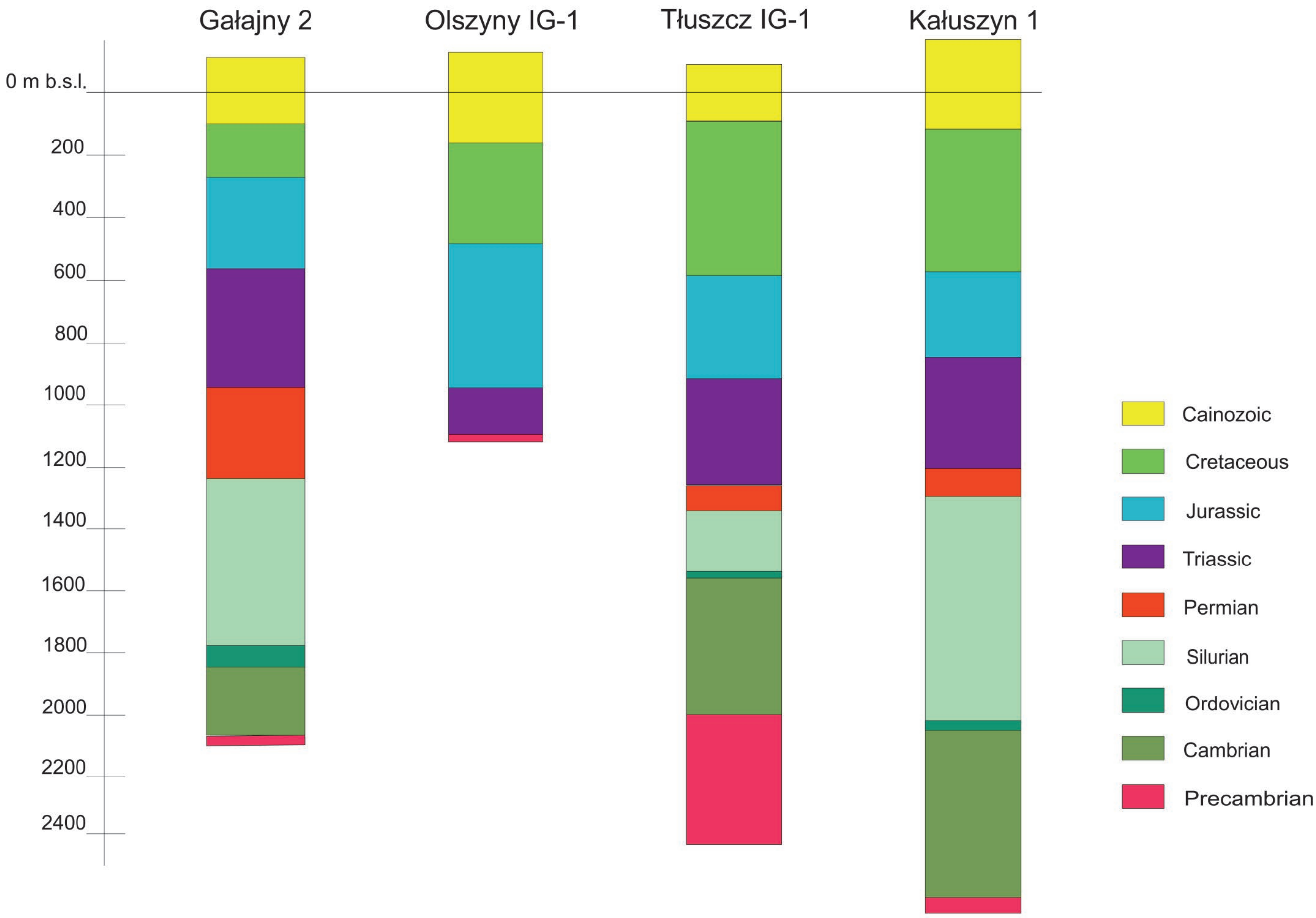

Fig. 4. Simplified stratigraphic profiles in selected wells along the line of section.

zoic evolution of the Baltic and Podlasie basins can be subdivided into several stages (e.g., Pacześna, 2006; Poprawa, 2006a, b; Šliaupa *et al.*, 2006; Mazur *et al.*, 2015, 2018b; Golonka *et al.*, 2019). After Neoproterozoic rifting and the opening of the Tornquist Ocean, the study area passed from syn- to post-rift subsidence of the passive continental margin (Nawrocki and Poprawa, 2006; Poprawa, 2006a, b; Golonka, 2007; Cocks and Torsvik, 2008). At the end of the Cambrian, there was tectonic uplift, which caused the widespread erosion of the Furongian deposits along the western edge of the EEC. It is thought that this event might have been related to the docking of the peri-Baltican Małopolska Terrane (Poprawa, 2006a). The Silurian collision of Baltica with the East Avalonia microcontinent along the southwestern edge of the EEC resulted in the formation of a foredeep in front of the Caledonian orogen. This collisional event caused a rapid increase in subsidence rates and the deposition of a thick complex of fine-grained mudstones and claystones, pinching out to the east or northeast (e.g., Mazur *et al.*, 2017b). From the Devonian to the Carboniferous, the southwestern edge of the EEC underwent significant tectonic deformation, especially in its southern part, which resulted in basin inversion. This event included Late Devonian basement faulting and tectonic shortening of the sedimentary cover, due to thin-skinned folding and thrusting (for details see Narkiewicz, 2007; Krzywiec *et al.*, 2017a, b; Tomaszczyk and Jarosiński, 2017; Mazur *et al.*, 2018a). Uplift and concomitant erosion resulted in the formation of the widespread Late Devonian and Late Carboniferous unconformities. From the Permian to the Cretaceous, the area investigated was dominated by epicontinental sedimentation (Dadlez *et al.*, 1995, 1998). A flat-lying Permian–Mesozoic sedimentary sequence, up to 1,600 m thick, covers unconformably the southwestern margin of the EEC.

DATA AND METHODS

As the main input for the reconstruction performed, a set of regional structural and palaeothickness maps were used. The maps were based on the published maps of Modliński (2010) and Dadlez *et al.* (1998), refined using interpretations of recently acquired seismic data and updated chronostratigraphic information from both archival and recently drilled boreholes (Michna *et al.*, 2017; Papiernik, 2017a, b; Golonka *et al.*, 2019; Papiernik *et al*, 2019;).

Owing to the regional scale of the model, the flexure isostasy approach was applied (Roberts *et al.*, 1998; Watts, 2001) and the compaction of the sediments and flexural bending of the lithosphere were regarded as the main modes of deformation. Because of the lack of significant faults along the line of section, it was assumed that there was no out-of-section movement. A set of faults interpreted as occurring in the Baltic Basin exhibit only small vertical (less than 50 m) displacement and no indicators of strike-slip movement were observed. Thus the assumption of "no out-of-section movement" is believed not to have been violated.

The restoration procedure, carried out using Move software (Move, 2019), began with the establishment of the contacts between the main horizons (i.e., Precambrian, Cambrian, Ordovician, Silurian, Devonian, Permian, Triassic, Jurassic, Cretaceous, and Cainozoic). Then, after each deformation event, i.e., folding, faulting, a compaction correction was applied. For restoration of the deformation related to folding and faulting, a simple shear algorithm was used. When necessary, before the decompaction procedure, the eroded thickness was reconstructed on the basis of available paleothickness maps. Owing to the regional scale of the analysis, the lithological composition of the lithostratigraphic divisions was generalized (Tab. 1) and standard compaction curves were used (Dickinson, 1953; Scalter and Christie, 1980; Baldwin and Butler, 1985).

Table 1

Main lithologies for horizons used during the restoration.

Horizon	Lithology
Cainozoic	Diversified terrigenous clastic rocks, partially not lithified
Cretaceous	Mainly marls and limestones, also fine grained terrigenous rocks
Jurassic	Mainly terrigenous clastic rocks, also limestones
Triassic	Mainly terrigenous clastic rocks, also limestones
Permian	Carbonates, anhydrites, salt, terrigenous clastic rocks
Silurian	Fine-grained terrigenous rocks (shales)
Ordovician	Fine-grained terrigenous rocks (shales), carbonates
Cambrian	Sandstones and mudstones

The calculation of the flexural isostasy was carried out using the equation given by Turcotte and Schubert (1982). As demonstrated by previous studies on the subsidence of the Baltic Basin (Lazauskienė *et al*., 2002, 2003), for reliable computation of isostatic response using the equation mentioned above, the following parameters should be known: mantle density (*Md*), elastic thickness (*Te*) and Young's modulus (*E*). In the present study, the authors used the average Fennoscandian parameters (Watts *et al*., 1982): $Te = 87$ km, $E = 10^{11}$ and $Md = 3.3$ g/cm^3.

RESULTS AND DISCUSSION

The results of the analysis are presented as a set of cross-sections, representing selected steps of the reconstruction performed (Figs 3, 5). Owing to large profile length, it is presented with x10 vertical exaggeration. The cross-section presented in Figure 3 shows the present-day geometry of selected chronostratigraphic horizons. The Permian–Mesozoic and Cainozoic sedimentary cover, which was not affected by faulting, exhibits smooth changes in thickness over a range of 1,300–2,000 m and its geometry resembles a "layer-cake" model. In the central part of the profile, the Palaeozoic sedimentary cover is absent and the crystalline basement is overlain directly by the Mesozoic–Cainozoic cover (Fig. 3). The flanks of the Mazury High are overlain by a partly eroded Neoproterozoic–Silurian sedimentary sequence, which constitutes the sedimentary infilling of the Baltic and Podlasie basins to the north and south, respectively. A set of faults is interpreted as occurring in the Baltic Basin. The faults transect the entire Lower Palaeozoic sequence and do not continue into the Permian and younger strata. Owing to the model dimensions as well as the lack of reliable data, the geometry of the faults was simplified and they were modelled as high-angle faults.

Figure 5A represents the geometry of the Cainozoic sediments after decompaction. As a result, an anticlinal structure was created above the set of faults in the Baltic Basin (Fig. 5A). This deature is most probably related to erroneous mapping procedures or incorrect estimations of the eroded thickness of the Cretaceous sediments. However, other geological explanations also should be considered. On the basis of the restorations, it can be observed that the structure is formed in pre-Jurassic complexes, which might indicate the reactivation of faults during the latest Triassic. This interpretation implies the existence of discordance between Triassic and Jurassic complexes in the area of uplift. This observation is supported by the stratigraphic information from the Gałajny 2 borehole, where the absence of the lowermost part of the Jurassic sediments was observed. The Mesozoic basement, with faulting in the study area, additionally is legitimized by the observation of similar tectonic activity along the SW slope of the Mazury High (Motyl-Rakowska and Schoeneich, 1970).

Figure 5B presents the geometry before the Carboniferous erosion episode (Motyl-Rakowska and Schoeneich; 1970; Żelichowski, 1987). The initial thicknesses of the Cambrian-to-Carboniferous complexes were restored on the basis of the palaeothickness maps. The thickness variation of the Devonian complex along the line of cross-section indicates the deepening of both basins during the Devonian. The restored Carboniferous complex is present solely in the Podlasie Basin, which indicates ongoing subsidence of this basin, most probably during the earliest Carboniferous, followed by uplift and erosion.

The subsequent figures (Fig. 5C, D) present the geometry at the end of the Silurian and the Ordovician, respectively. It can be noted that thickness of the Silurian and Cambrian complexes tends to increase in a SE direction, while the thickness of the Ordovician does not exhibit large variation.

On the basis of the restoration performed, it may be noted that three main episodes can be distinguished within the study area. The first episode is related to the formation of the Cambrian–Lower Devonian complex. This episode is characterized by almost continuous sedimentation (with the exception of the Furongian erosion episode). The sedimentation rates differ significantly during this period, reflecting changes in geotectonic setting. The highest rates of sedi-

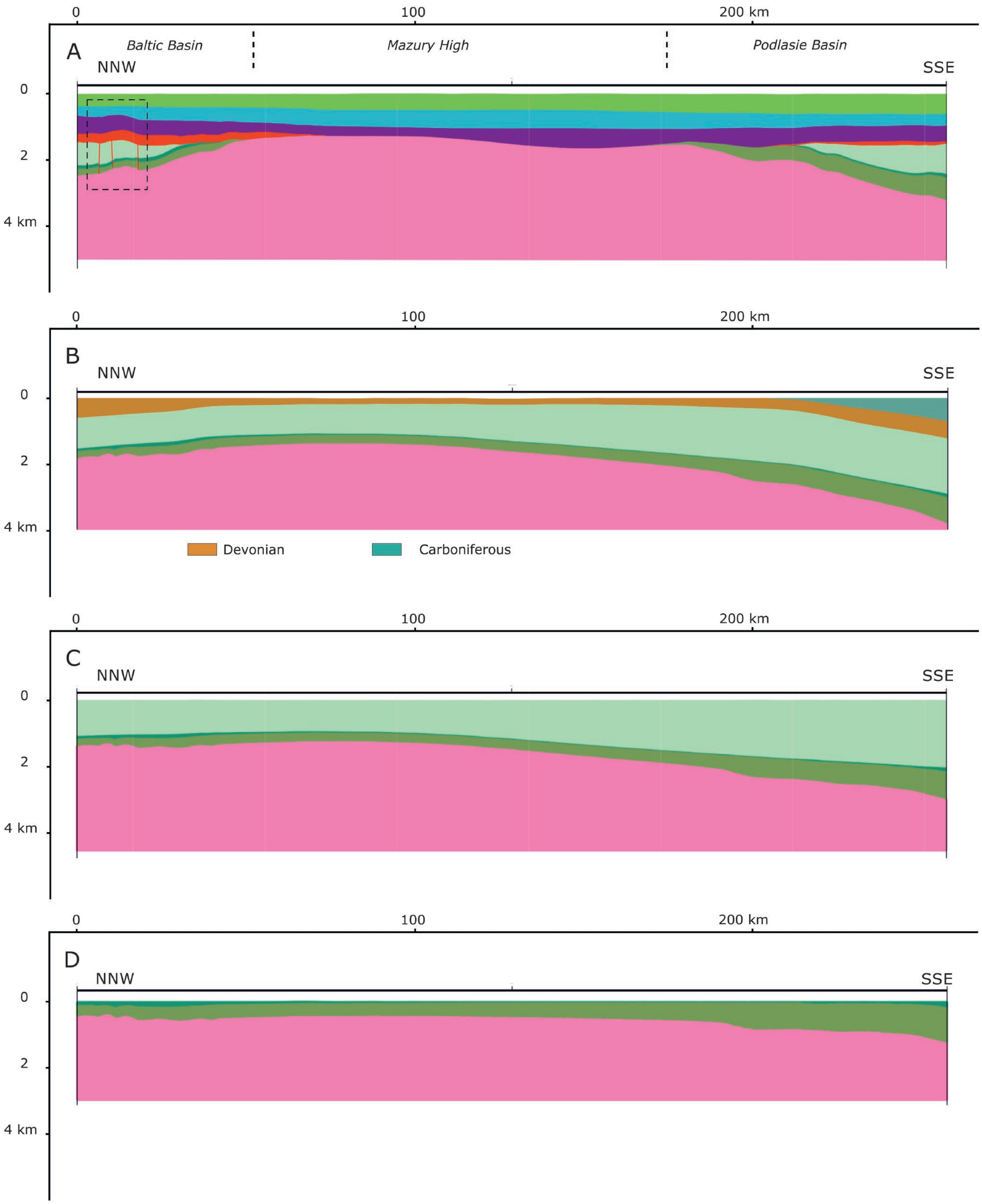

Fig. 5. Selected reconstruction steps. **A.** Basin geometry after removal of the Cainozoic strata. Note the formation of an anticlinal structure above the faults in the northern part of the cross-section (marked with a dashed line). **B.** Reconstructed thickness of the eroded Palaeozoic complex. **C.** Restored geometry at the end of the Silurian. **D.** Restored geometry at the end of the Ordovician. Colour coding as in Figure 3.

mentation were observed for the Cambrian and the Silurian and were related to the rifting and flexural bending phases of the present western edge of the EEC (Poprawa *et al*., 1999; Poprawa, 2006b; Golonka, 2007). The relatively small and constant thickness of the Ordovician strata corresponds with the thermal subsidence phase (Poprawa *et al*., 1999). On the basis of the observed thickness variation within the Cambrian and Silurian strata, it may be seen that thickness tends to increase in a SE direction and almost no thickness variation is observed above the Mazury High. It appears that this elevation had little or almost no effect on sedimentation up to the end of the Silurian.

In contrast, when considering the pre-Late Carboniferous erosion period, it can be seen that the Devonian–Carboniferous sedimentary complex exhibits huge thickness variation along the cross-section. On the basis of the palaeothickness maps, it is inferred that this thick sequence of the Devonian rocks was deposited in both basins, while the Mazury High was covered with only ca. 200 m of deposits (Modliński *et al*., 2010; Papiernik, 2017b). On the basis of this interpretation, it can be stated that the amplitude of the Mazury High increased significantly during Devonian time. The analysis performed does not permit the precise determination of when exactly this process occurred. However, owing to the continuous sedimentation in the Lublin Basin, it possibly happened during the passage from Silurian to Devonian (Miłaczewski, 2007). As indicated by the palaeothickness maps, the Carboniferous complexes were deposited only in the Podlasie Basin, while Permian deposits are seen only in the southern and northern parts of the profile in the Podlasie and Baltic basins. It appears that the Mazury High was subjected to subaerial erosion, while the basins mentioned acted as bays (Geluk, 2007). It should be noted also that the thickness of the overlying Mesozoic and Cainozoic complexes was not controlled by the uplift of the Mazury High.

Ambiguity in the work presented is related mainly to the estimation of palaeoextent and palaeothickness of each complex as well as to the generalization of the parameters used for isostasy modelling. As mentioned previously, owing to the lack of appropriate data, the published, general compaction curves were used, which might not be relevant for the study area and therefore also might be a basis for uncertainty.

SUMMARY

The restoration performed along the cross-section provides geologically valid results and reaffirms the present-day state of knowledge, regarding the tectonic evolution of this part of the EEC. Thus, it is noted that the structural and palaeothickness maps produced in the framework of the BLUE GAS Project do not contain significant errors. However, some areas, such as the fault zone in the Baltic Basin should be verified to exclude potential mapping errors. The presented reconstruction cannot be analysed quantitatively owing to the regional scale of the approach and uncertainty in the estimation of the input parameters. However, taking into the consideration the fact that the reconstruction was designed mainly to verify the correctness of the mapping procedures, the results obtained are regarded as adequate for this purpose.

The restoration proves that, despite the pre-Palaeozoic framework of both basins, sedimentation during Cambrian to early Devonian times took place on the relatively flat morphology of the EEC edge. The uplift of the Mazury High most probably was initiated during the earliest Devonian and acted as an important palaeogeographic feature until the end of the Permian.

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