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GEOLOGICAL SETTING AND EDIACARAN–PALAEOZOIC EVOLUTION OF THE WESTERN SLOPE OF THE EAST EUROPEAN CRATON AND ADJACENT REGIONS

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Abstract: A set of geological maps and geological cross-sections was prepared to document the geological setting of sedimentary basins developed on the western slope of the EEC and adjacent areas to the west. On the basis of these data and literature on the subject, the evolution of the sedimentary basins in the study area was reviewed, with special emphasis on the Ediacaran–Lower Palaeozoic basin. The basin originated during late Ediacaran rifting, related to the latest stages of breakup of the Precambrian super-continent Rodinia/Pannotia, associated with large-scale igneous activity. The rifting ultimately led to the formation of the Tornquist Ocean and subsequently, during the latest Ediacaran to Middle Ordovician, the SW margin of the newly formed Baltica became a passive continental margin. The upper Cambrian depocentre in the Biłgoraj-Narol Zone and the Łysogóry Block tentatively is interpreted as a small, narrow foredeep, related to the docking of the Małopolska Block to the western margin of Baltica. From the Late Ordovician through the Silurian, a gradual change to a collisional tectonic setting is observed across the entire SW margin of Baltica, as well as in the zones adjacent to it from the west, which together became the site of development of the extensive Caledonian foredeep basin, related to the convergence and collision of Avalonia and Baltica. The oblique character of the collision resulted in a prominent diachronism in the development of the foredeep basin. This refers to the initiation of basin subsidence, the starved basin phase, the main phase of rapid subsidence and supply of detritus from the west, and the termination of basin development. The Early Mississippian (Bretonian) phase of uplift and erosion and, to a lesser degree, also the Late Pennsylvanian one significantly affected the structure of the western EEC. During the Mississippian, extensive magmatic activity took place at the SW margin of East European Craton, in the region referred to here as the Baltic-Lublin Igneous Province.

Key words: Lower Palaeozoic, Ediacaran, Baltic Basin, Lublin-Podlasie Basin, geological map, geological cross-section, tectonic evolution.

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INTRODUCTION

The western slope of the East European Craton (EEC) is a side of development of one of the most extensive Ediacaran–Lower Palaeozoic sedimentary basins globally. It extends over more than 2,000 km in a NW–SE direction between the Black Sea and the North Sea and is a few tens of kilometres to more than 800 km wide northeastwards of the western margin of the EEC, i.e., of the Teisseyre-Tornquist Zone (TTZ; Fig. 1). This system of sedimentary basins is sometimes referred to as the Pery-Tornquist Basins, although mainly with respect to its central and northwestern parts. Therefore, for the entire system an alternative name, the Baltic-Dniester Basin, is proposed here. Its development is crucial for an understanding of the late Ediacaran breakup of the Neoproterozoic supercontinent Rodinia/Pannotia, the reconstruction of subsequent development of the Tornquist Ocean, and the Late Ordovician to Silurian collision of Avalonia and Baltica. Apart from this, the basin is one of only a few basins globally that contain targets for shale gas exploration in Lower Palaeozoic strata (e.g., Poprawa, 2010).

Moreover, the western part of the EEC is covered with Devonian–Carboniferous basins that were subjected to several phases of denudation as well as with the subsequent Permian–Mesozoic sedimentary cover. Development of the Devonian–Carboniferous complex is of substantial importance for the reconstruction of interactions between the Variscan orogen and its foreland. It documents also the Variscan extensional and transtensional tectonic regimes. Therefore, the geological setting of the western part of the EEC, as well

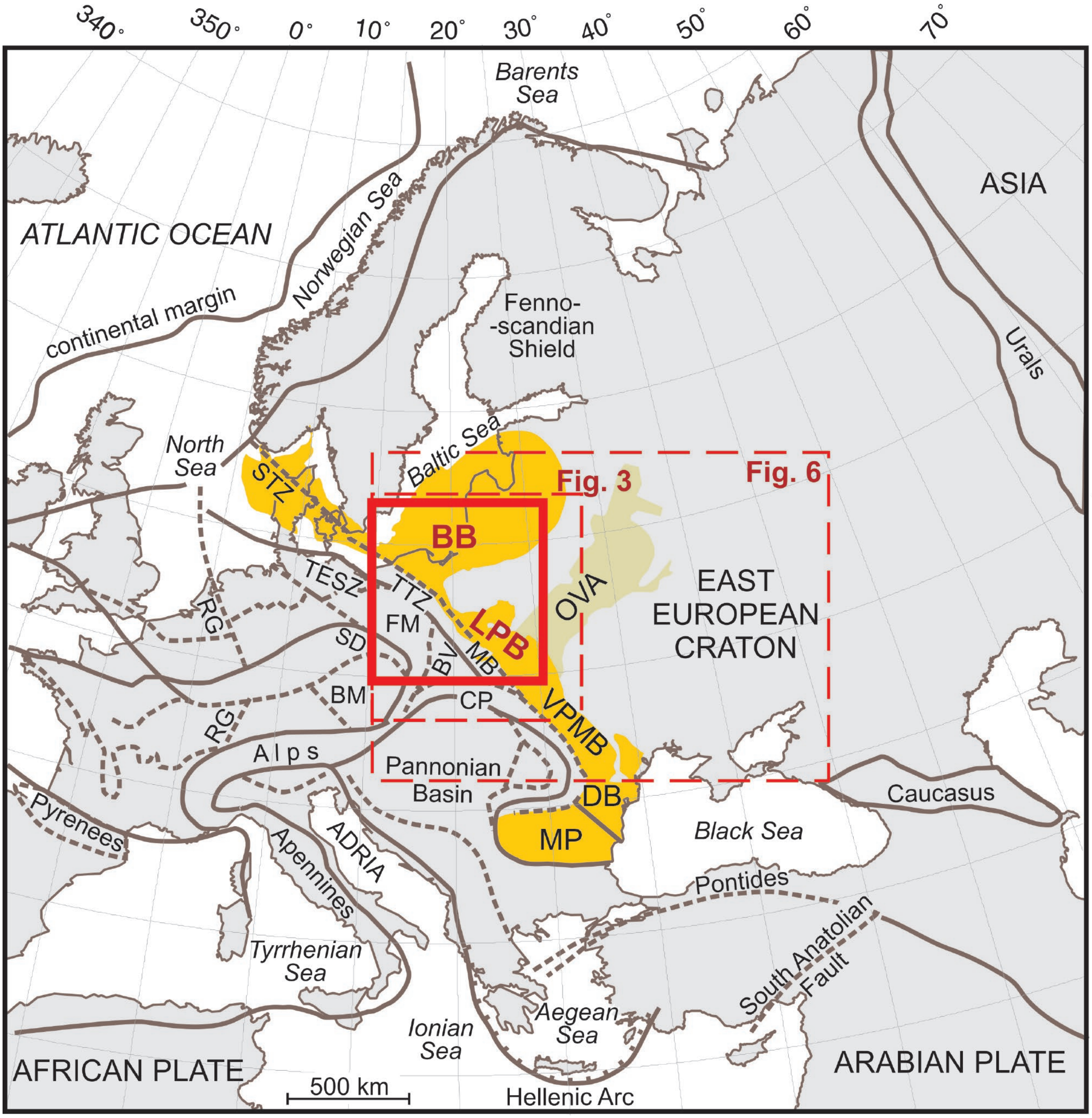


Fig. 1. Lower Palaeozoic basins on the western slope of the East European Craton and surrounding areas. Simplified tectonic map of Europe after Berthelsen (1992), Jarosiński *et al*. (2009). BB – Baltic Basin, LPB – Lublin-Podlasie Basin, VPMB – Volyn-Podilia-Moldavia Basin, MP – Moesian Platform, DB – Dobrogea Block, OVA – Orsha-Volyn Aulacogen, MB – Małopolska Block, TTZ – Teisseyre-Tornquist Zone, TESZ – Trans-European Suture Zone, STZ – Sorgenfrei-Tornquist Zone, CP – Carpathians, BV – Brunovistulian Block, FM – Fore-Sudetic Monocline, SD – Sudetes, BM – Bohemian Massif; RG – Rhein Graben. Solid red line: study area. Dashed lines: extend of Figures 3 and 6.

as the adjacent Palaeozoic structures, located west of the TTZ, is a valuable record of geological process, the importance of which is on a scale broader than regional.

The Palaeozoic geology of the study area and, to a lesser degree, also the Mesozoic geology are mostly in the subsurface, owing to the presence of an extensive cover of Cainozoic sediments. A few exceptions in the study area are the Palaeozoic outcrops in the Holy Cross Mountains and southern Scandinavia, as well as in the Dobrogea Block, to the SE of the area under consideration. The Ediacaran to Lower Palaeozoic rock outcrops are also locally accessible at the eastern limits of the sedimentary basins analysed.

Knowledge of the Ediacaran to Lower Palaeozoic complex at the western slope of the EEC, therefore, is solely dependent on deep boreholes and geophysical data. During the last decades, this region experienced a significant increase in the amount of subsurface geological information, with a major contribution from the exploration wells and seismic data of the petroleum industry. The availability of these new data and the potential for the cross-border correlation of data provided the main motivation for this attempt to review the current understanding of the geological setting of the area. This is documented here with a set of geological maps, geological cross-sections and a structural map. This paper also reviews the tectonic evolution of the area on the basis of the literature on the subject, including in particular the Ediacaran to Early Palaeozoic tectonic relations between the western margin of the EEC and the Koszalin-Chojnice Zone and the Biłgoraj-Narol Zone. At the same time, it is meant to serve as a geological introduction to the contributions that follow in this special volume.

GEOLOGICAL BACKGROUND

The area discussed in the present account comprises the western part of the EEC and the adjacent tectonic units in Poland and neighbouring regions. The EEC extends far beyond the study area, over all of Eastern Europe and a significant part of northern and central Europe (Bogdanova *et al*., 1997; Kheraskova *et al*., 2015). The western limit of the EEC is commonly associated with the TTZ, being also the eastern limit of the Trans-European Suture Zone (TESZ; Fig. 2; Królikowski and Petecki, 1997; Berthelsen, 1998; Pharaoh, 1999). Recent geophysical studies indicate, however, that the thinned crust of the EEC continues farther westward within the TESZ (Jarosiński and Dąbrowski, 2006; Mazur *et al*., 2015). In the eastern part of the TESZ, a few tectonic units with a Lower Palaeozoic sedimentary cover occur, the development of which is closely related to that of basins in the western part of the EEC. In particular, these are the Koszalin-Chojnice Zone and the Biłgoraj-Narol Zone (the latter is called the Rava Ruska Zone in Ukraine), covered in this paper, as well as the Łysogóry Block, the Małopolska Block, the Brunovistulian Block, and the Dobrogea Block (see Fig. 2 for location), which are outside of the focus of the present discussion.

The crystalline basement of the EEC is made up of the Archean to Mesoproterozoic metamorphic and igneous rocks that constitute three major tectonic units of the craton, i.e., the Volga-Uralia, the Sarmatia and the Fennoscandia, separated by Proterozoic collisional tectonic sutures (Ryka, 1984; Gaál and Gorbatschev, 1987; Gorbatschev and Bogdanova, 1993; Kheraskova *et al*., 2015). The western part of the EEC, discussed in the present account, is characterised by the presence of the two last units mentioned above as well as by the occurrence of Palaeo- and Mesoproterozoic crystalline rocks (Krzemińska and Krzemiński, 2017). The suture of Sarmatia and Fennoscandia was reactivated during the Neoproterozoic and became the location of the Orsha-Volyn Aulacogen (Bogdanova *et al*., 1997, 2008).

The Neoproterozoic and Lower Palaeozoic sedimentary cover of the western slope of the EEC can be divided into a few genetically related sedimentary basins. Within the study area, these are the Baltic Basin in the NW and the Lublin-Podlasie Basin in the SE (for location, see Figs 2, 3). Farther east, the Orsha-Volyn Aulacogen developed, while SE part of the western slope of the EEC is occupied by the Volyn-Podilia-Moldavia Basin (Fig. 1).

The oldest sedimentary cover at this part of the EEC is the Polesie Series sandstone and mudstone, mostly of a continental depositional environment, deposited within the rift-related tectonic grabens of the Orsha-Volyn Aulacogen (Mahnatsch *et al*., 1976; Bogdanova *et al*., 1997, 2008; Poprawa and Pacześna, 2002). In the western part of the aulacogen, including the Lublin region, the Polesie Series is unconformably covered with alluvial conglomerates and sandstone as well as by the association of volcanic rocks of the Volyn Series (Figs 4, 5), in Poland referred to as the Sławatycze Formation (Pacześna, 2006, 2014). Characteristic components of the Volyn Series are flood basalts, interbedded with agglomerates and pyroclastics (Juskowiakowa, 1971; Rozanov and Łydka, 1987; Emetz *et al*., 2004). This large volcanic province is spread over roughly 140,000 km^2 across Belarus, Ukraine, Poland, Lithuania and Russia (Fig. 6; Ryka, 1984).

The Volyn Series passes upsection into a thick complex of clastic sediments of the uppermost Ediacaran, locally referred to as the Valday Series (Fig. 4) and into a lower Cambrian (Terreneuvian) to middle Cambrian (Series 2 and lower part of Miaolingian) complex (Fig. 4). It is composed mostly of shallow-marine sandstone and mudstone (Fig. 5), except for the bottom continental part, and was deposited in a Ediacaran to early Cambrian transgressive cycle and a middle Cambrian regressive cycle (Areń and Lendzion, 1978; Areń *et al*., 1979; Jaworowski, 1997; Pacześna and Poprawa, 2005). This basin expanded with time and since the early Cambrian covered both the Lublin-Podlasie and the Baltic regions (Figs 5, 7A, B; Poprawa and Pacześna, 2002; Modliński *et al*., 2010). The thickness of the Cambrian sediments increases generally westwards, i.e., towards the edge of the craton.

The upper Cambrian (uppermost Miaolingian and/or Furongian; Fig. 4) and lower Tremadocian is missing from a major part of the western EEC (Figs 5, 7C, D). The exception is the NW part of the Baltic Basin, mainly offshore, where the black bituminous shale of the Piaśnica Formation was deposited at that time (Fig. 7C, D; Szymański, 2008). Its thickness is very limited onshore, increasing towards the Baltic offshore and SW Scandinavia. The upper Cambrian sediments also are recognised in the southern part of the TESZ, although with very different development there. In the Łysogóry Block, they are represented by sandstone- and mudstone-dominated sediments of relatively great thickness (Orłowski, 1992), however, the exact stratigraphic thickness is difficult to determine, owing to significant tectonic deformation (Salwa, 2002; Gągała, 2005). A similar development of the upper Cambrian is characteristic for the Biłgoraj-Narol Zone (Figs 5, 7C).

The Ordovician sediments are broadly distributed across most of the EEC and in the eastern part of the TESZ (Fig. 5). In the Baltic Basin and the Lublin-Podlasie Basin, their development is similar and characterised by a minor thickness (Porębski and Podhalańska, 2017, 2019). The Lower and Middle Ordovician overlie the Cambrian to lower Tremadocian with a hiatus and are composed of sandstone and shale in the lower part (Floian) and limestone in the upper part (Dapingian, Darriwilian; Fig. 7E, F; Modliński, 1982; Modliński and Szymański, 1997, 2008; Levendal

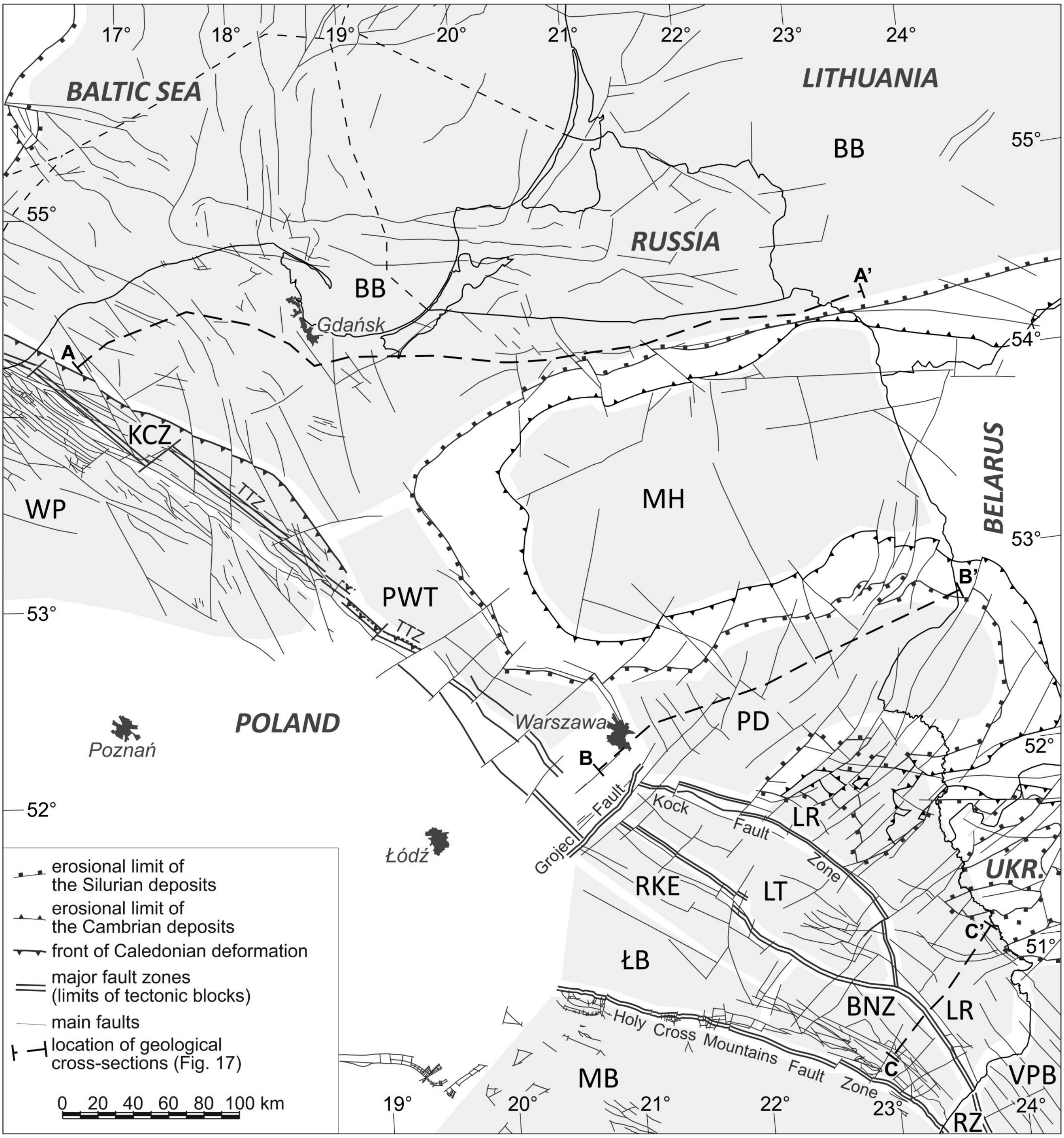


Fig. 2. Tectonic fabric of the Baltic Basin, the Lublin-Podlasie Basin, the Biłgoraj-Narol Zone, and the surrounding areas: location of the main faults and limits of tectonic blocks. MH – Mazury High, BB – Baltic Basin, PWT – Płock-Warsaw Trough, PD – Podlasie Depression, LR – Lublin Region (referred to also as Lublin slope of the EEC), LT – Lublin Trough, VPB – Volyn-Podilia Basin, RZ – Rava Ruska Zone, BNZ – Biłgoraj-Narol Zone, RKE – Radom-Kraśnik Elevation, ŁB – Łysogóry Block, MB – Małopolska Block, KCZ – Koszalin-Chojnice Zone, WP – Western Pomerania, TTZ – Teisseyre-Tornquist Zone.

et al., 2019). The Upper Ordovician is represented by shale and marl (Sandbian, lower Katian), becoming more carbonate-rich upsection (upper Katian, Hirnantian) (Fig. 7G, H), owing to a eustatic fall in sea level (Fig. 4; Modliński and Szymański, 1997; Porębski and Podhalańska, 2017, 2019).

In the Koszalin-Chojnice Zone, the Middle to Upper Ordovician is composed of mudstone and subordinate claystone of considerably greater thickness than in the Baltic Basin (Figs 5, 8, 9; Podhalańska and Modliński, 2006). Farther NW, in the adjacent Rügen Zone, the lower part of the Ordovician also is recognised, represented by fine clastic sandstone – shale, passing upwards into dark-grey greywacke and shale (Giesse *et al*., 1994). The Ordovician of the Biłgoraj-Narol Zone is composed of sandstone and shale in the lower part (Tremadocian), while the remainder is domi-

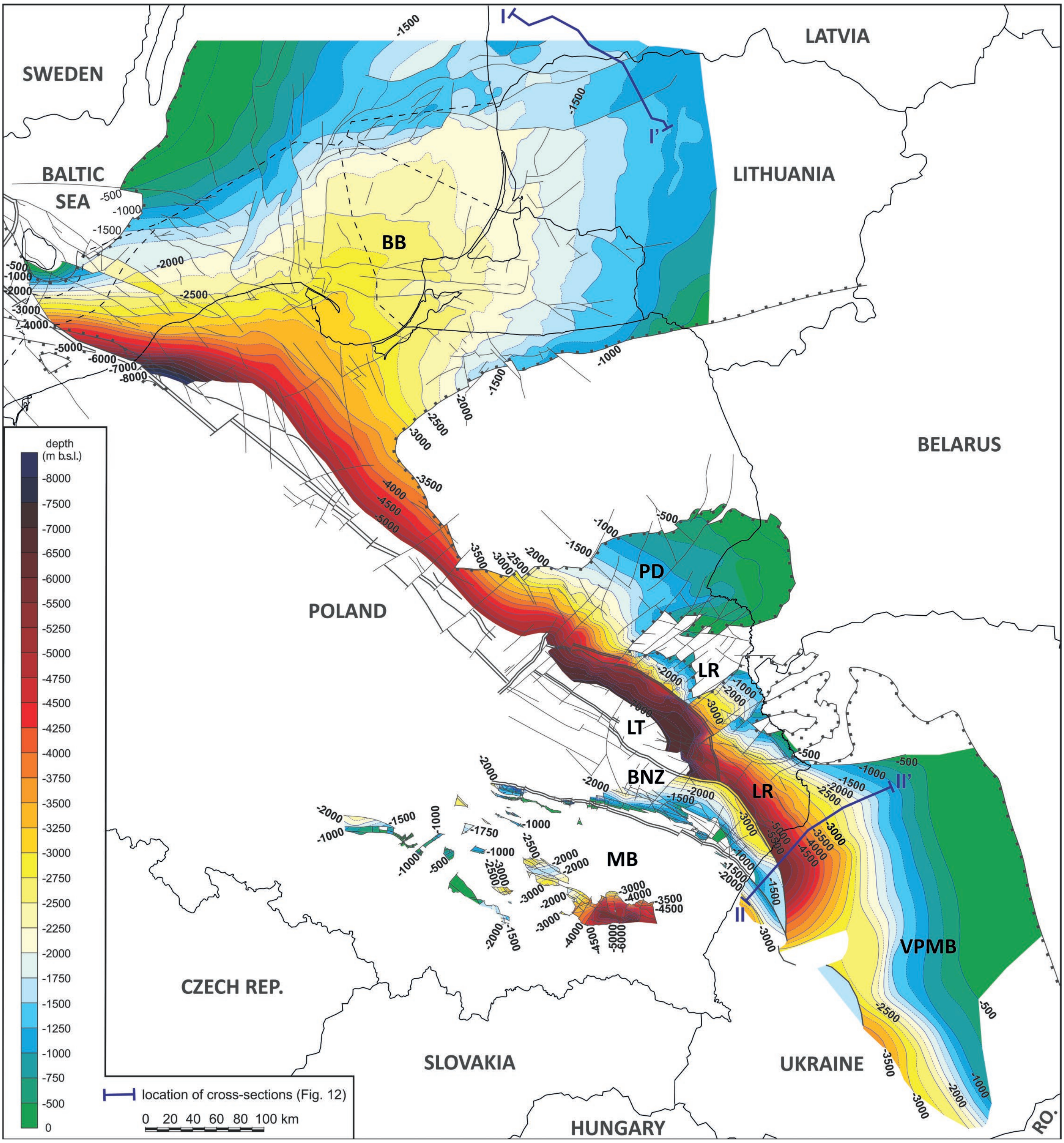


Fig. 3. Recent burial depth to the top of the Caradoc in the Baltic-Podlasie-Lublin Basin, the Biłgoraj-Narol Zone, the Małopolska Block, and surrounding areas. For explanation of abbreviations, see Figure 2. Blue lines (I-I' and II-II'): location of cross-sections presented in Figure 12.

nated by marl, shale and limestone (Figs 5, 8, 9; Modliński and Szymański, 2005; Drygant *et al*., 2006).

The Silurian of the Baltic Basin and the Lublin-Podlasie Basin is a continuous succession of fine-grained, partly marly sediments (Figs 5, 7I–L; Tomczykowa, 1988; Modliński *et al*., 2006). The Lower Silurian, particularly the lower Llandovery (Rhuddanian), is composed of intervals of bituminous shale (Modliński *et al*., 2006). Within the Lublin-Podlasie Basin, a southward increase in a hiatus in the lower part of Llandovery is observed and in the SE part of the Lublin region, as well as farther SE in the Volyn-Podilia-Moldavia Basin, the entire Llandovery is missing (Podhalańska, 2017; Poprawa *et al*., 2018a). A significant thickness increase from the east and NE towards the west and SW is characteristic for the Wenlock and Ludlow and also for the Pridoli in the Lublin-Podlasie Basin (Fig. 9).

The Silurian of the Koszalin-Chojnice Zone is composed mostly of mudstone, with lesser amounts of claystone and the subordinate presence of sandstone (Figs 5, 8, 9; Podhalańska and Modliński, 2006). The facies are similar compared with the Baltic Basin, although with a higher proportion of mudstone to claystone and a smaller amount of marly shale. Moreover, the Silurian of the Koszalin--Chojnice Zone is characterised by its lesser thickness in comparison to the Baltic Basin, except for the Llandovery (Figs 8, 9). The facies development of the Silurian in the Biłgoraj-Narol Zone is similar to that in the Lublin-Podlasie Basin (Fig. 5), although the Llandovery, Wenlock and Ludlow are characterized by greater thickness (Figs 8, 9).

The Devonian–Carboniferous sedimentary cover of the area analysed is diverse (Fig. 5). It is preserved mainly in the Lublin Basin, which continues farther SE into the Lviv Basin. The lower part of Lower Devonian is a continuation of marine shelf sedimentation of fine-grained, clastic sediments, passing upsection into alluvial clastic deposits, an equivalent of the Old Red facies (Miłaczewski and Radlicz, 1974; Miłaczewski, 1981). In the Middle Devonian, the deposition of limestone, dolomite and marl, locally interbedded with evaporites, predominates (Miłaczewski and Radlicz, 1974; Narkiewicz *et al.*, 1998a). The Upper De-

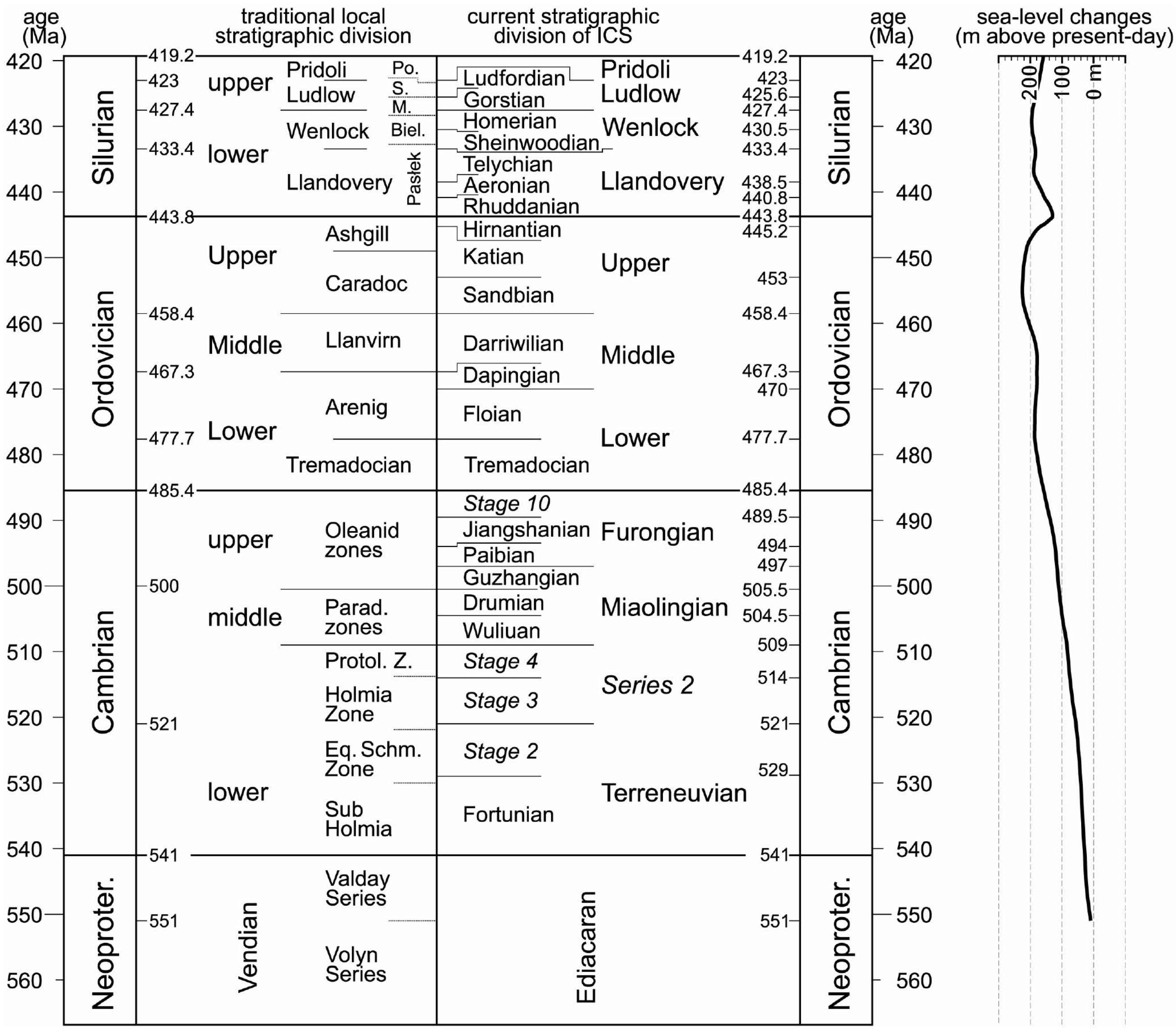
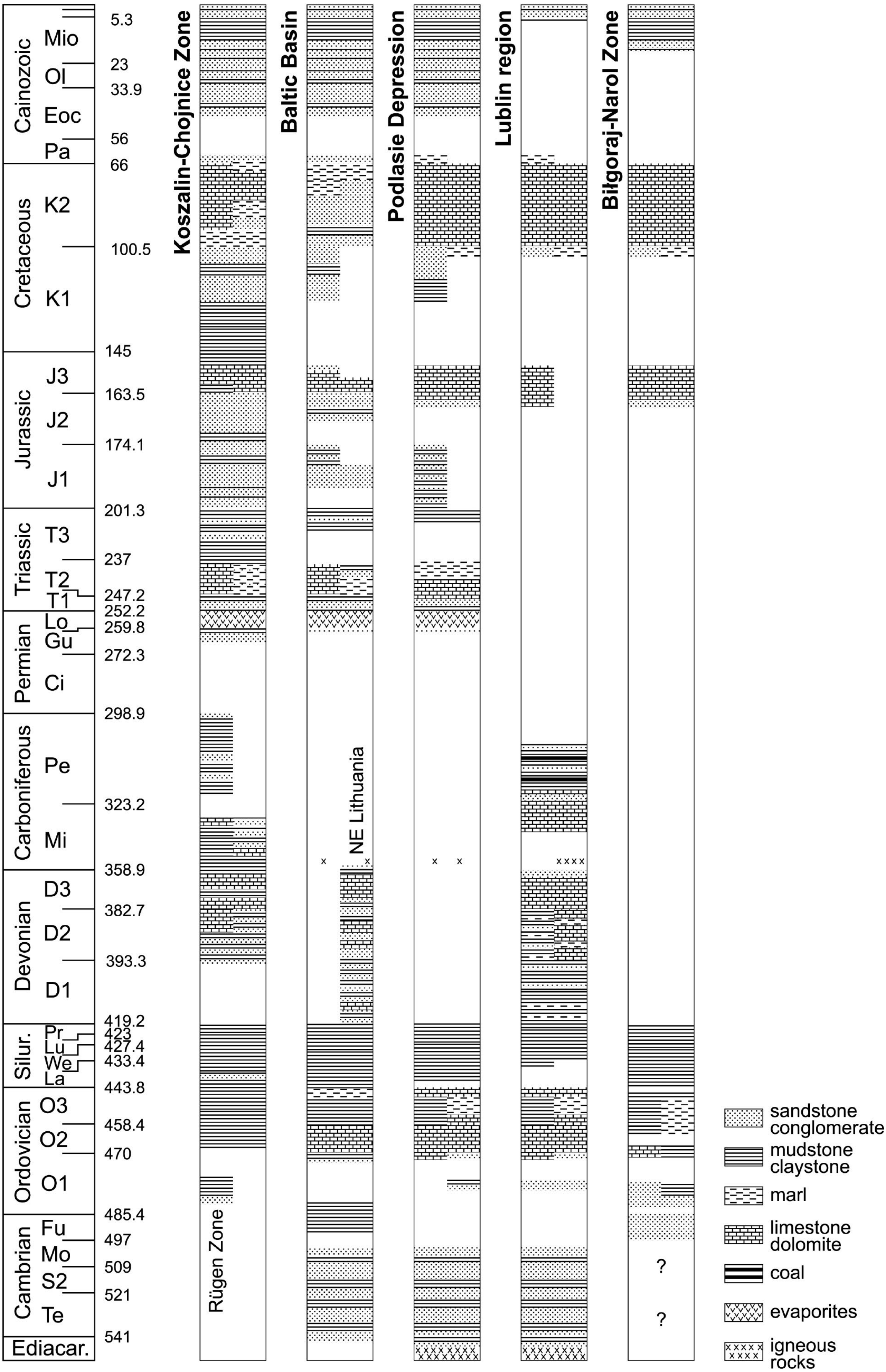


Fig. 4. Local stratigraphic division of the Neoproterozoic and Lower Palaeozoic in the western part of the East European Craton, correlated with recent division of the International Commission on Stratigraphy (Cohen *et al.*, 2013, updated). Cambrian trilobite zones: Eq. Schm. Zone – equivalent Schmidtiellus mickwitzi Zone, Protol. Z. – Protolenus Zone, Parad. zones – Paradoxides zones. Silurian lithofacies units: Biel. – Bielsk, M. – Mielnik, S. – Siedlce, Po. – Podlasie. Neoproter. – Neoproterozoic. Eustatic sea level changes after Haq and Schutter (2008).

Fig. 5. Simplified lithological sections of sedimentary basins developed in the western part of the East European Craton and adjacent areas. Mio – Miocene, Ol – Oligocene, Eoc – Eocene, Pa – Paleocene, Lo – Lopingian, Gu – Guadalupian, Ci – Cisuralian, Pe – Pennsylvanian, Mi – Mississippian, Silur. – Silurian, Pr – Pridoli, Lu – Ludlow, We – Wenlock, La – Llandovery, Fu – Furongian, Mo – Miaolingian, S2 – Series 2, Te – Terreneuvian, Ediacar. – Ediacaran.


Cainozoic
Mio
Ol
Eoc
Pa
Cretaceous
K2
K1
Jurassic
J3
J2
J1
Triassic
T3
T2
T1
Permian
Lo
Gu
Ci
Carboniferous
Pe
Mi
Devonian
D3
D2
D1
Silur.
Pr
Lu
We
La
Ordovician
O3
O2
O1
Cambrian
Fu
Mo
S2
Te
Ediacar.
5.3
23
33.9
56
66
100.5
145
163.5
174.1
201.3
237
247.2
252.2
259.8
272.3
298.9
323.2
358.9
382.7
393.3
419.2
423
427.4
433.4
443.8
458.4
470
485.4
497
509
521
541
Koszalin-Chojnice Zone
Rügen Zone
Baltic Basin
NE Lithuania
Podlasie Depression
Lublin region
Biłgoraj-Narol Zone
?
?
sandstone conglomerate
mudstone claystone
marl
limestone dolomite
coal
evaporites
igneous rocks

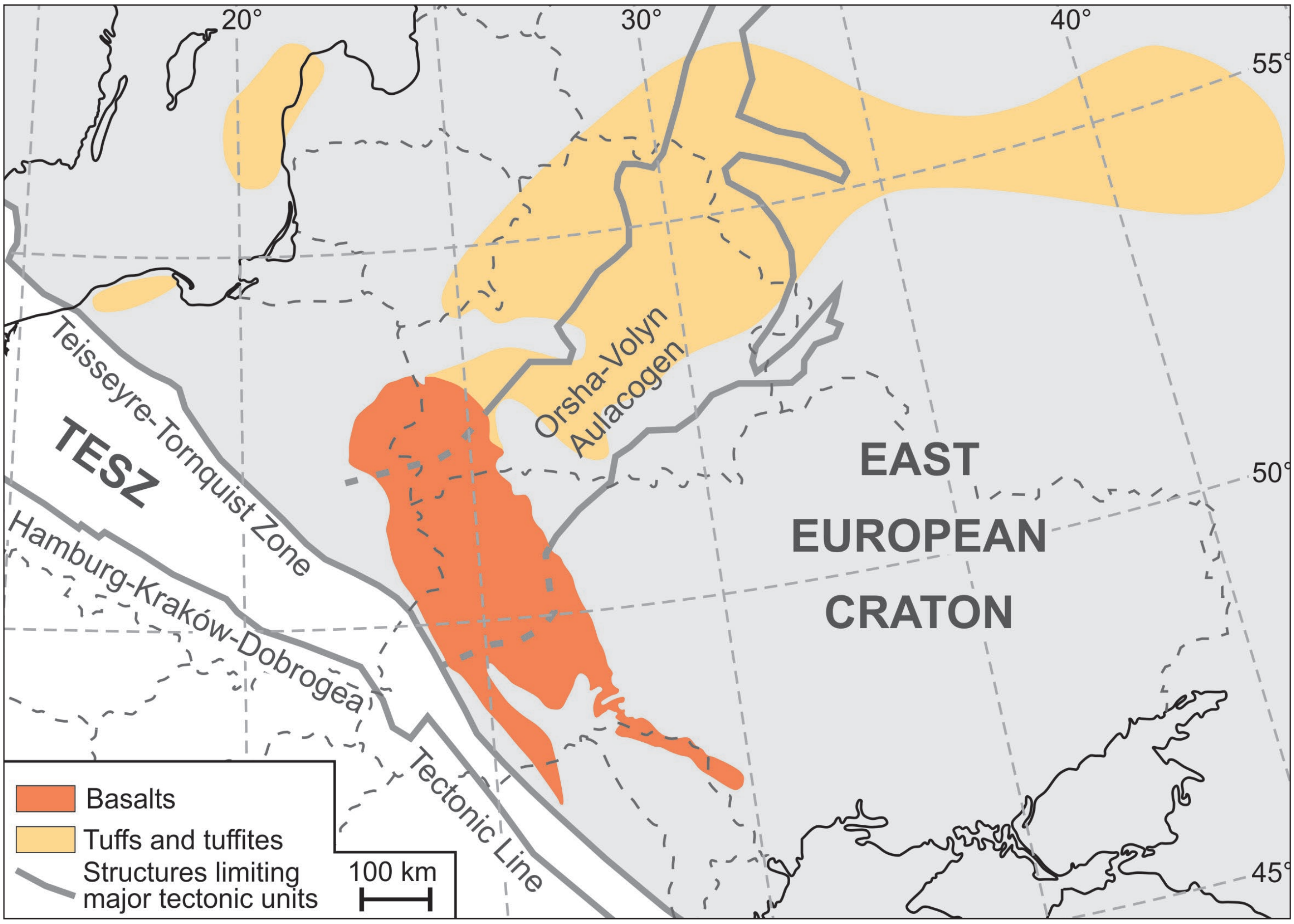


Fig. 6. Extent of the Volyn Igneous Province (after: Kuzmenkova *et al*., 2010; Środoń *et al*., 2019, with minor modification). TESZ – Trans-European Suture Zone.

vonian is dominated by carbonate sediments of ramp and shelf settings, passing upsection into marginal-marine, clastic and carbonate deposits (Narkiewicz *et al*., 1998a). The Carboniferous of the Lublin Basin comprises sediments of a shallow shelf as well as deltaic and fluvial systems (Waksmundzka, 1998). The Mississippian is composed mostly of carbonate and fine-grained clastic sediments, while the Pennsylvanian mostly consists of sandstone and mudstone, with a characteristic contribution of hard coal (Fig. 5; Żelichowski, 1972; Porzycki and Zdanowski, 1995).

Farther to the NW of the Lublin Basin, over a vast part of the EEC, the Devonian and Carboniferous sediments were removed by erosion. This is also the case for the Biłgoraj-Narol Zone. However, in the northeastern part of the Baltic Basin, the Devonian and Lower Mississippian are preserved, represented by mainly siliciclastic-evaporitic sediments, with interbedded, open-marine carbonate (Fig. 5; Paškievičius, 1997; Jacyna *et al*., 1997; Matyja, 2006). To the west of the TTZ, there developed a Pomeranian Devonian–Carboniferous basin, the extent of which covered also the Lower Palaeozoic Koszalin-Chojnice Zone. This basin accumulated marine carbonate and mixed carbonate-clastic sediments (Fig. 5; Matyja, 2006, 2008; Seidel *et al*., 2018). Locally, in the western part of the area, the Pennsylvanian clastic sediments, occasionally with coal seams, are preserved (Kuberska *et al*., 2007).

A regional unconformity separates the Devonian–Carboniferous sedimentary complex from the Permian–Mesozoic one across all the area considered (Figs 5, 10). In the Late Permian and throughout the Mesozoic the western part of the EEC as well as the adjacent Koszalin-Chojnice Zone and the Biłgoraj-Narol Zone became the eastern flank of the Polish Basin. The presence of hiatuses, covering a significant part of late Permian and Mesozoic time span, is characteristic for the southeastern, eastern and northeastern parts of the area, while towards the west, the Permian–Mesozoic section becomes more nearly complete (Figs 5, 10; Dadlez and Marek, 1997). The Upper Permian sediments are of continental, clastic facies (Rotliegend) and Zechstein evaporite facies (Wagner, 1994; Kiersnowski, 1998). The Triassic is dominated by clastic deposits, except in its middle part, mainly consisting of carbonates (Senkowiczowa, 1976). Clastic sediments predominate also in the Lower and Middle Jurassic, while the upper part is characterized by a large contribution by carbonates (Dadlez and Marek, 1997). Clastic sediments predominate also in the Lower Cretaceous, while the Upper Cretaceous, locally together with the Lower Paleocene, is composed mostly of carbonates of chalk-type facies (Dadlez and Marek, 1997).

The development of the Permian–Mesozoic Polish Basin terminated with Laramian uplift and erosion, although quite limited, in the study area being (Fig. 10). The Cainozoic sedimentary cover in the western part of the EEC and adjacent areas is characterised by the presence of unconsolidated, clastic sediments of minor thickness (Piwocki and Kramarska, 2004; Jarosiński *et al*., 2009).

TECTONIC EVOLUTION OF THE WESTERN EEC AND THE ADJACENT AREAS

The development of sedimentary basins on the western slope of the EEC, including the Baltic-Dniester system of basins and the Orsha-Volyn Aulacogen, commenced in the Neoproterozoic with rifting, related to the latest stages of breakup of the Precambrian super-continent Rodinia/Pannotia, which ultimately led to the formation of the Tornquist Ocean (Figs 10, 11; Poprawa *et al*., 1999; Poprawa 2006a; Golonka *et al*., 2017, 2019). This process was initiated in the Orsha-Volyn Aulacogen with development of tectonic grabens, filled with sandstones of the Polesie Series (Mahnatsch *et al*., 1976; Bogdanova *et al*., 1997, 2008). The associated tectonic regime was interpreted as the first phase of the Neoproterozoic rifting on the western slope of the EEC (Poprawa and Pacześna, 2002). The age of this process is uncertain owing to the lack of stratigraphic constraints, although on the basis of the isotope age of detrital mica from the Polesie Series (Semenenko, 1968), it was tentatively assigned to the late Cryogenian or Ediacaran (Poprawa, 2006a).

A major phase of extension and rifting on the western slope of the EEC took place during the late Ediacaran (Fig. 10). This is evidenced by a relatively rapid tectonic subsidence in the latest Ediacaran, which was followed by systematically declining subsidence during the Cambrian and Ordovician (Greiling *et al*., 1999; Poprawa *et al*., 1999, 2018a; Poprawa and Pacześna, 2002; Poprawa, 2006a; Eriksson, 2012). The observed pattern of subsidence is characteristic of the thermal sag of rifted basins, where a syn-rift phase is expressed by rapid tectonic subsidence, mainly within extensional tectonic grabens, whereas the subsequent post-rift basin development is governed by cooling of the lithosphere, resulting in a systematically decreasing rate of tectonic subsidence, coeval with the lateral expansion of the basin.

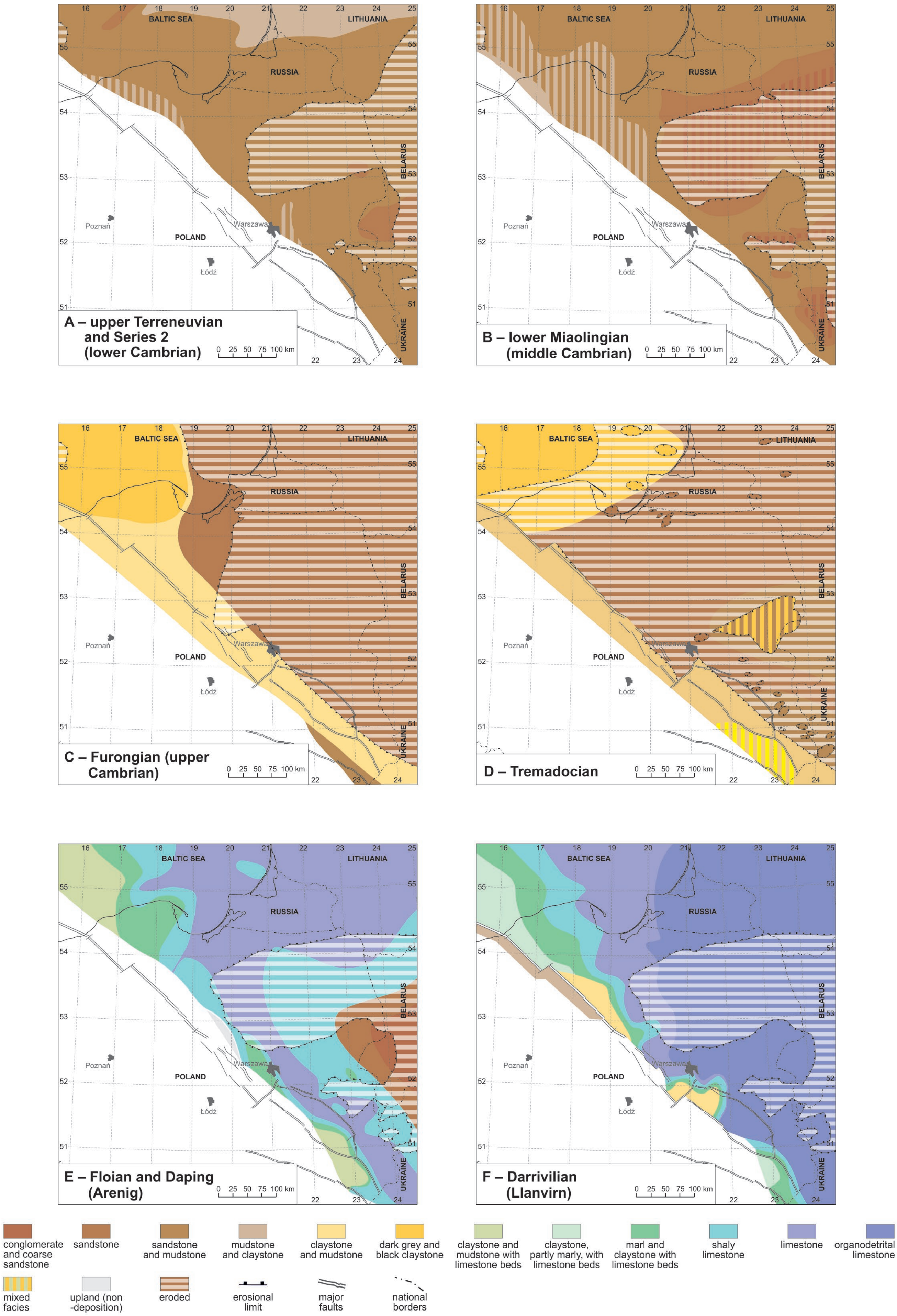
The late Ediacaran syn-rift tectonic subsidence increased westwards, i.e., towards the edge of the EEC, where the Ediacaran rift zone was located (Poprawa, 2006a). At that time, the rift developed along the entire SW margin of the EEC from Scandinavia to the Black Sea. The rifting was initiated with the emplacement of volcanic rocks, mainly flood basalts, in the western Orsha-Volyn Aulacogen, as well as at its intersection with the Baltic-Dniester system of sedimentary basins (Fig. 6; Ryka, 1984; Rozanov and Łydka, 1987; Bogdanova *et al*., 1997; Emetz *et al*., 2004; Środoń *et al*., 2019). The rift origin of the late Ediacaran basalts and associated volcanic and pyroclastic rocks is supported by their geochemical and petrological characteristics (Bakun-Czubarow *et al*., 2002; Białowolska *et al*., 2002; Emetz *et al*., 2004; Krzemińska, 2005). The late Ediacaran age of the rift-related, volcanic and pyroclastic rocks is documented from radiometric geochronology (Savchenko *et al*., 1984; Sokolov and Fedonkin, 1990; Compston *et al*., 1995, Velikanov and Korenchuk, 1997; Shumlyanskyy and Andréasson, 2004; Elming *et al*., 2007; Shumlyanskyy *et al*., 2007, 2016; Paszkowski *et al*., 2019).

The rifting also is evidenced by the presence of a large, extensional half-graben, revealed in the Lublin region by recent, deep seismic data (Krzywiec *et al*., 2018). The graben developed in the Palaeoproterozoic crystalline basement and was filled with a syn-rift volcano-sedimentary succession, presumably of late Neoproterozoic age (Krzywiec *et al*., 2018). A Neoproterozoic half-graben of similar scale was documented also by deep, seismic reflection data farther NW at the western EEC margin, in the SW part of the Baltic Sea (Lassen *et al*., 2001). Moreover, the rift model is consistent with facies development in the Ediacaran succession of the Lublin-Podlasie Basin (Pacześna and Poprawa, 2005; Pacześna, 2006, 2014).

The latest Ediacaran to Middle Ordovician tectonic subsidence pattern of the Baltic-Dniester system of sedimentary basins was characteristic for the post-rift thermal sag stage of extensional basins (Greiling *et al*., 1999; Poprawa *et al*., 1999, 2018a; Poprawa and Pacześna, 2002, Poprawa, 2006a). Such an interpretation also is confirmed by a lateral expansion of the analysed sedimentary basins during the late Ediacaran, Cambrian and Ordovician (Gareckij *et al*., 1987; Poprawa and Pacześna, 2002), characteristic of a thermal sag mechanism. At that time, the SW margin of the newly formed Baltica became a passive continental margin (Fig. 11).

The post-rift subsidence of the passive margin was interrupted in the late Cambrian by uplift and erosion on a limited scale, occurring at the western slope of the EEC, south of the Baltic Sea and Łeba Elevation (Fig. 10; Poprawa, 2006a). In the adjacent Biłgoraj-Narol Zone and Małopolska Block, it was coeval with the rapid deposition of a sandstone-dominated succession of great thickness (Figs 5, 10), while in the Małopolska Block it was assisted by compressional deformation (Salwa, 2002; Gągała, 2005). On the basis of the constraints mentioned above, the Upper Cambrian basin in the Biłgoraj-Narol Zone and the Małopolska Block was interpreted as a small flexural basin, the development of which resulted from tectonic loading, related to the oblique docking of the Małopolska Block to Baltica (Poprawa, 2006a). In such a model, the late Cambrian uplift of the western slope of the EEC was caused by a compressional stress regime. An alternative interpretation also was considered, which assumed that the uplift was related to the far-field effects of other contractional events or intra-plate stresses. It ceased in the early Tremadocian and during the remaining part of the Early and Middle Ordovician, the subsidence of the Baltic-Dniester system of sedimentary basins continued, owing to thermal sag mechanisms.

Since the Late Ordovician, a gradual change to a collisional tectonic setting is observed across the SW margin of Baltica. This is indicated by a systematic increase in subsidence rate from Late Ordovician to Late Silurian and/or Early Devonian, creating subsidence curves with convex shapes, typical of foreland basin development (Poprawa *et al*., 1999; Poprawa and Pacześna, 2002; Poprawa, 2006b; Eriksson, 2012). The Late Ordovician to Late Silurian/Early Devonian phase of development of the Baltic-Dniester


A – upper Terreneuvian
and Series 2
(lower Cambrian)
B – lower Miaolingian
(middle Cambrian)
C – Furongian (upper
Cambrian)
D – Tremadocian
E – Floian and Daping
(Arenig)
F – Darrivilian
(Llanvirn)
BALTIC SEA
LITHUANIA
RUSSIA
BELARUS
UKRAINE
POLAND
Poznań
Warszawa
Łódź
0 25 50 75 100 km
conglomerate and coarse sandstone
sandstone
sandstone and mudstone
mudstone and claystone
claystone and mudstone
dark grey and black claystone
claystone and mudstone with limestone beds
claystone, partly marly, with limestone beds
marl and claystone with limestone beds
shaly limestone
limestone
organodetrital limestone
mixed facies
upland (non -deposition)
eroded
erosional limit
major faults
national borders

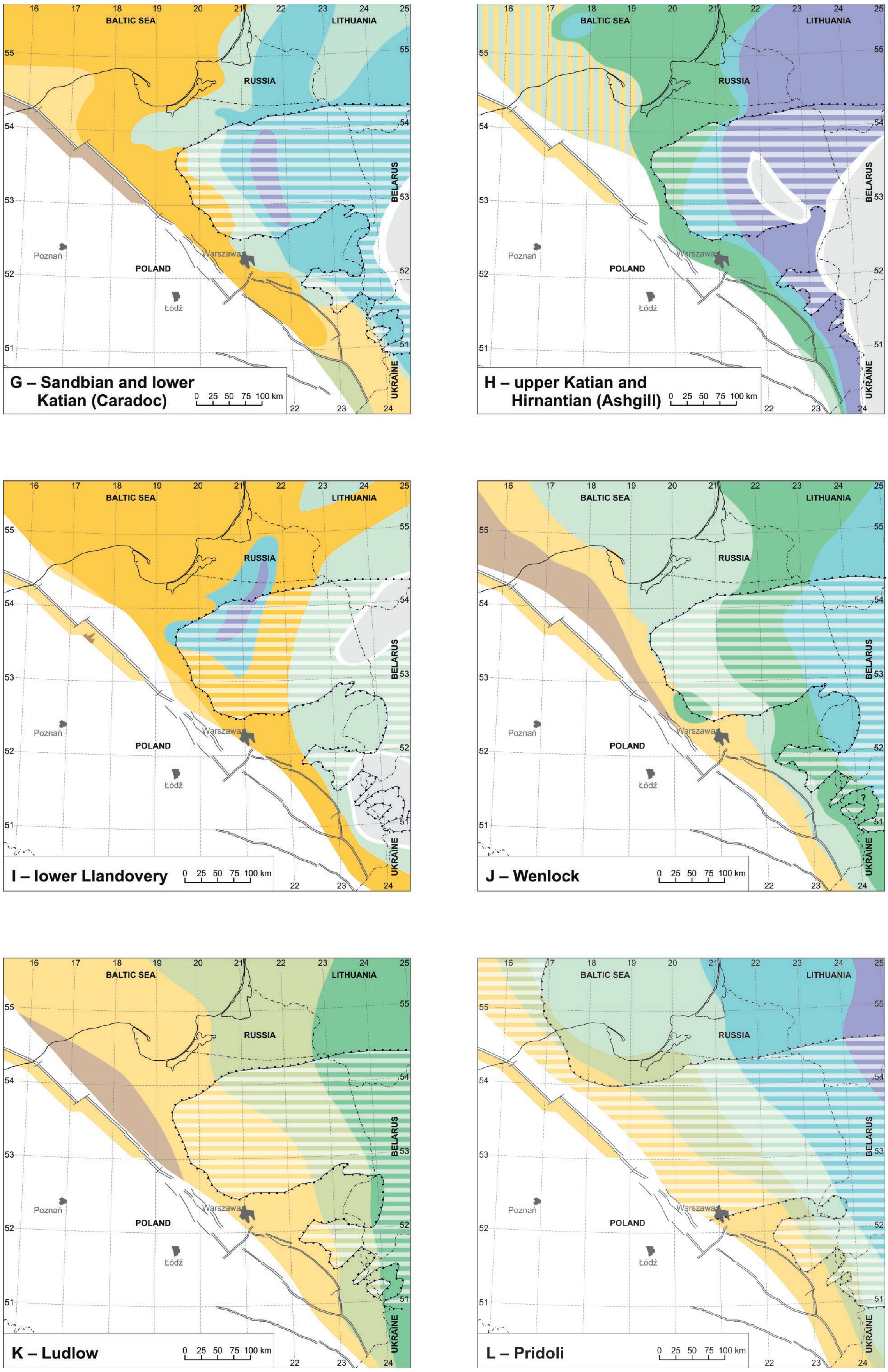


Fig. 7. Lithofacies of the Lower Palaeozoic sedimentary fill of the Baltic-Podlasie-Lublin Basin. After Modliński *et al.* (2010), Spaw and Hlava (2014), simplified, modified and supplemented.

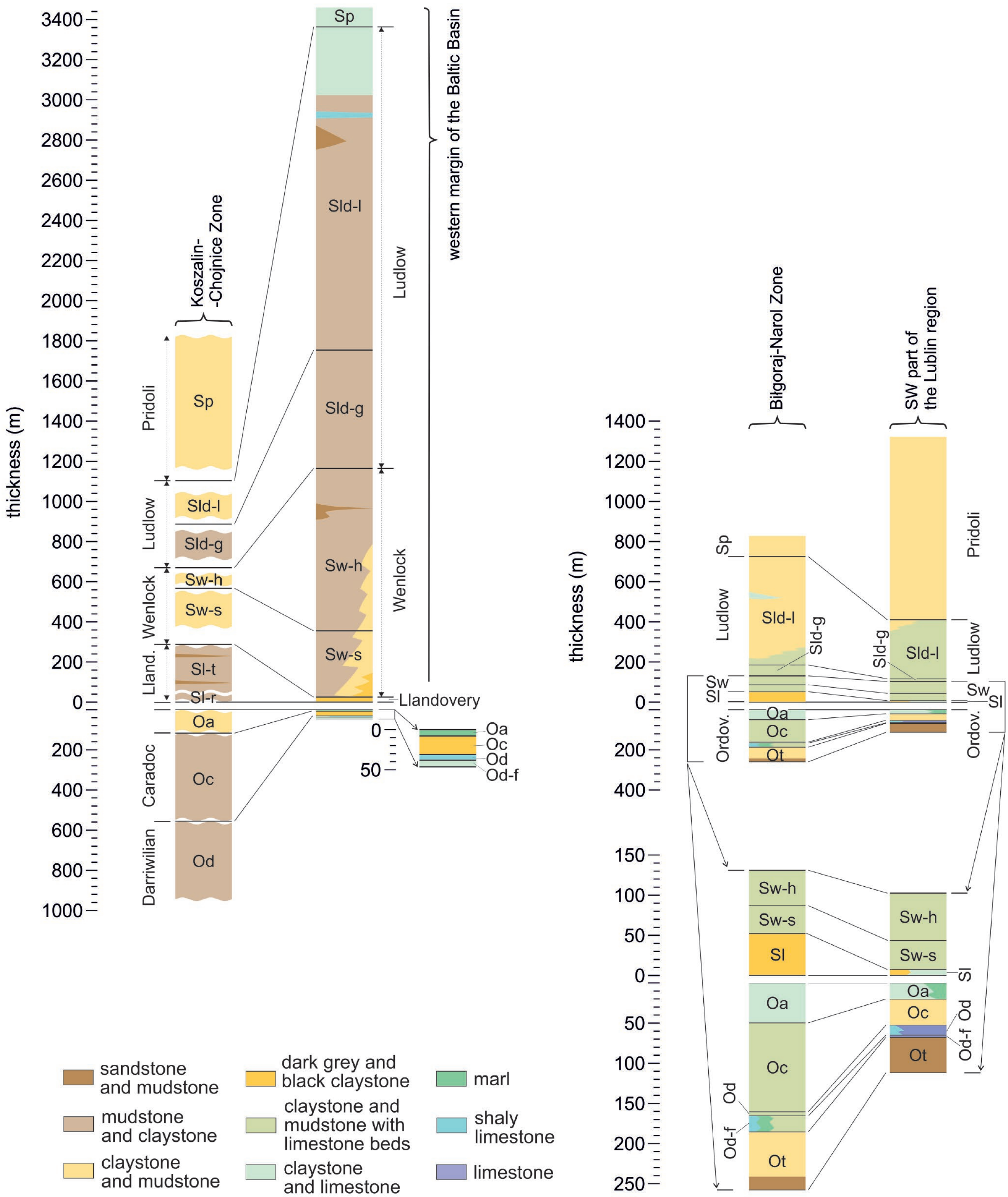


Fig. 8. Comparison of lithofacies and thickness of the Ordovician and Silurian sediments in the western Baltic Basin and the adjacent Koszalin Chojnice Zone, as well as in the Lublin region and the adjacent Narol-Biłgoraj Zone. Sp – Pridoli, Sld-l – Ludfordian, Sld-g – Gorstian, Sw – Wenlock, Sw-h – Homerian, Sw-s – Sheinwoodian, Lland., Sl – Llandovery, Sl-r – Rhuddanian, Sl-t – Telychian and Aeronian, Oa – Ashgill, Oc – Caradoc, Od – Darriwilian (Llanvirn), Od-f – Dapingian–Floian (Arenig), Ot – Tremadocian.

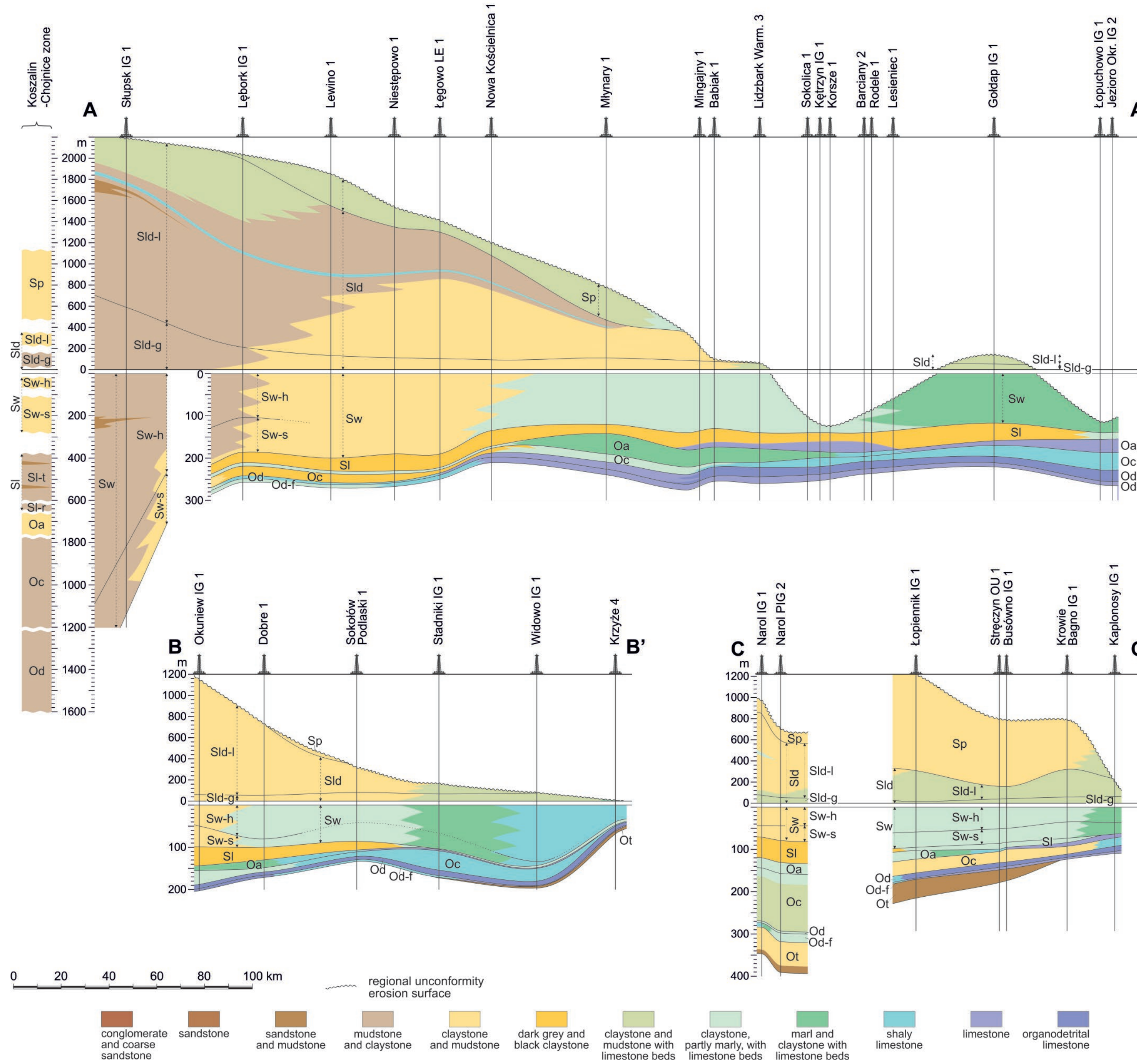
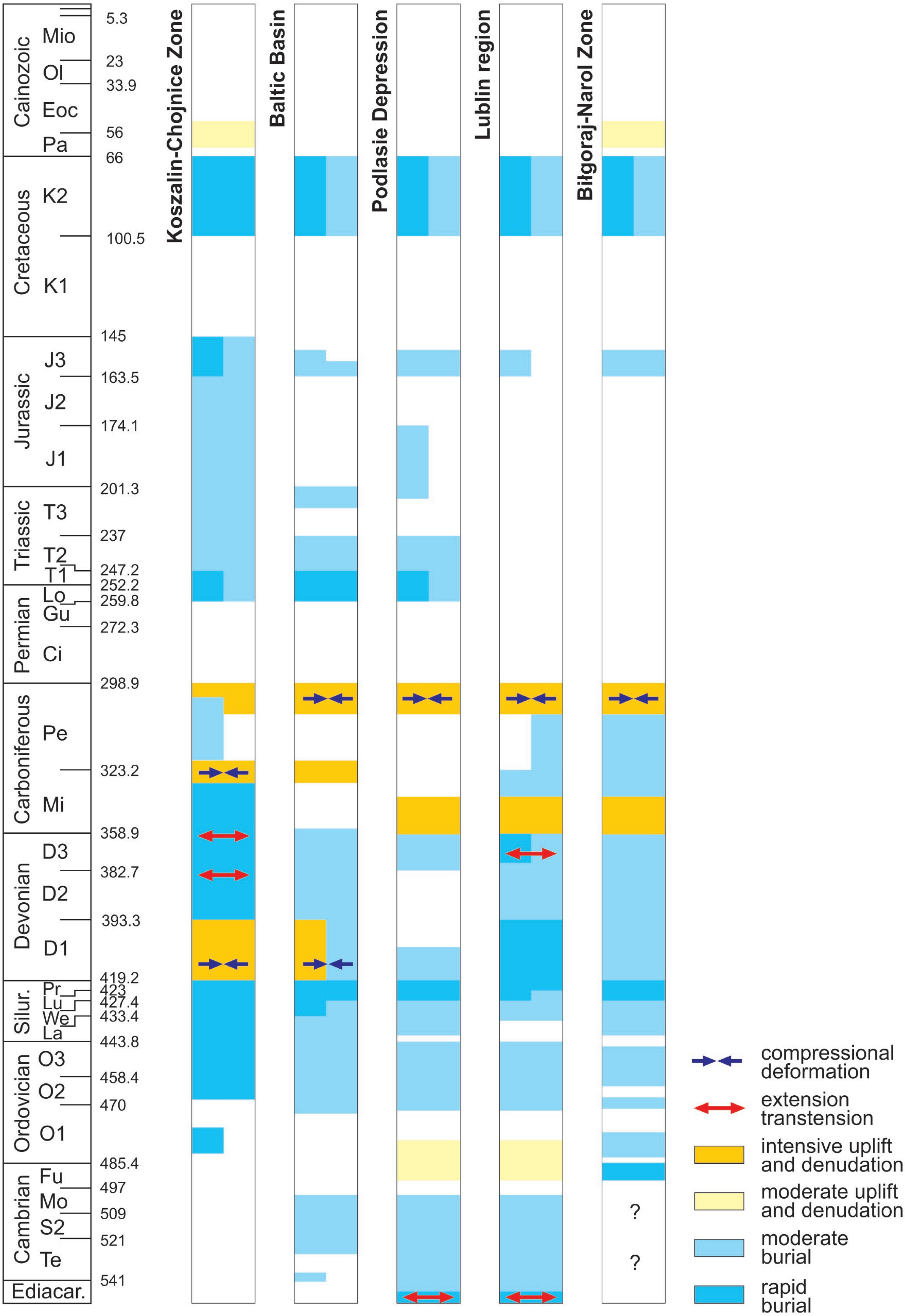


Fig. 9. Lithofacies cross-sections through (**A**) the Baltic Basin, (**B**) the Podlasie Depression, and (**C**) Lublin region. B and C based on data of Modliński and Szymański (1997, 2005, 2008), Modliński *et al.* (2006, 2010), Drygant *et al.* (2006), Podhalańska (2017). Note the different vertical scales for the Upper Silurian and the Lower Silurian to Upper Ordovician. Sp – Prodoli, Sld – Ludlow, Sld-l – Ludfordian, Sld-g – Gorstian, Sw – Wenlock, Sw-h – Homerian, Sw-s – Sheinwoodian, Sl – Llandovery, Sl-r – Rhuddanian, Sl-t – Telychian and Aeronian, Oa – Ashgill, Oc – Caradoc, Od – Darriwilian (Llanvirn), Od-f – Dapingian-Floian (Arenig).

system of sedimentary basins is interpreted here as a flexural foredeep, related to the convergence and collision of Avalonia and Baltica and to the subsequent development of a Caledonian collision zone (Fig. 11; Poprawa *et al.*, 1999; Lazauskienė *et al.*, 2002; Poprawa, 2006b; Tari *et al.*, 2016; Mazur *et al.*, 2018).

The foredeep model is consistent with the facies characteristics of Silurian sediments in the Baltic, Lublin-Podlasie Basin and the Volyn-Podilia-Moldavia basins (Vejbæk *et al.*, 1994; Maletz *et al.*, 1997; Beier *et al.*, 2000; Jaworowski, 2000; Radkovets, 2015; Poprawa *et al.*, 2018a). In the Baltic Basin, the Silurian foredeep model also is supported by deep seismic data, illustrating a westward flexure with the seismic horizons onlapping eastwards, i.e., outwards with respect to the collision zone (Krzywiec *et al.*, 2014; Mazur *et al.*, 2016; Tari *et al.*, 2016). The presence of the Ashgill intensive, collisional, tectonic deformation in the Koszalin-Chojnice zone, representing part of the Caledonian accretionary prism, is also supportive of the collision model (Fig. 10; Żaba and Poprawa, 2006).

The rate of deposition of detritus also increases with time since the Late Ordovician in all the basins analysed, in the Late Silurian maximum reaching values of up to 1,000 m/My in the western Baltic Basin (Poprawa,


Cainozoic
Mio
Ol
Eoc
Pa
Cretaceous
K2
K1
Jurassic
J3
J2
J1
Triassic
T3
T2
T1
Permian
Lo
Gu
Ci
Carboniferous
Pe
Mi
Devonian
D3
D2
D1
Silur.
Pr
Lu
We
La
Ordovician
O3
O2
O1
Cambrian
Fu
Mo
S2
Te
Ediacar.
5.3
23
33.9
56
66
100.5
145
163.5
174.1
201.3
237
247.2
252.2
259.8
272.3
298.9
323.2
358.9
382.7
393.3
419.2
423
427.4
433.4
443.8
458.4
470
485.4
497
509
521
541
Koszalin-Chojnice Zone
Baltic Basin
Podlasie Depression
Lublin region
Biłgoraj-Narol Zone
?
?
compressional deformation
extension transtension
intensive uplift and denudation
moderate uplift and denudation
moderate burial
rapid burial

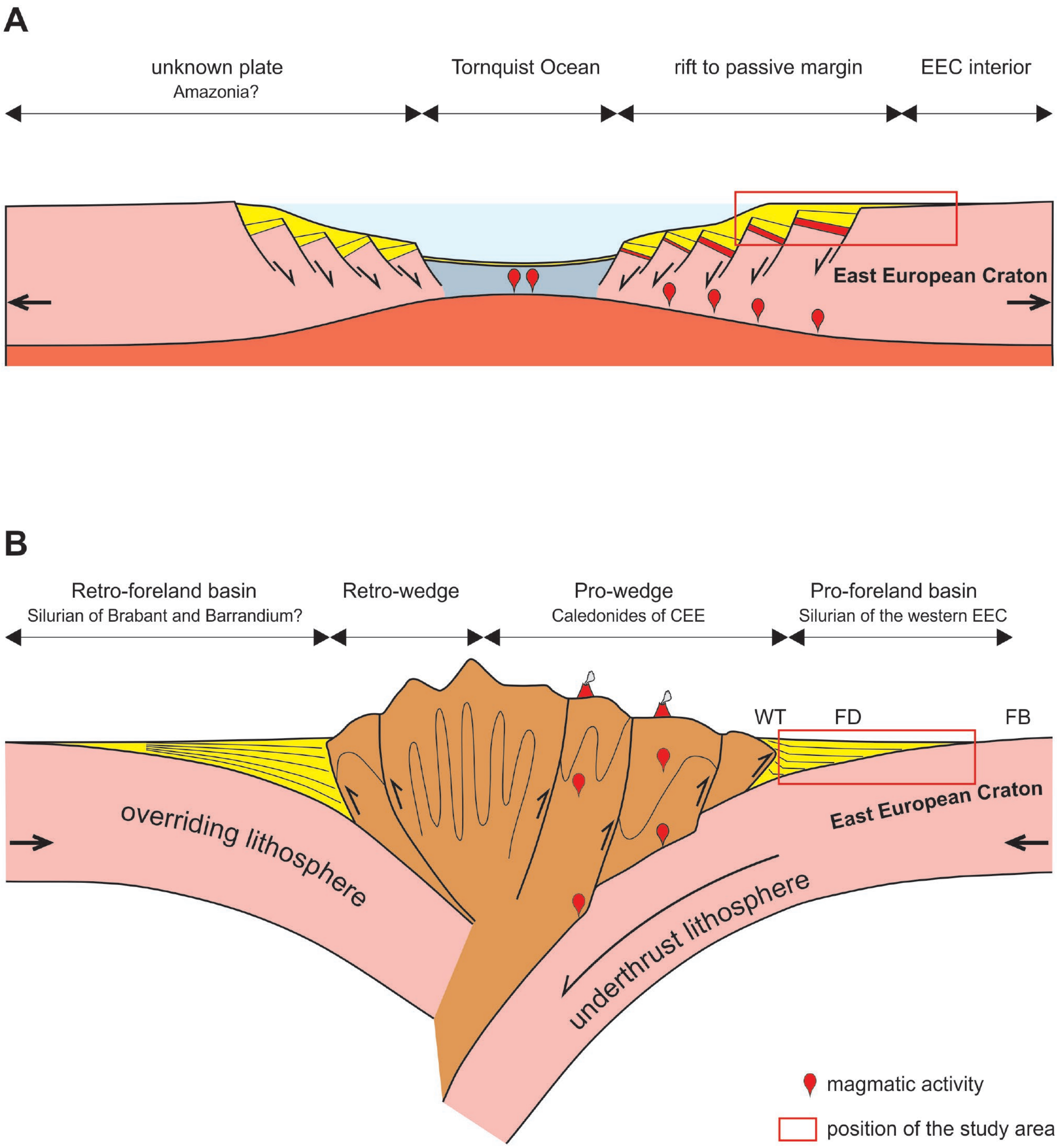


Fig. 11. Summary figure illustrating major tectonic mechanisms controlling development of the sedimentary basins on the western slope of the East European Craton. **A**. Ediacaran extension resulted in the development of the rift basin and subsequent transition to the passive continental margin (after Poprawa, 2006a and Poprawa *et al*., 2018a). EEC – East European Craton. **B**. Silurian collision and development of foredeep basin (after Tari *et al*., 2016, Poprawa *et al*., 2018a). CEE – Central and Eastern Europe. WT – Wedge top. FD – Foredeep. FB – Forebulge.

Fig. 10. Key phases of subsidence/burial and uplift/denudation in the sedimentary basins at the western part of the East European Craton and adjacent areas. Explanations of the abbreviations as in Figure 5.

2006b). Such high deposition rates require a very active sediment source area, which in this case was in the Caledonian collision zone. The characteristics of such a provenance area were confirmed by the isotope dating of detrital mica, indicating Caledonian metamorphism, presumably of an orogenic nature, in the sediment source area (Poprawa *et al*., 2006a). The regional facies distribution of the Upper Ordovician and Silurian, with open-marine mudstone to sandstone predominant in the western parts of the basins and carbonates rimming the basins in the east (Fig. 7G–L; Modliński *et al*., 2010; Levendal *et al*., 2019), is coherent with the foredeep basin model.

The concept of convergence and collision of Avalonia and Baltica is supported also by palaeomagnetic analysis and sediment provenance studies, although they indicate that collision of the plates commenced later than was interpreted from the subsidence history, i.e., in Ashgill time (Dallmeyer *et al*., 1999; Torsvik and Rehnström, 2003; Cocks and Torsvik, 2005; Golonka, 2009). Nonetheless, the results of recent, geochemical and geochronological studies of Ordovician K-bentonites from the Baltic Basin provide evidence for the initiation of collision taking place 455 Ma, i.e., in the early Caradoc (Anczkiewicz *et al*., 2017). Convergence-related subduction is evidenced by the common presence of K-bentonites in the foredeep basin, derived from a subduction-related, volcanic island arc (Huff *et al*., 1992, 2000; Bergström *et al*., 1995; Anczkiewicz *et al*., 2017).

The prominent diachronism of the initiation of the foredeep basin development on the scale of the entire SW margin of Baltica is consistent with the model of oblique collision of Avalonia and Baltica. The diachronism refers to the initiation of foredeep development, the starved basin phase, the main phase of rapid supply of detritus from the west, the late Caledonian compressional deformation and the development of an unconformity related to it, and the termination of foredeep basin development. The considerably lesser thickness of the coeval sediments filling the Volyn-Podilia-Moldavia Caledonian foredeep, compared with the Lublin-Podlasie and the Baltic ones, indicates its more distal position, relative to the Caledonian collision zone and the associated tectonic load (Poprawa *et al*., 2018a).

In the Lublin-Podlasie and Volyn-Podilia-Moldavia basins, the development of the Caledonian foredeep continued until Lochkovian time (Poprawa *et al*., 2018a). During the Pragian–Emsian, both basins became part of a system of post-collisional Old Red basins. Their subsidence was driven by a lithospheric, isostatic imbalance, caused by the development of the Caledonian accretionary wedge (Poprawa *et al*., 2018a).

During the terminal stage of the Caledonian collision and foredeep development, intra-plate compressional to transpressional deformations developed, well documented in the eastern Baltic Basin, expressed in a system of reverse faults of late Lochkovian age, as well as by a late Caledonian unconformity (Fig. 12A; Poprawa *et al*., 2006b). Reverse faults, present farther west in the Baltic Basin, could develop during this deformation phase and/or during the late Variscan compression and transpression. Their age cannot be defined as precisely as in the case of the eastern part of the basin, since they terminated at the top Silurian-bottom Permian unconformity.

Farther SE, in the NW part of the Volyn-Podilia-Moldavia Basin, a late Caledonian subconformity developed as well, although later in time. In this case, the subconformity is related to differential tectonic uplift and erosion, the results of which are revealed in cartographic data (Fig. 12B; Gierasimov *et al*., 2003; Radkovets *et al*., 2017b) and are expressed as the deposition of the Middle Devonian directly on top of the Tyver and Rukshyn formations (lower part of the Lower Devonian), owing to the reduction of the younger Dniester Formation (upper part of the Lower Devonian). However, there are some uncertainties as to the exact age of the sediments being subjected to erosion and therefore also as to the age of the subconformity. According to the recent study by Tsegelnyuk (1994) and Radkovets (2016), the Dniester Formation is of the Pragian–Emsian age. Since it is covered by an Eifelian–Givetian complex, the unconformity developed during the late Emsian. The alternative interpretation designates the age of these sediments as Lochkovian (Nikiforova *et al*., 1972), therefore, in such an approach the age of the subconformity would be constrained less precisely to the late Lochkovian–late Emsian.

During the Middle Devonian to Pennsylvanian on the western slope of the EEC and the adjacent area, a system of Variscan sedimentary basins developed, covering the Ediacaran–Lower Palaeozoic (locally to Lower Devonian) sedimentary complex (compare Figs 13, 14). In the southern part of the area, these are the Lublin and Lviv basins (Żelichowski, 1972; Porzycki and Zdanowski, 1995; Narkiewicz, 2007; Radkovets *et al*., 2017a). Cartographic data indicate that the division into these two basins is based on a cultural rationale, rather than a geological one (Figs 14, 15). The development of the both basins was governed by an extensional to transtensional tectonic regime (Fig. 10; Narkiewicz *et al*., 1998b; Poprawa *et al*., 2018a).

In the northern part of the craton, the Variscan complex is preserved in the eastern part of the Baltic Basin (Figs 14, 15; Paškevičius, 1997; Matyja, 2006). To the west of the Baltic Basin, the (upper Emsian–?) Middle Devonian to Mississippian sedimentary complex was deposited in the Western Pomerania Basin, including the Koszalin-Chojnice Zone (Figs 14, 15; Matyja, 2006, 2008; Seidel *et al*., 2018). The development of the Pomerania Basin was preceded by late Caledonian deformation and subsequent uplift and denudation, which led to the development of an angular unconformity in this region (Figs 10, 13–14). The erosion was related to post-collisional, isostatic uplift, which also affected the western part of the Baltic Basin (Fig. 10; Poprawa, 2006b). The development of the Middle Devonian to Mississippian Western Pomeranian Basin was governed by regional-scale extension (Fig. 10), expressed as a characteristic subsidence pattern (Narkiewicz *et al*., 1998b), as well as by the presence of large, extensional-tectonic half-grabens (Poprawa *et al*., 2018b and references therein).

In the SE part of the EEC, the development of the Variscan basins was interrupted by intensive uplift and erosion during Tournaisian to early Visean time, referred to

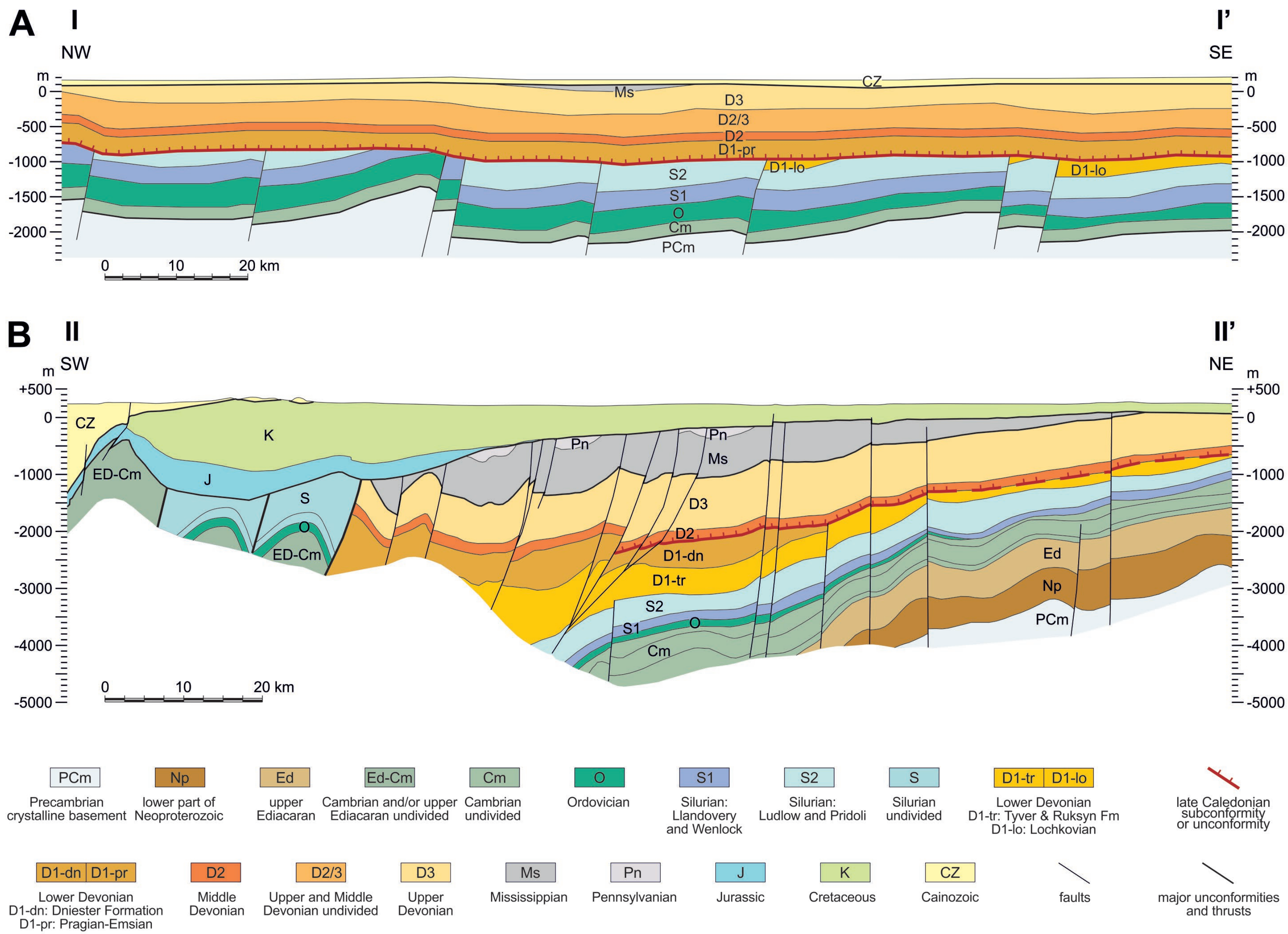


Fig. 12. Geological cross-sections through the western part of the East European Craton with position of the late Caledonian unconformity. **A**. Cross-sections through the eastern part of the Baltic Basin in Lithuania and Latvia (after Poprawa *et al*., 2006b), illustrating post-Lochkovian unconformity. **B**. Cross-sections through the north-western part of the Volyn-Podilia-Moldavia Basin (after Gierasimov *et al*., 2003 and Radkovets *et al*., 2017a, b), modified, illustrating the subconformity at the top of the Lower Devonian. Structure of the Rava Ruska Zone is adopted from the model of Krzywiec *et al*. (2017). For location see Figure 3.

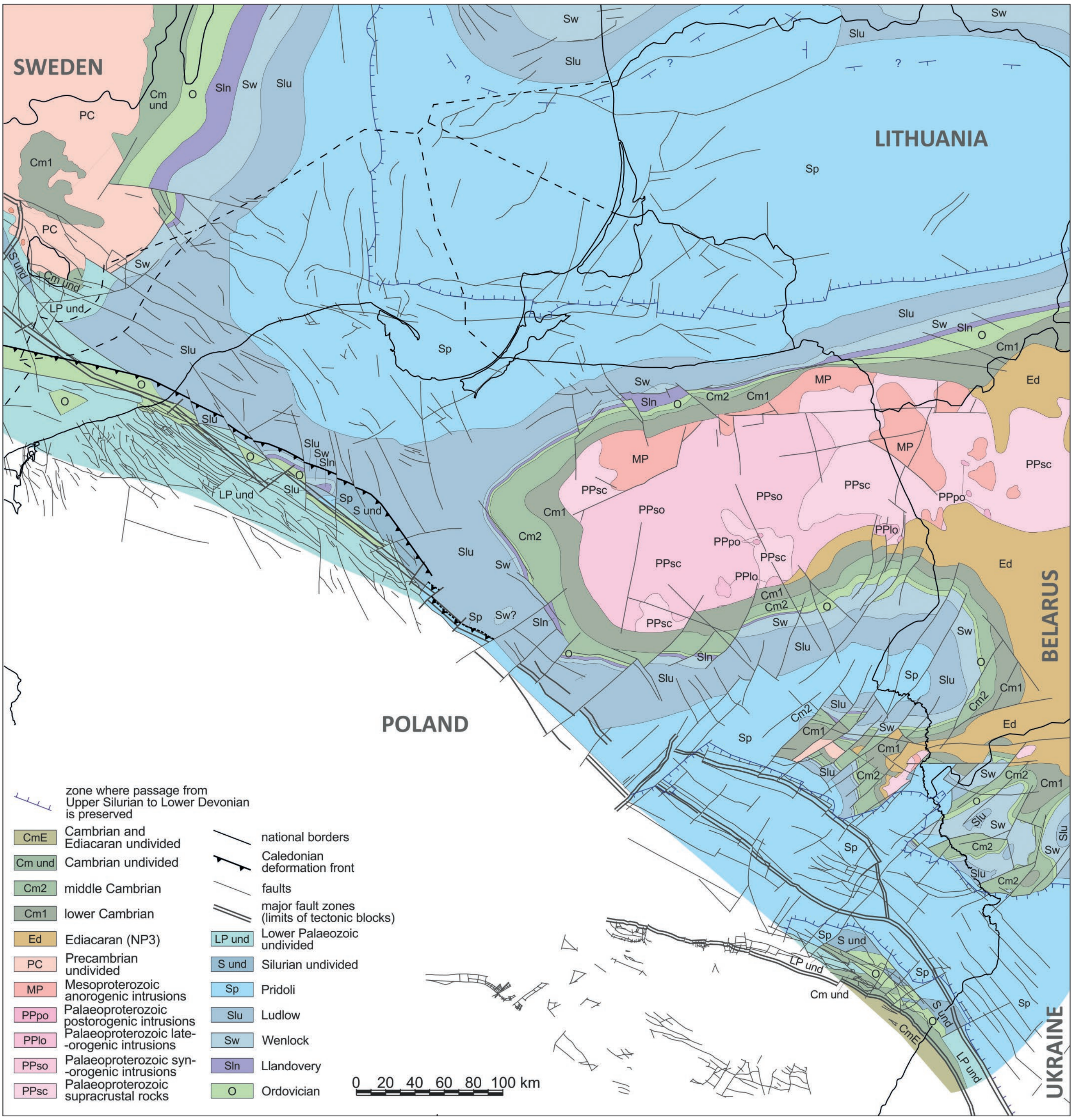


Fig. 13. Geological map of the western part of the East European Craton and surrounding regions without the Devonian and younger strata. Based on maps of Pożaryski and Dębowski (1983), Paškevičius (1997), Stolarczyk *et al*. (2004), Modliński *et al*. (2010), Sopher *et al*. (2016), Krzemińska and Krzemiński (2017), modified and supplemented by the present author.

as the Bretonian uplift (Figs 10, 14; Żelichowski, 1972; Narkiewicz, 2007). The uplift affected the Lublin and Lviv basins and presumably also the Biłograj-Narol Zone, the Podlasie Depression and the Mazury High. Further north, Western Pomerania and the adjacent part of the EEC were not affected by uplift and erosion and sedimentary basins continued to develop there at that time (Fig. 10). A younger, latest Visean to Serpukhovian phase of uplift brought to an end the main phase of development of the Western Pomerania Basin (Fig. 10). This was followed by local deposition of the Pennsylvanian (Bashkirian to Gzhelian) clastic complex (Fig. 15; Matyja, 2006; Kuberska *et al*., 2007).

The Variscan stage of evolution of the area analysed terminated with compressional, tectonic deformation, as well as uplift and denudation of a broad Variscan foreland during the Late Pennsylvanian (Fig. 10). In the Biłgoraj-Narol Zone, the Variscan contraction led to the development of thrust sheets (Krzywiec *et al*., 2017). Following this, during most of the Early Permian (Cisuralian), the study area was subjected to peneplanation. The uplift, erosion and tectonic deformation resulted in an extensive Variscan unconformity,

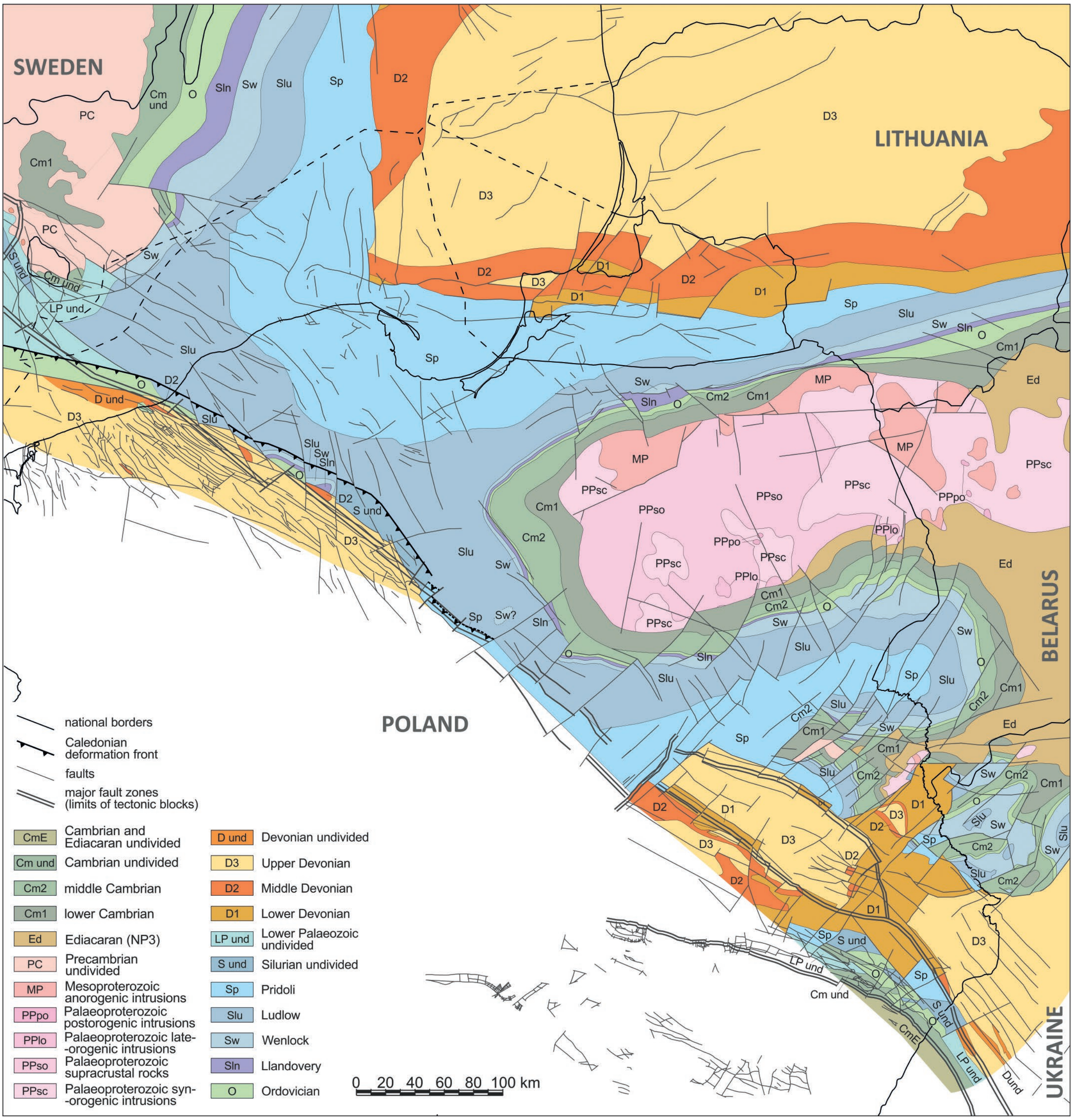


Fig. 14. Geological map of the western part of the East European Craton and surrounding regions without the Carboniferous and younger strata. Based on maps of Pożaryski and Dębowski (1983), Lech (1993), Paškevičius (1997), Stolarczyk *et al.* (2004), Matyja (2006), Modliński *et al.* (2010), Sopher *et al.* (2016), Krzemińska and Krzemiński (2017), modified and supplemented by the present author.

the bottom part of which is presented cartographically in Figure 15.

Since the Late Permian throughout the Mesozoic, the Trans-European Suture Zone in Poland became the site of development of the Polish Basin, being part of the system of Permian–Mesozoic rift basins of northwestern and central Europe (e.g., Ziegler, 1990). The study area became at that time the eastern flank of the basin. The Polish Basin developed, owing to two extension episodes, i.e., the Late Permian and Late Jurassic ones, followed by long periods of thermal sag (Dadlez *et al*., 1995). The area analysed was located to the east of the main depocentre of that basin, referred to as the Mid-Polish Trough, therefore the Late Permian and Mesozoic subsidence was of a limited scale (Fig. 10), governed mainly by the thermal subsidence mechanism. During the Late Cretaceous in the Polish Basin, including its eastern flank, a phase of accelerated subsidence and burial took place (Fig. 10), interpreted as the onset of regional compression, being a far-field effect of the collision phase in the Alpine domain (Dadlez *et al*., 1995).

The Late Cretaceous compressional stress ultimately led to the inversion of the Mid-Polish Trough and subsequent erosion of a newly born Mid-Polish Swell. The cartographic expression of the differential erosion in the basin is presented in Figure 16. Inversion of the Mid-Polish Trough terminated development of the sedimentary basins in the study area, which subsequently became part of a structure, referred to as the Polish Lowlands. During Cainozoic time, only some 100–200 m sediments, mostly continental, with lesser amounts of marginal marine deposits, were laid down in a few individual phases of sedimentation in this region (e.g., Piwocki and Kramarska, 2004; Jarosiński *et al*., 2009).

GEOLOGICAL STRUCTURE OF THE WESTERN PART OF THE EEC

The geological structure of the study area is presented in the present account with a set of geological maps (Figs 13–15), geological cross-sections (Figs 12, 17), lithofacies cross-sections (Fig. 9A–C), a map of the tectonic fabric of the area (Fig. 2), and a structural map for the top of the Caradoc (Fig. 3). The geological maps are based on pre-existing cartographic data, available, however, only for individual zones within the western EEC and adjacent

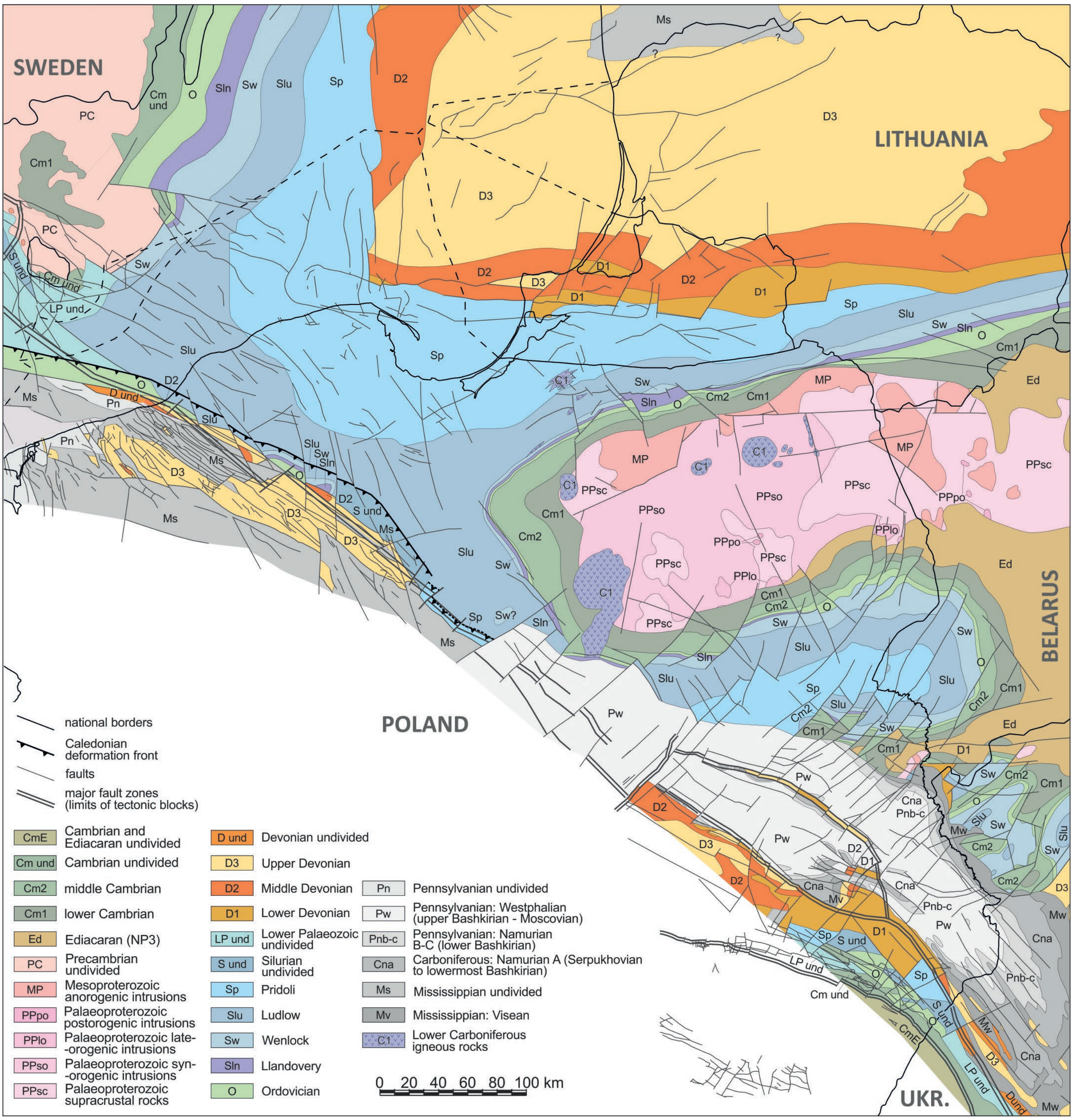


Fig. 15. Geological map of the western part of the East European Craton and surrounding regions without the Permian and younger strata. Based on maps of Pożaryski and Dębowski (1983), Żelichowski and Porzycki (1983), Lech (1993), Paškevičius (1997), Stolarczyk *et al*. (2004), Matyja (2006), Modliński *et al*. (2010), Krzemińska and Krzemiński (2017), modified and supplemented by the present author.

regions. The key data used for the maps and cross-sections were borehole sections and to a lesser degree seismic data, as well as published maps, mainly of Pożaryski and Dębowski (1983), Żelichowski and Porzycki (1983), Lech (1993), Paškevičius (1997), Dadlez *et al*. (2000), Matyja (2006), Stolarczyk *et al*. (2004), Modliński *et al*. (2010), Grigelis (2011), Sopher and Juhlin (2013), Sopher *et al*. (2016), Krzemińska and Krzemiński (2017), and Rosentau *et al*. (2017).

During recent years in Poland, new data, mostly related to hydrocarbon exploration, brought additional constraints for the geological setting of the study area. Among the examples is the BRO Nowe Miasto Lubawskie-01 well (Marathon Oil), the outcome of which was a significant westward shift of the limit of the Mazury High (Fig. 13). The borehole Kraśnik-1 (Chevron) documented the presence of 454 m of Visean sediments in the southern part of the Radom-Kraśnik Elevation (Fig. 15), in general characterized by the absence of Carboniferous sediments. Other examples are the wells Tuszynki-1K and Bajerze-1K (Orlen Upstream), which allowed the identification of Mississippian carbonates in the southern part of the Koszalin-Chojnice Zone, in an area

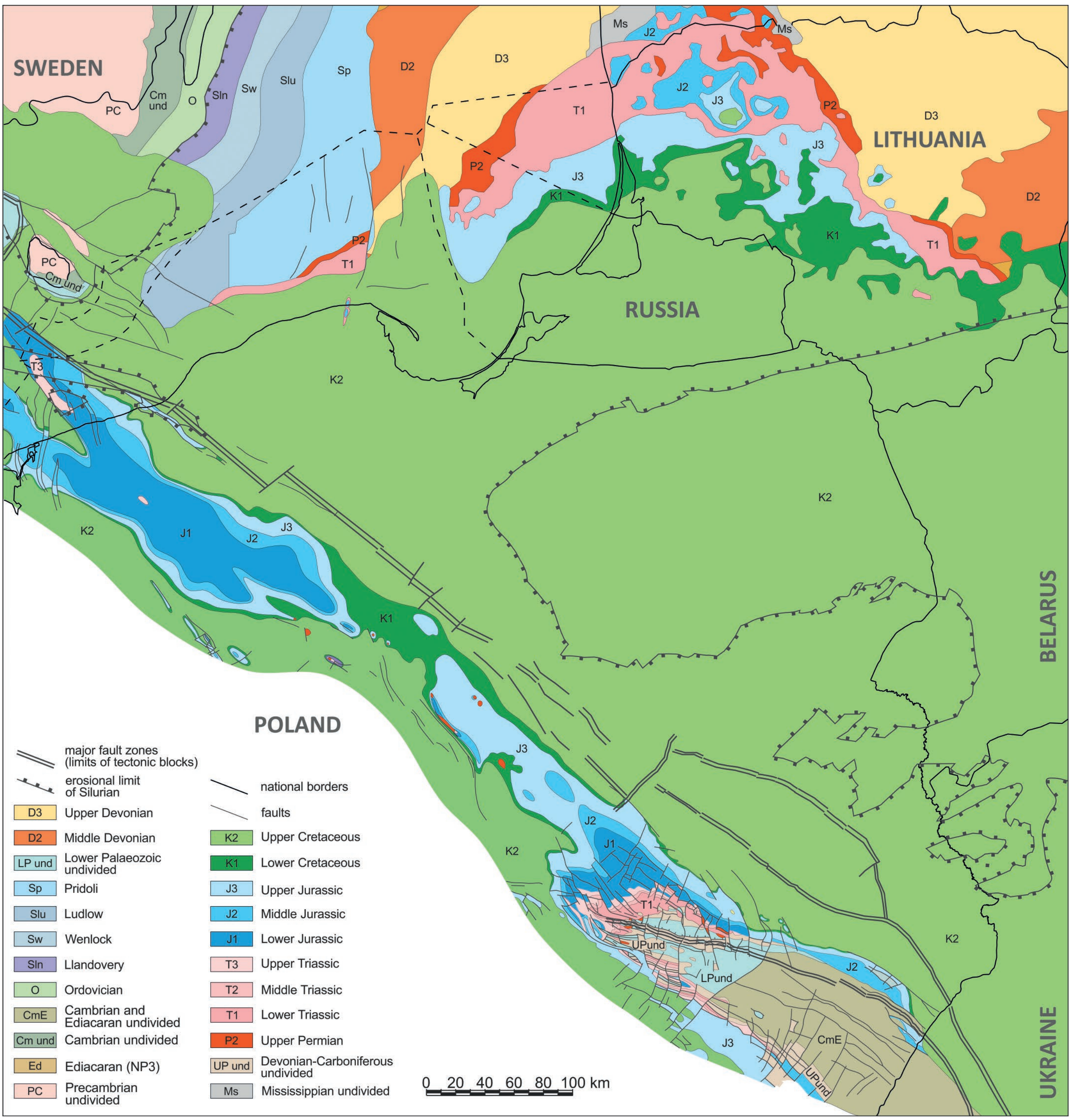


Fig. 16. Geological map of the western part of the East European Craton and surrounding regions without the Cainozoic. Based on maps of Dadlez *et al*. (2000), Grigelis (2011), Sopher and Juhlin (2013), Sopher *et al*. (2016), Rosentau *et al*. (2017), modified and supplemented by the present author.

previously regarded as being without Carboniferous sediments. Moreover, detailed stratigraphic studies of both pre-existing and new exploration wells recently contributed higher stratigraphic resolution for the Ordovician and Silurian than had been obtained traditionally in this region (Fig. 4; Podhalańska, 2017; Porębski and Podhalańska, 2017, 2019).

New seismic data, particularly those of Krzywiec *et al*. (2014, 2017), Mazur *et al*. (2016) and Tari *et al*. (2016), were useful for the preparation of the geological cross-sections (Fig. 17) and also to a lesser degree brought new constraints for the structural map (Fig. 3). Industrial seismic data, acquired for the western EEC during shale gas exploration, allowed refinement of the distribution of the fault network in the study area (Fig. 2).

The general structure of the sedimentary cover at the western slope of the EEC and adjacent areas is well shown on the map of depth to the top of the Caradoc (Fig. 3). The map illustrates the cumulative thickness of the sediments from Ashgill to Recent. The structure presented is an outcome of the development of the Caledonian, the Variscan and the Permian–Mesozoic basins, as well as the phases of inversion, uplift and erosion of them. However, in its northern part, the map mainly shows the structure of the Silurian basin, in the southeastern part (Lublin Basin, Biłgoraj-Narol Zone) predominantly the Silurian and Variscan basin, while in the Małopolska Block, the Cainozoic basin.

The Bretonian phases of uplift and denudation had a significant impact on the structure of the study area. They resulted in the compartmentalisation of the Lower Palae-

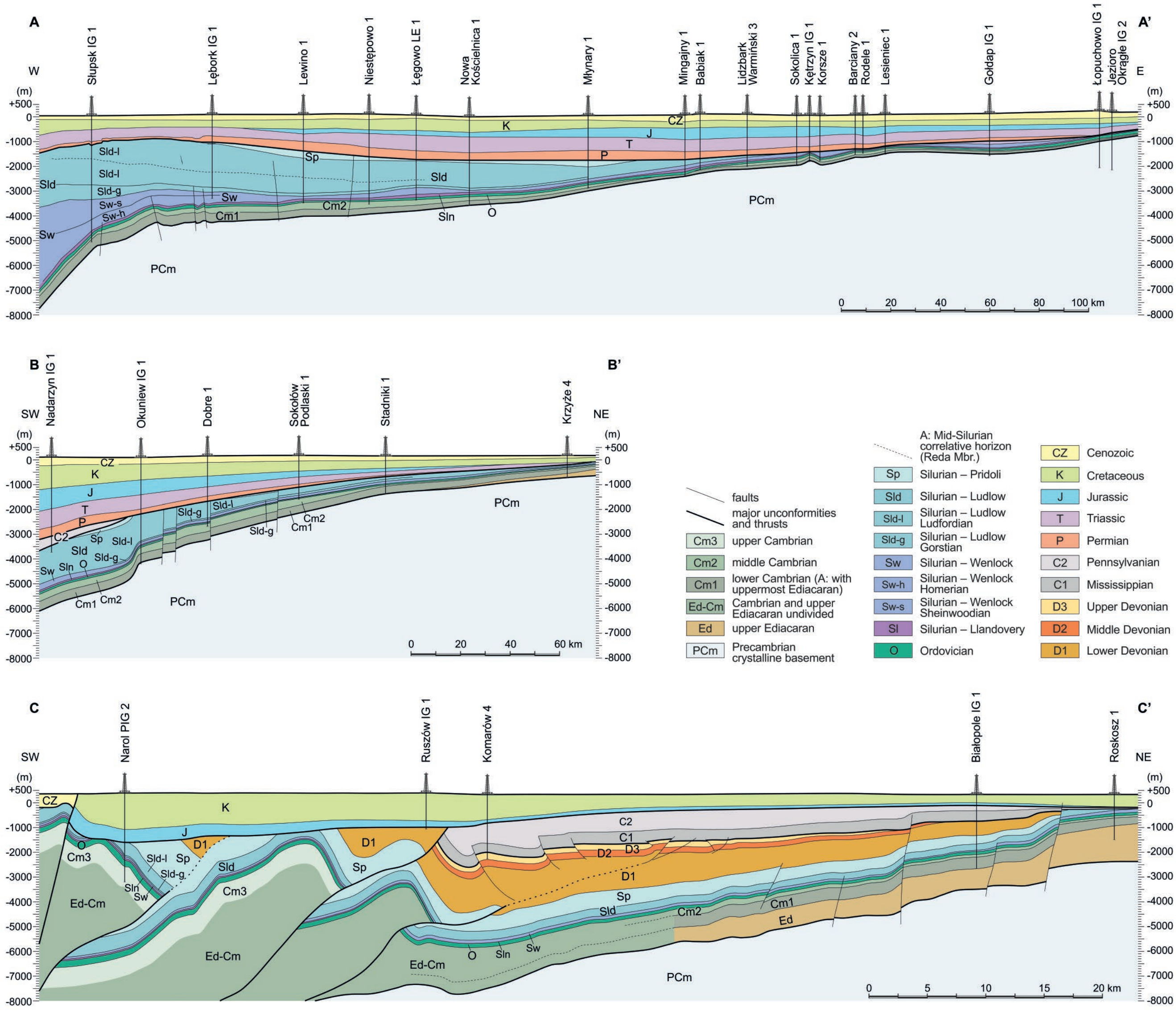


Fig. 17. Geological cross-sections through the Lower Palaeozoic basins on the western slope of the East European Craton. For the location of cross-sections, see Figure 3. **A**. W–E cross-sections through the central onshore Baltic Basin (westernmost part of the section adopts seismic data of Krzywiec *et al*., 2014; Mazur *et al*., 2016, and Tari *et al*., 2016, supplemented); vertical exaggeration X10. **B**. SW–NE cross-sections through the Podlasie Depression; vertical exaggeration X10. **C**. SW–NE cross-sections through the southern Lublin Basin and Biłgoraj-Narol Zone (general geometry and division into systems based on seismic data of Krzywiec *et al*., 2017, supplemented and modified); vertical exaggeration X2.

ozoic complex at the western EEC into the Baltic Basin and the Podlasie Depression, separated by the Mazury High, as well as the Lublin Basin, continuing farther SE as the Volyn-Podilia-Moldavia Basin (Fig. 3). The smooth transition of the above basins from one to the other at the pre-Bretonian stages of their development (Modliński *et al*., 2010) justifies the usage of an alternative nomenclature, which defines the Lower Palaeozoic sedimentary complex of the western EEC as the Baltic-Dniester Basin or Peri-Tornquist Basin. The eastward extent of that system of sedimentary basins increases from the southeast towards the northwest and it becomes widest in the Baltic Basin, where it spreads over roughly 800 km (Fig. 1). The northern limit of the Baltic Basin in Scandinavia is more the result of syn-sedimentary thickness changes, than of post-depositional erosion.

The map of depth to the top of the Caradoc illustrates a general southwestward flexure of the foreland plate, expressed clearly also on cross-sections through the Baltic Basin (Fig. 17A), the Podlasie Depression (Fig. 17B), as well as the Lublin region and the Biłgoraj-Narol Zone (Fig. 17C). The flexure is illustrated also on cross-sections through the NW Volyn-Podilia-Moldavia Basin (Fig. 12B). For the Baltic Basin, a smooth lateral change in the depth to the top of the Caradoc is characteristic, except at its western limit, where a sharp increase in depth over a small distance is governed by a westward increase of the thickness of the Wenlock and Ludlow (Figs 9A, 17A). The flexural profile of the Caledonian foredeep in this region changes significantly with time. After a phase of starved basin development in Caradoc to Llandovery time, the initial, abrupt subsidence, with compensation by rapid deposition, began here in the early Wenlock–Sheinwoodian within a very narrow foredeep (roughly 50 km wide), which continued to develop in this form until the early Ludlow–Gorstian (Figs 9A, 17A). However, since the Ludfordian (late Ludlow), the flexural profile of the Caledonian foredeep was modified considerably and the basin became much broader (> 200 km).

The minor thickness of the Pridoli complex in this zone (Fig. 9A), partly being a result of subsequent erosion, illustrates the transition of the foredeep basin into the terminal phase of its development. In the western part of the Baltic Basin, a pattern of elevation of stratigraphic horizons towards the west seems to have been a consequence of post-Caledonian, isostatic uplift and erosion on a scale of up to roughly 2,000 m, taking place since the Lochkovian. However, owing to the absence of Devonian and Carboniferous sediments, the relative importance of the post-Caledonian and the post-Variscan erosion (Fig. 10) cannot be quantified here. Both phases of erosion and tectonic deformation resulted in the development of the major unconformity, dividing the Lower Palaeozoic complex from the Permian-Mesozoic one.

As a result of both phases of uplift and denudation, the stratigraphic extent of the erosion within the Lower Palaeozoic complex became systematically deeper westwards, as well as northwards and southeastwards (Fig. 13). In the eastern part of the basin, the Lower Palaeozoic is preserved entirely within the western region of Lithuania and Kaliningrad and their offshore sectors, while westwards, i.e., in the central Baltic Basin in Poland, the Pridoli was removed partly by erosion. In the western part of the basin, it is not preserved and the upper part of the Ludlow was eroded, as well (Figs 9A, 13, 17A).

The southwestern part of the Baltic Basin is characterized by the presence of a fault grid, roughly parallel to the TTZ, i.e., mostly NW–SE-oriented and therefore expected to have been induced by the tectonic processes governing the evolution of the Trans-European Suture Zone (Fig. 2). In the eastern and northwestern part of the basin, the pattern of the fault grid is different and the main fault zones are oriented E–W and N–S, respectively (Fig. 2).

To the west of the Baltic Basin, in the Koszalin-Chojnice Zone and the Western Pomerania Basin, the presence of the Devonian–Carboniferous complex allows the determination of the results of the post-Caledonian and the post-Variscan deformation, uplift and erosion, in cartographic terms selectively, as illustrated in Figures 13 and 15. In the Koszalin-Chojnice Zone, Early Devonian erosion removed part or all of the Silurian, so that the Middle Devonian to Mississippian complex rests unconformably on different series of the Silurian or on the Ordovician, depending on the location (Fig. 13). The Western Pomerania and Koszalin-Chojnice zones are also characterised by an extremely dense grid of faults, mainly TTZ-parallel, i.e., oriented NW–SE, and subordinately perpendicular ones, which divide these two units into an array of small tectonic blocks (Fig. 2).

Farther to the southeast, in the Podlasie Depression, the Lower Palaeozoic basin becomes significantly narrower than the Baltic Basin and its eastward extension does not exceed 200 km. The burial depth of the top of the Caradoc increases from east to west in this tectonic unit from less than 500 m to more than 5,000 m (Fig. 3). In this case, the westward flexure of the basement is the cumulative result of a lateral increase of thickness in that direction of both the Permian–Mesozoic complex and the Silurian one (Fig. 17B). In addition, at the western limits of the Podlasie Depression, the Pennsylvanian (Westphalian) unconformably covers the partly eroded Silurian section (Figs 15, 17B). This indicates that erosion of the Lower Palaeozoic and Devonian took place here prior to the Westphalian, presumably during the Bretonian (Early Mississippian) phase of uplift and denudation (Fig. 10).

The characteristic feature of the Silurian section in this unit is a different development of the Caledonian flexure in comparison to the western Baltic Basin, displaying significant diachronism in the development of the foredeep basin in the western EEC. The Sheinwoodian to Gorstian deep and narrow foredeep, observed in the western Baltic Basin, is not present here. The phase of rapid subsidence, compensated by deposition, commenced only in Ludfordian time in the western part of the Podlasie Depression within a foredeep with a broad, eastward extension (Figs 9B, 17B). The Ludfordian phase of Caledonian foredeep basin development is, therefore, similar in the Baltic Basin and the Podlasie Depression. The Pridoli is not preserved in the northern part of the Podlasie Depression (Fig. 13).

In the Lublin region, the Lower Palaeozoic basin narrows to a few tens of kilometres (Fig. 3). Its eastern limits are erosional and the depth to the top of the Ordovician increases systematically across the area to the SW. In terminology that is appropriate for the Ediacaran–Lower Palaeozoic complex, this part of the basin analysed is referred to alternatively as the Lublin slope of the EEC. Strong compartmentalisation of that zone into individual tectonic blocks and a dense grid of faults, mainly oriented NE–SW, are shown in Figures 2 and 3. The Lublin slope of the EEC is delimited in the west by the Kock Fault Zone, west of which the Lublin Trough developed (Fig. 2). The latter is characterised by a very great thickness of the Upper Devonian; this is why the Lower Palaeozoic complex has never been reached by borehole. However, on the basis of reconstructed, synthetic sections, the depth to the top of the Caradoc in the Lublin Trough is estimated as 5,000–8,000 m (Fig. 3).

In the southern part of the Lublin region, the Kock zone and the Lublin Trough terminate and the Lublin slope of the EEC is juxtaposed directly against the Biłgoraj-Narol zone along a fault zone that is a Variscan frontal thrust (Fig. 3). The Biłgoraj-Narol Zone, continuing in Ukraine as the Rava Ruska Zone, has the character of a pile of Variscan thrust sheets (Figs 12B, 17C; Krzywiec *et al*., 2017). Thrust stacking in this zone resulted in uplift of the Lower Palaeozoic complex, erosion of the Devonian and Carboniferous overburden, and, therefore, a small recent burial depth of the top of the Caradoc (Fig. 3).

The geological cross-section though the southern Lublin region and adjacent Biłgoraj-Narol Zone (Fig. 17C) demonstrates the deformation of the latter unit, on the basis of the interpretation of seismic data by Krzywiec *et al*. (2017). Moreover, it illustrates the progressive diachronism of the Caledonian foredeep basin. In each of the units mentioned above, the scale of subsidence and the thickness of individual series or stages were very limited prior to the Ludfordian (Figs 9C, 17C). The phase of rapid subsidence of the basin commenced in the Ludfordian, as in the Podlasie Depression, although here it was on a significantly smaller scale. The main phase of the foredeep basin subsidence continued in Pridoli time, particularly in the Lublin-Podlasie Basin and to a lesser degree also in the Biłgoraj-Narol Zone (Fig. 9C).

The three cross-sections analysed (Fig. 17) also illustrate some regional principles for the development of the Cambrian and Ediacaran successions on the western EEC. In the Baltic Basin, the Podlasie Depression and the Lublin region, the Cambrian is characterised by a gradual increase in its thickness towards the southwest (Fig. 17A–C), consistent with the model of post-rift thermal-sag subsidence, related to the Ediacaran rifting at the western margin of the newly developing Baltica. However, the thickness of the Ediacaran in the southern Lublin region increases from SW to NE (Fig. 17C), i.e., towards the main axis of the Orsha-Volyn Ediacaran rift zone, perpendicular to the TESZ.

In the southern part of the western EEC, south of the Baltic Basin, there were two major phases of tectonic deformation, uplift and erosion, i.e., Early Mississippian (Bretonian) and post-Variscan (Late Pennsylvanian). Their consequences for the geological setting of the study area could be illustrated by the juxtaposition of Figures 14 and 15. The Bretonian phase was characterised by compartmentalisation of the area into individual blocks, limited by NW–SE and NE–SW systems of faults (Fig. 14). The degree of uplift varied significantly between the blocks and as a result of this, the downward stratigraphic extent of erosion varied, too. As a consequence, the Carboniferous sediments rest unconformably on different Devonian, Silurian, Ordovician, Cambrian, Ediacaran, and Middle Proterozoic units (Fig. 14). The amount of denudation is highly variable laterally, though it could reach a significant scale (up to approx. 3,000 m).

In contrast, the Late Pennsylvanian phase of uplift and erosion resulted in the development of large, narrow syncline structures, regional in scale and with a NW–SE elongation (Fig. 15), consistent with the model of late Variscan contraction and compressional deformation of the foreland. In general, the amount of denudation during this phase of uplift was considerably lower than is the case for the Bretonian phase.

West of the Biłgoraj-Narol Zone and the Łysogóry Block, the Lower Palaeozoic sediments are preserved on the Małopolska Block only as erosional patches of an originally more extensive sedimentary cover (Fig. 2). On this block, an increase of the depth to the top of the Caradoc towards the south (Fig. 3) is primarily an expression of its burial beneath the Miocene Carpathian Foredeep Basin and in the southern part also beneath the Outer Carpathian thrust sheet pile.

In the northern part of the Volyn-Podilia-Moldavia Basin, the regional, structural style continues from the southern Lublin slope of the EEC and is characterised primarily by a southwestward flexure, although the Lower Palaeozoic Basin becomes wider there (Figs 3, 12B). In this region, the southwestward increase of the depth to the top of the Caradoc seems to be smoother than farther north, although it might be an apparent consequence of the lower resolution of the geological data, namely of lesser density of modern seismic data and deep boreholes. The division between the Lublin-Podlasie Basin and the Volyn-Podilia-Moldavia Basin is, as in the case for the Devonian–Carboniferous complex, purely cultural and does not have any geological rationale.

The entire study area was unconformably covered with the Permian or Mesozoic sediments of the eastern flank of the Polish Basin, which achieved its broadest extent during the Late Cretaceous. Subsequently, it became subjected to the Laramian inversion and selective uplift and erosion, giving the origin of the Mid-Polish Trough, located directly west of the TTZ. Along the Mid-Polish Trough, the entire Upper Cretaceous cover was removed (Fig. 16). In the northern and central parts of this structure, erosion removed additionally the Lower Cretaceous and part of the Jurassic section, while in the southeastern part in the Małopolska Block also the entire Mesozoic and part or all of the Palaeozoic were removed. The study area was not affected by the Laramian uplift and all or most of the Upper Cretaceous cover is preserved there (Fig. 16).

LOWER PALAEOZOIC OF THE WESTERN EEC VERSUS THE KOSZALIN-CHOJNICE AND BIŁGORAJ-NAROL ZONES

The geological setting of the Lower Palaeozoic complex in the zones, located directly west of the EEC, is recognised only locally, owing to its generally great burial depth within the Trans-European Suture Zone. In the study area, it occurs primarily in the Koszalin-Chojnice Zone and the Biłgoraj-Narol Zone (see Fig. 2 for location). It is well documented also in the outcrops of the Holy Cross Mountains and the shallow wells nearby; however, these locations are beyond the scope of the current study. The sedimentary record of the Koszalin-Chojnice and Biłgoraj-Narol zones remains a key constraint for a model of the Early Palaeozoic evolution of the western EEC.

Both units have, to some extent, similar characteristics in relation to the Lower Palaeozoic cover of the western EEC. They are located directly to the west of the traditionally defined western margin of the EEC (Fig. 2). During the Ordovician and Early Silurian, they accumulated sediments of greater thickness than their equivalents in the western EEC, although in the later part of Silurian these proportions were reversed (Figs 8, 9). The facies of the Ordovician–Silurian sediments of both zones are generally more proximal in relation to the sediment source area than their equivalents in the Baltic-Dniester Basin and are of generally deeper sedimentary environments. Nonetheless, in both the zones, irrespective of the apparent differences, the affinity of the Ordovician–Silurian facies to the sedimentary cover of the EEC is evident. They are also characterised by a significantly higher degree of tectonic deformation than the Baltic Basin and the Lublin-Podlasie Basin (Fig. 2).

In terms of Lower Palaeozoic geology, the Koszalin-Chojnice Zone can be associated with the adjacent Rügen Zone, both having a model of geological evolution consistent with that of the Baltic Basin. In the Koszalin-Chojnice and Rügen zones, the rocks of each Ordovician stage have a thickness at least one order of magnitude higher than in the Baltic Basin. The zones together represent an amalgam of the sedimentary cover in the active continental margin of Avalonia and that in the proximal part of the Caledonian foredeep basin at the western slope of the EEC (e.g., Giese *et al*., 1994; Poprawa, 2006b). The upper Tremadocian to lower Arenig (lower Floian) complex in the Rügen Zone is represented by fine-grained sandstone, greenish, brownish and grey shale and greywacke (Fig. 5), the stratigraphic thickness of which is in the order of 400 m (Giese *et al*., 1994; Podhalańska and Modliński, 2006). Their equivalent in the Baltic Basin is a hiatus or several metres of shallow-marine shale (Fig. 8).

The Middle Ordovician (Dapingian and Darriwilian; Fig. 4) of the Rügen Zone in its lower part is a dark claystone, more than 500 m thick, with thin mudstone interbeds (Jaeger, 1967), while the upper part is a dark grey and greenish shale with a thickness of roughly 500–1,000 m and with greywacke interbeds (Jaeger, 1967; Servais, 1994). In the Koszalin-Chojnice Zone, grey to dark grey claystone and mudstone are documented in the upper part of the Middle Ordovician (Podhalańska and Modliński, 2006), the stratigraphic thickness of which is at least 380–400 m (Fig. 8; Poprawa, 2006b). Their Middle Ordovician stratigraphic equivalent on the western slope of the EEC is shallow-marine limestone, several to a few tens of metres thick (Figs 8, 9; Modliński and Szymański, 1997).

The Caradoc of the Koszalin-Chojnice Zone is a greyish to dark greenish mudstone and claystone with interbeds of sandstone, dolomite and siderite (Podhalańska and Modliński, 2006). Its stratigraphic thickness is at least 500 m and could reach even 1,000 m (Figs 8, 9; Poprawa, 2006b). During the same time, in the western Baltic Basin, a few tens of metres of black shale were deposited (Modliński and Szymański, 1997). The Ashgill of the western EEC is represented by 5–20 m of marls (Podhalańska and Modliński, 2006), while the stratigraphic thickness of their shale equivalent in the Koszalin-Chojnice Zone is at least 100 m (Figs 8, 9; Poprawa, 2006b).

There is also a distinctive difference between the development of the Llandovery in the western EEC and in the Koszalin-Chojnice Zone (Figs 8, 9). In the first region, it is represented by a few tens of metres of dark claystone-dominated shale, in the bottom part mainly bituminous, deposited in a starved basin. In the latter region, a mudstone with sandstone inter-beds was observed (Podhalańska and Modliński, 2006), with a stratigraphic thickness that exceeds 400 m (Poprawa, 2006b).

A significant change in the tectonic relationship between the Koszalin-Chojnice Zone and the Baltic Basin took place during the early Wenlock (Sheinwoodian). There are uncertainties as to the original stratigraphic thickness of the Sheinwoodian in the first zone, since an incomplete profile of these sediments was recognised in only two wells (Podhalańska and Modliński, 2006). Nonetheless, there is no indication of a greater thickness of the Sheinwoodian strata in the Koszalin-Chojnice Zone than in the Baltic Basin (Figs 8, 9). The contrast in facies between the two zones also diminished during the early Wenlock.

Similar characteristics continue upsection. The Homerian, Gorstian and Ludfordian stages are characterised by a significantly greater thickness of deposits in the Baltic Basin in comparison with those of the Koszalin-Chojnice Zone, as well as by the absence of any significant facies contrast between these two zones (Figs 8, 9). This trend apparently terminated in the Pridoli, which in the Baltic Basin is preserved as an incomplete section only in its central part (Fig. 13); therefore, it is difficult to constrain the relationship of the Pridoli thickness in the two zones discussed.

The relationship between the Biłgoraj-Narol Zone and the Lublin slope of the EEC is generally similar in character. Some of the Ordovician stages attain in the first zone a greater thickness than in the Lublin region, although in this case the difference in thickness is not as great as in the case of the Koszalin-Chojnice Zone and the Baltic Basin (Figs 8, 9). The Biłgoraj-Narol Zone and the Lublin slope of the EEC differ in particular in the thickness of the Lower Ordovician strata. For the Tremadocian, it is equal to roughly 60–110 m and 20–40 m, respectively (Figs 8, 9), while for the Floian and Dapingian (~Arenig; Fig. 4) it is up to 80 m in the first zone, but in the latter it does not exceed 10 m

(Modliński *et al*., 2010). Moreover, the Lower Ordovician in the both zones exhibits contrasts in facies development. A higher proportion of shale to limestone and sandstone is characteristic for the Koszalin-Chojnice Zone, whereas in the Lublin region sandstone and carbonate facies predominate (Figs 8, 9). Similar differences in facies development between the two zones were observed for the Darriwilian.

Comparable thickness differences characterise also the Caradoc of the Biłgoraj-Narol Zone and the Lublin region, which in the first zone is on average 130–140 m, while in the latter it does not exceed 50–60 m. This is also associated with facies differences between the two zones, with a deeper environment in the first zone, characterised by the presence of mainly shale and marl, compared with carbonate-rich, shallow-marine deposits in the latter (Figs 8, 9). The thickness of the Ashgill strata is in a similar range in both zones.

During the Llandovery, the two zones still provided contrasts, both in terms of cumulative sediment thickness and facies development. In the Biłgoraj-Narol Zone, the Llandovery, developed as a shales facies, is roughly 50 m thick, while in the southern Lublin region, marls of the same age are less than 10 m thick. The Wenlock facies and their thickness are comparable in both zones. A greater thickness of sediments was deposited in the Biłgoraj-Narol Zone compared with the southern Lublin region and this is observed also for the Ludlow (Figs 8, 9), both Gorstian and Ludfordian, which in the first zone is 600–850 m, while in the latter it is roughly 300 m or less (Modliński *et al*., 2010).

For the Pridoli, the proportions of the sediment thickness referable to the two zones are reversed (Figs 8, 9). In the Biłgoraj-Narol Zone it is a maximum of 210 m, while in the southern Lublin region, the thickness increases westwards to nearly 1,000 m. However, in the first zone, the thickness of the Pridoli was reduced by erosion to some extent, so their original thickness contrast was somewhat lower.

LUBLIN-BALTIC MISSISSIPPIAN IGNEOUS PROVINCE

One of characteristic features of the western EEC is the presence of extensive igneous bodies. The magmatic activity took place in two phases. The first one was the late Ediacaran emplacement of large amounts of flood basalts and pyroclastics in the Volyn Igneous Province (Fig. 6), characterised in previous paragraphs and broadly discussed in the literature (e.g., Juskowiakowa, 1971; Ryka, 1984; Velikanov and Korenchuk, 1997; Białowolska *et al*., 2002; Emetz *et al*., 2004; Krzemińska, 2005; Shumlyanskyy *et al*., 2007, 2016; Środoń *et al*., 2019).

The second phase of igneous activity, which so far has attracted less scientific attention, took place during the Mississippian. The igneous rocks of this age in the western EEC were observed and studied separately in a few individual regions, the relations of which remained ambiguous.

In the southern and eastern parts of the Lublin Basin, the volcanic rocks, tuffo-lavas and tuffites historically were identified in the bottom part of the Carboniferous section at several locations (e.g., Żelichowski, 1983, 1987; Porzycki, 1988). The dense grid of boreholes in this region allowed the mapping of a few volcanic flood bodies (comp. Żelichowski, 1983), the location of which often is related to the presence of major fault zones (Fig. 18), allowing magma to migrate upwards within the crust and its sedimentary cover. These volcanic rocks are classified as foidites, tephrites and basanites and trachybasalts (Grocholski and Ryka, 1995). Their genetic relationship to igneous activity in the Dnieper-Donets and Pripyat Basins was postulated by Narkiewicz *et al*. (1998b). Alkaline basalts from the eastern part of the Lublin Basin have yielded Ar-Ar plateau ages of 338.5 ± 0.7 Ma to 348.2 ± 0.8 Ma, allowing the dating of these rocks as upper Tournaisian to middle Visean (Pańczyk and Nawrocki, 2015).

Carboniferous igneous bodies were studied more intensively in the region of the Mazury High. In this area, a few large alkaline and carbonatite intrusions were formed (Juskowiak, 1973; Krystkiewicz and Krzemiński, 1992; Ryka, 1994; Krzemińska *et al*., 2006; Krzemińska and Krzemiński, 2012), including the Pisz massif (gabbro-syenite), the Ełk massif (syenite), the Tajno body (alkaline-ultramafic clinopyroxenite cumulates and syenites with carbonatite veins) and the Mława massif (syenite). The lateral extent of the individual intrusions (Fig. 18), covered with Permian–Mesozoic–Cainozoic sediments, was constrained by sparse boreholes and by a magnetic survey (Kubicki and Ryka, 1982; Wybraniec and Cordell, 1994; Krzemińska and Krzemiński, 2012, 2017; Petecki and Rosowiecka, 2017). The intrusions mentioned above yielded zircon U-Pb ages in the range of 345.5 ± 7.9 Ma to 348.0 ± 15 Ma, equivalent to Tournaisian (Krzemińska *et al*., 2006; Demaiffe *et al*., 2013) and therefore roughly coeval with the Lublin Basin volcanism.

Further north, Mississippian igneous intrusions were studied in the central and eastern parts of the Baltic Basin in the Baltic offshore of Lithuania and Russia. In this region, dolerite sills were recognised in the sections of a few boreholes, as well as on magnetic data and industrial reflection-seismic data (Fig. 18; Motuza *et al*., 1994, 2015; Kharin and Eroshenko, 2014). The 351 ± 11 Ma $^{40}Ar/^{39}Ar$ plateau age of the dolerite sill in the Baltic offshore (Motuza *et al*., 2015) indicates an age of magmatic activity consistent with the cases of the Mazury High and the Lublin Basin discussed above.

The Mississippian igneous activity at the western EEC was accompanied by the formation of volcaniclastic sediments, particularly in the basin developed in the eastern part of the TESZ, adjacent to the EEC. A volcaniclastic, arkosic arenite formation of great thickness (>400 m), supplied with detritus from the erosion of trachytes and alkaline rhyolites, was documented by Krzemiński (1999) in the segment of the TESZ to the west of the northern part of the Lublin Basin. Further north, a similar arkosic sandstone, with subordinately interbeds of tuffites, is recognised in the Western Pomerania Basin (Muszyński *et al*., 1996; Matyja, 2008). The Western Pomerania volcaniclastic formation, with a maximum thickness of 370 m, created a clinoform decreasing in thickness westwards, clearly indicating the supply of detritus from the EEC (Matyja, 2008). Since the volcaniclasts in both regions have not undergone any significant alteration, the stratigraphic age of the sediment is the approximate time

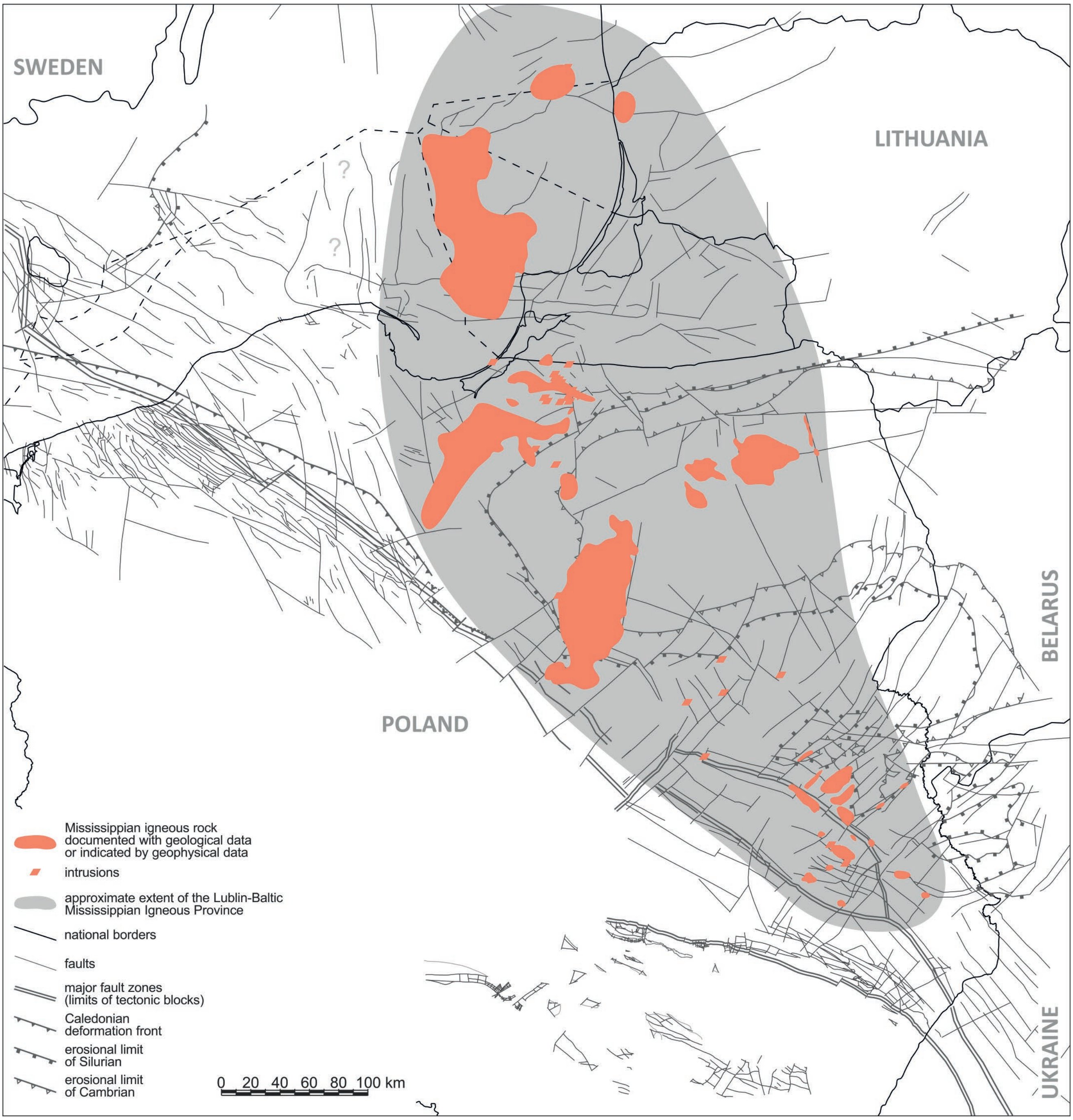


Fig. 18. Extent of the Lublin-Baltic Mississippian Igneous Province on the western slope of the EEC.

equivalent of the igneous activity within the provenance area. The Western Pomerania volcaniclastic sandstone is of middle Tournaisian age (Matyja, 2008). In the previous case, the stratigraphic precision is lower, although a Tournaisian age is also possible (Krzemiński, 1999).

The studies mentioned above, scattered over a large part of the western EEC, were supplemented with the analysis of the lithological sections of boreholes, carried out in the present research. Numerous additional boreholes with igneous intrusions, tuffs/tuffites and volcaniclasts were identified. Where volcanic rocks are interbedded with sediments, tuffs/tuffites and non-weathered volcaniclasts, biostratigraphic dating is conclusive for the age of the igneous activity. However, many of igneous intrusions, recognised in the study area, are without direct, geochronological constraints. Nonetheless, owing to the general lack of any other post-Ediacaran igneous activity in the part of the western EEC analysed, any intrusion identified in the Cambrian to Devonian section were regarded as being Mississippian in age.

All observations on the presence of Mississippian igneous activity in the western EEC were combined in Figure 18. The numerous igneous intrusions and volcanic bodies, recognised directly in borehole sections or indirectly from geophysical data, occur in the central and northern Lublin

Basin, the Podlasie Depression, the Mazury High, and also in the central and eastern Baltic Basin (Fig. 18). In all these areas, the scarce geochronological data for the igneous bodies and stratigraphic constraints for the volcaniclastics and tuff/tuffites indicate a Tournaisian age for the main phase of igneous activity. Therefore, the igneous rocks in the western EEC, presented on Figure 18, are regarded here as co-genetic.

The combined data allow recognition of a region, characterised by Mississippian igneous activity, in the present study referred to as the Lublin-Baltic Mississippian Igneous Province (LBMIP). The origin of the igneous activity remains ambiguous, though the location of the LBMIP roughly along the eastern limit of the TESZ, less clear towards the north, indicates its connection to the tectonic processes within the zone, rather than to igneous activity in the Dnieper-Donets and Pripyat Basins. Therefore, the igneous activity in the western EEC might be related to an extensional tectonic regime within the TESZ, which in its Pomeranian sector is constrained by subsidence analysis (Narkiewicz *et al*., 1998b) and seismic data (Poprawa *et al*., 2018b, and references therein). This conclusion is supported by geochemical evidence, indicating an intra-continental rift origin of the igneous intrusions and volcanoclastics in the study area (e.g., Krzemiński, 1999; Motuza *et al*., 2015).

CONCLUSIONS

The geological setting of the sedimentary basins, developed on the western slope of the EEC, is documented here with a set of geological maps, geological cross-sections, a structural map for the top of the Caradoc and a tectonic fabric map. The structure of the study area was shaped by several phases of Ediacaran–Phanerozoic subsidence and the development of Caledonian, Variscan and Permian–Mesozoic basins, as well as phases of deformation, uplift and erosion, as products of the tectonic evolution of the nearby Trans-European Suture Zone.

The Ediacaran–Lower Palaeozoic sedimentary basin on the western slope of the EEC, the main focus of the present account, was one of the most extensive basins of that age worldwide, extending in a NW–SE direction between the Black Sea and the North Sea for more than 2,000 km. It originated during the late Ediacaran phase of extension and rifting and was related to the latest stages of breakup of the Precambrian super-continent, Rodinia/Pannotia. This process ultimately led to the opening of the Tornquist Ocean and subsequently from the latest Ediacaran to the Middle Ordovician, the SW margin of the newly formed Baltica became a passive continental margin.

The model of post-rift thermal sag of the passive margin does not explain the late Cambrian development of the southern Lublin region and the adjacent Biłgoraj-Narol Zone and Łysogóry Block. The deposition of a sandstone-dominated succession of great thickness in the two last-mentioned units and the coeval compressional deformation of the nearby Małopolska Block indicate the foredeep nature of the upper Cambrian depocentre, associated with docking of the Małopolska Block to the western margin of Baltica.

Since Late Ordovician through Silurian, a gradual change to a collisional, tectonic setting is observed across the entire SW margin of Baltica and zones adjacent to it in the west. This became the site of development of the extensive Caledonian foredeep basin, related to the convergence and collision of Avalonia and Baltica. The oblique character of the collision resulted in prominent diachronism in the development of the foredeep basin, becoming younger towards the SE. The diachronism refers to the initiation of basin subsidence, the starved basin phase, the main phase of rapid subsidence and the supply of detritus from the west, and the termination of basin development.

During the initial stage of foredeep development in the Caradoc, the Koszalin-Chojnice Zone experienced very rapid subsidence and deposition, due to tectonic loading, while in the central and western Baltic Basin, a starved basin accumulated bituminous shale. By the Llandovery, the starved basin expanded eastwards and southeastwards to the eastern part of the Baltic Basin and the Podlasie Depression, while the main foredeep depocentre still was located in the Koszalin-Chojnice Zone.

From the Sheinwoodian (early Wenlock) until the Gorstian (early Ludlow), significant tectonic restructuring of the foreland of the collision zone took place and the main foredeep depocentre migrated eastwards to the position of the western Baltic Basin. At the same time, subsidence and accumulation of sediments in the Koszalin-Chojnice Zone slowed down, presumably owing to the collision-related, compressional, tectonic regime. During the Sheinwoodian, the zone of organic-rich shale deposition, characteristic of a starved basin, was shifted farther southeast to the Lublin-Podlasie Basin and the northern part of the Volyn-Podilia-Moldavia Basin.

Beginning with the Ludfordian (early Ludlow), the flexural profile of the Caledonian foredeep changed significantly and the main depocentre become much wider. At that time, the zone of rapid subsidence expanded significantly southeastwards to the Lublin-Podlasie Basin and the Biłgoraj-Narol Zone. In the Lublin-Podlasie Basin, the main phase of foredeep development continued to the Pridoli, while in the Baltic Basin the coeval sediments are of much lesser thickness. In the southern part of the western slope of the EEC, the foredeep basin subsidence continued until the Lochkovian.

During the late Lochkovian, Caledonian collision-related compressional stress induced foreland plate deformation, represented by a system of reverse faults and uplift and erosion on a limited scale, as well as development of the regional, late Caledonian unconformity, characteristic for the central and eastern Baltic Basin. The late Caledonian subconformity also developed locally later in time in the NW part of the Volyn-Podilia-Moldavia Basin, most probably during the late Emsian.

Development of the Devonian–Carboniferous basins and Variscan phases of deformation, uplift and erosion, affected the structure of the western EEC significantly. This is particularly true for the early Mississippian (Bretonian) phase of uplift and erosion, which caused compartmentalisation of the area into individual blocks, characterised by a highly variable, though in some cases, very significant scale of denudation.

The Bretonian uplift was followed by a phase of regionally extensive igneous activity during the Tournaisian. Compiled observations allowed the recognition of the presence of the Lublin-Baltic Mississippian Igneous Province in the central and northeastern parts of the western EEC. Its origin here tentatively is related to the coeval extension in the adjacent part of the TESZ.

Areas to the west of the EEC lack Bretonian deformation and denudation and in the Western Pomerania Basin the main Variscan phase of uplift and erosion took place at the turn of the Mississippian and Pennsylvanian. The ultimate phase of Variscan uplift and erosion in the Late Pennsylvanian, related to the contraction and compressional deformation of the Variscan foreland, resulted in the development of an extensive, regional unconformity. In the western EEC, south of the Baltic Basin, the scale of denudation in the Late Pennsylvanian was generally smaller than that during the Bretonian. During Permian–Mesozoic time, the entire study area was covered with the sediments of the eastern flank of the Polish Basin.

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