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PALAEOZOIC PALAEOGEOGRAPHY OF THE EAST EUROPEAN CRATON (POLAND) IN THE FRAMEWORK OF GLOBAL PLATE TECTONICS

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Abstract: Global palaeogeographic maps were constructed for eight time intervals in the Palaeozoic. The maps contain information concerning plate tectonics and palaeoenvironment during the Cambrian, Ordovician, Silurian, Devonian and Carboniferous. The East European Craton belonged to the Palaeozoic Baltica Plate, which originated as a result of disintegration of the supercontinent Pannotia during the early Cambrian. Baltica included part of Poland and adjacent areas northeast of a line that extends between Scania and the Black Sea. This plate was located in the Southern Hemisphere and drifted northward during Early Palaeozoic time. The Early Ordovician was the time of maximum dispersion of continents during the Palaeozoic. Avalonia probably started to drift away from Gondwana and moved towards Baltica during Ordovician time. Between Gondwana, Baltica, Avalonia and Laurentia, a large longitudinal oceanic unit, known as the Rheic Ocean, was formed. Avalonia was probably sutured to Baltica by the end of the Ordovician or in the Early Silurian. This process was dominated by the strike-slip suturing of the two continents, rather than a full-scale continent-continent collision. Silurian was a time of Caledonian orogeny, closing of the Early Palaeozoic oceans, collision of Baltica with Avalonia and Laurentia and the assembly of the supercontinent Laurussia. The Variscan orogeny in Poland was caused by the collision of the Bohemian Massif plates and the Protocarpathian terrane with Laurussia. The Protocarpathian terrane acted as an indentor that caused thrust tectonics in the East European Platform, Holy Cross Mountains and the Lublin area.

Key words: Palaeozoic, Baltica, Avalonia, Gondwana, Laurussia, plate tectonics.

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INTRODUCTION

Global palaeogeographic maps were constructed in order to aid research on the exploration potential of the Lower Palaeozoic organic-rich shales. The global maps are based on the Polish version (Golonka *et al.,* 2017a) that used the work of Golonka and Gawęda (2012), modified to include recent geological results (Golonka *et al*., 2015, 2017b; Barmuta *et al*., 2016; Botor *et al*., 2017a, b, c; Dziadzio *et al*., 2017; Kędzior *et al*., 2017; Krzywiec *et al*., 2017; Papiernik *et al*., 2017; Poprawa, 2017; Porębski and Podhalańska, 2017, 2019; Skompski and Paszkowski, 2017; Stadnik *et al*., 2017, 2019; Stypa *et al*., 2017; Wendorff, 2017; Mazur *et al*., 2018a, b; Kasperska *et al*., 2019), acquired from a Lower Palaeozoic subcrop belt in the East European Craton (EEC) in Poland (Figs 1–5). The maps portray the large-scale palaeogeography of the EEC during the Cambrian, Ordovician, Silurian, Devonian and Carboniferous and place this area within the Earth's geodynamic evolution, showing spreading centres, the origin and closure of oceans, continental collisions and the assembly of new supercontinents. The palaeotectonic-palinspastic results provide the rational circumstances for the successful prediction of intervals enriched in organic matter and open new fields for interregional correlation. In particular, they will allow researchers to place local geology within its proper palaeogeographic

Fig. 1. Sketch map of main tectonic units of sub-Permian basement of Poland and surrounding area (after Mazur and Jarosiński, 2006; Nawrocki and Poprawa, 2006; Mazur *et al.*, 2018). K-LF – Kraków-Lubliniec Fault.

context, reconstruct the arrangement of faults active during the sedimentation of potential source rocks, show the distribution and geodynamics of the ridges separating basins and recognize the history of the Early Palaeozoic subsidence and the age of thermal events important in the modelling of the maturity of organic matter.

METHODS

The plate tectonic reconstruction commonly utilizes the Euler theorem (Euler, 1736, 1741) to describe the movement of tectonic features on the Earth's globe (e.g., Bullard *et al.,* 1965; Pitman and Talwani, 1972; Greiner, 1999; Müller and Seton, 2014). Based on this theorem, to describe a wonder path of a given feature on the sphere an angular vector is needed. The vector is explicitly defined by an Euler pole latitude and longitude values and angular velocity, usually given in degrees per million year (Müller and Seton, 2014). The Euler pole is understood as an intersection of the sphere surface and the rotation axis crossing the centre of the globe (Fig. 6). These data are most commonly derived from palaeomagnetic measurements (Torsvik *et al.,* 2013), which provide information about the palaeolatitude position of a tectonic feature at a certain time. However, owing to the Earth's magnetic field symmetry, the palaeolongitude cannot be defined using this method (Müller and Seton, 2014). The palaeolongitudinal position of a plate during the Mesozoic and Cainozoic eras can be relatively easily deciphered using, for example, hotspot tracks or magnetic stripes, while for Palaeozoic time and earlier periods, the palaeolatitudes are much more difficult to determine and might be affected by much a greater error (Müller and Seton, 2014).

The rotations of all tectonic features are usually defined in relation to another (so- called finite rotations), with the exception of the African continent, which was the most stable during Phanerozoic time, moves with respect to the Earth's axis.

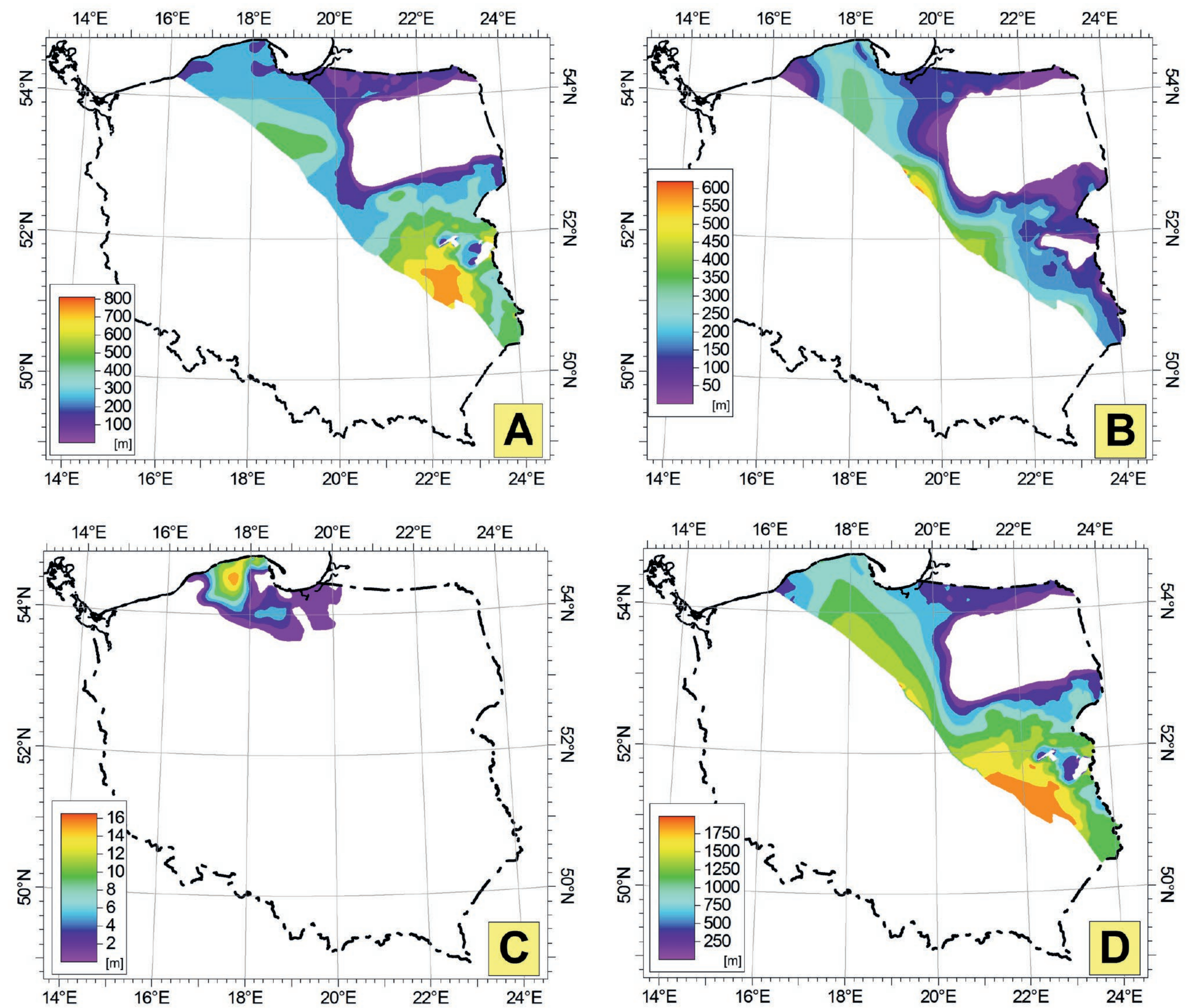


Fig. 2. Total thickness maps of Cambrian: **A.** Lower Cambrian. **B.** Middle Cambrian. **C.** Upper Cambrian. **D.** Undivided Cambrian.

The rotations are organized in a simple text file (Fig. 7), where each entry (row) contains information about a plate's position at a certain time. When provided with such information, the software can interpolate values and animate the movement of the tectonic plates. The rotation file also contains brief, bibliographic notes or general comments for each individual rotation.

The palaeogeographic maps (Figs 8–23) were derived from a series of global and megaregional maps (Golonka *et al.*, 2006, 2017a; Golonka, 2007, 2009, 2012; Golonka and Gawęda, 2012), which were constructed using PLATES, GPlates and PALEOMAP software (e.g., Scotese, 2004; Lawver *et al.*, 2011; Gurnis *et al.,* 2012; Cao *et al*., 2017).

Information derived from global and regional papers, aided by the research of the present authors, was posted on the maps and general palaeoenvironment zones were distinguished within the platforms, basins and ridges. A hotspot reference frame (Golonka and Bocharova, 2000) was used to determine the palaeolongitude. Palaeolatitudes were calculated using palaeomagnetic data (e.g., Torsvik *et al*., 2012; Domeier and Torsvik, 2014; Torsvik and Cocks, 2017). Several global and megaregional, geological and palaeogeographic works were used to construct the palinspastic maps (Ziegler *et al*., 1977; Modliński, 1982, 2010; Ziegler, 1989; Berthelsen, 1993; Jaworowski, 1997, 2000; Pharaoh, 1999; Poprawa *et al*., 1999; Bełka *et al*., 2002; Lazauskiene *et al*., 2002; Torsvik and Rehnström, 2003; Cocks and Torsvik, 2005; Pacześna *et al*., 2005; Dadlez, 2006; Pacześna, 2006; Poprawa, 2006a, b, 2017; Golonka, 2007, 2009; Nawrocki *et al*., 2007; Modliński and Podhalańska, 2010; Golonka and Gawęda, 2012; Torsvik *et al*., 2012). The palaeogeography of Baltica was depicted by Ziegler (1989), Nikishin *et al*. (1996), Golonka (2007, 2009), Nawrocki *et al*. (2007). The global position of Baltica and adjacent plates is the subject of various interpretations (Ziegler, 1989; Torsvik and Rehnström, 2003; Cocks and Torsvik, 2005; Golonka and Gawęda, 2012; Torsvik *et al*., 2012; Kroner and Romer, 2013; Domeier and Torsvik, 2014; Nawrocki, 2015; Domeier, 2016; Kroner *et al*., 2016; Gawęda *et al*., 2017, 2019; Torsvik and Cocks, 2017). The local palaeogeography in the

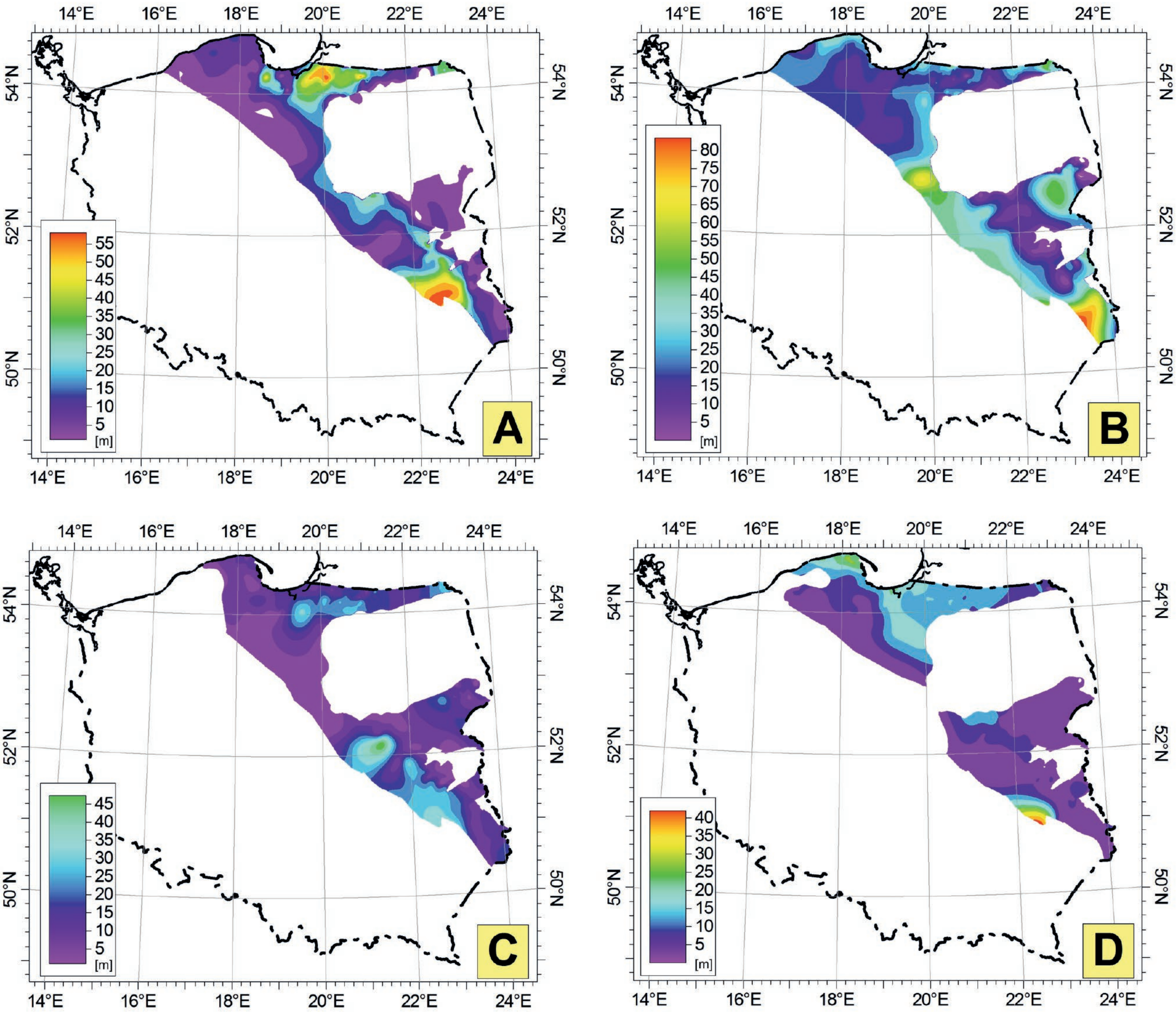


Fig. 3. Total thickness maps of Ordovician: **A.** Ashgill (Upper Ordovician). **B.** Caradoc (Upper Ordovician). **C.** Llanvirn (Middle Ordovician). **D.** Arenig (Lower–Middle Ordovician).

present-day coordinates was depicted by Modliński (1982, 2010). The example of palaeogeographic map from an atlas published by Modliński (2010) is provided in Figure. 3. The maps constructed by the present authors (Figs 9, 11, 13, 15, 17, 19, 21, 23), were assembled according to the rules described by Golonka (2012). The first step involved generating colour-filled polygons. These polygons encompassed the following environments: mountains, highlands active tectonically, topographic high elevations inactive tectonically, topographic medium-low elevations inactive tectonically, non-depositional, terrestrial undifferentiated, fluvial, fluvio-lacustrine, lacustrine, aeolian, marginal marine, paralic, intertidal, deltaic, shallow-marine, shelf, slope, deep basin with sedimentation, area covered by gravity deposits (fan, slump, turbidites), ocean basin without sedimentation. Black-and-white patterns indicating different lithologies (facies) were posted on the colour-filled environmental polygons. The following patterned lithologies (facies) were distinguished: conglomerate, sandstone, siltstone, shale, clay, mudstone, biogenic siliceous deposit, limestone, dolomite, chalk, evaporites undifferentiated, sand and shale, carbonate and shale, sand and carbonate, carbonates and evaporites, intrusives, extrusives. The product included both palaeolithology and palaeoenvironment for a given time interval.

PALAEOGEOGRAPHIC EVOLUTION

Cambrian

The disintegration of the supercontinent Pannotia occurred during Vendian and early Cambrian time (Figs 8, 9) and was preceded by a series of Vendian orogenic events, namely the Cadomian, Baikalian and Panafrican orogenies. New continents that originated owing to the Pannotia disintegration comprise Gondwana, Laurentia, Baltica and Siberia. Gondwana included South America, Africa,

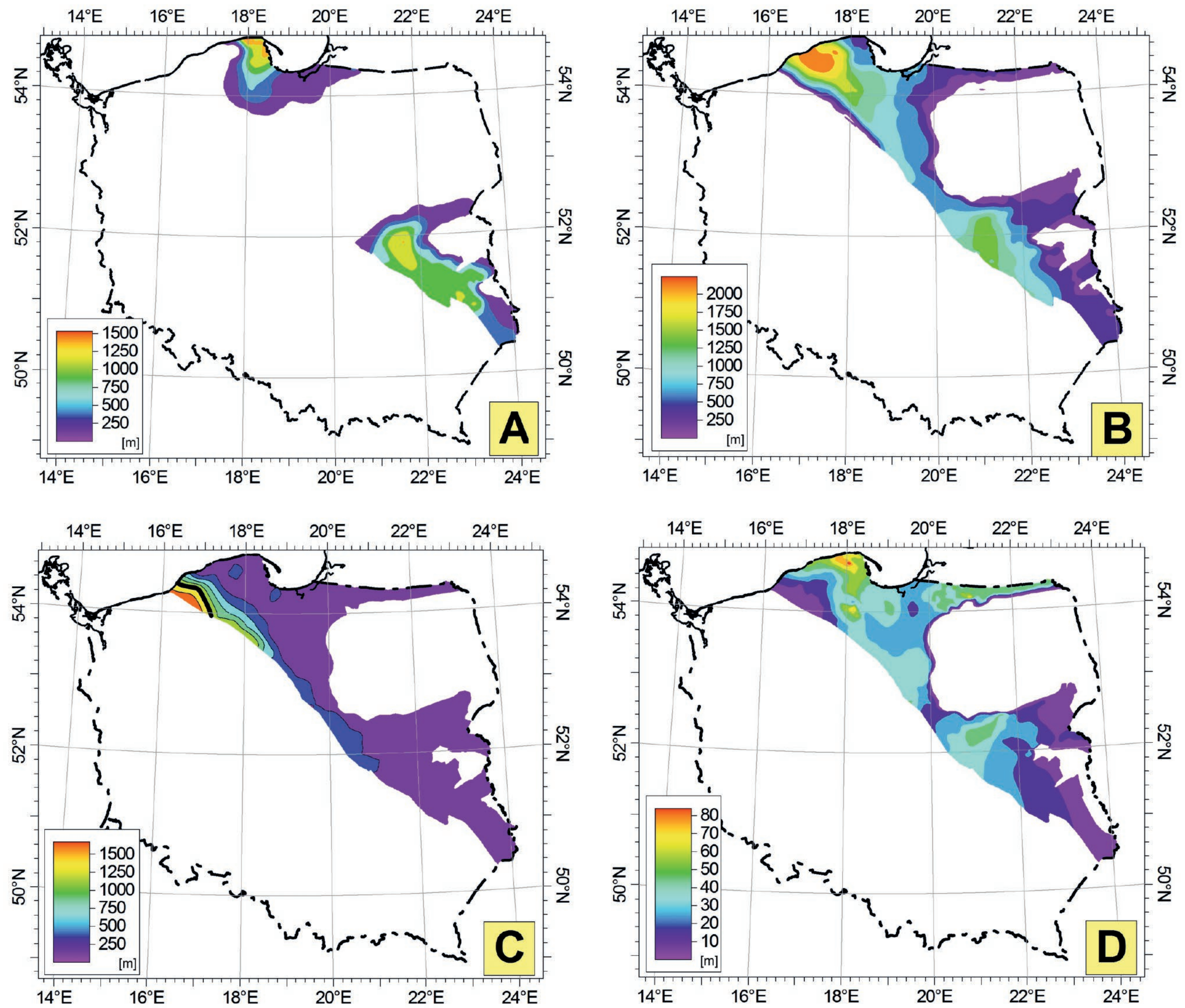


Fig. 4. Total thickness maps of Silurian: **A.** Pridoli, **B.** Ludlow, **C.** Wenlock, **D.** Llandovery.

Madagascar, India, Antarctica, and Australia as well as several smaller continental blocks and terranes such as Yucatan, Florida, Avalonia, Iberia, Cadomia (Central and Southern Europe), Tarim, Karakum, Turkey, Iran, Afghanistan, Tibet, China (three separate blocks), and Southeast Asia (Golonka *et al*., 2017a, b). The Laurentia continent included the largest part of North America, Northern Ireland, Scotland and Chukotka. The Siberian Plate included most of present-day Siberia. The supercontinents were separated by oceanic realms, mainly the Palaeoasian and Iapetus oceans (Golonka, 2009). Baltica included present-day NE Europe between the Teisseyre-Tornquist Zone and Ural Mountains. The East European Craton (EEC) constituted the SE part of Baltica. The Polish part of the EEC is located northeast of the Teisseyre-Tornquist Zone, which extends from Scania through Western Pomerania, central Poland to the Black Sea (Golonka, 2009; Golonka *et al*., 2015, 2017a, b; Poprawa, 2017). The Baltica Plate originally included also an area situated south–west from this line (Mazur *et al*., 2018a). The exact boundary of the Baltica crust is somewhat speculative, but in the Central Europe it most likely coincided with the Kraków-Lubliniec Fault (e.g., Smith *et al*., 2016; Mazur *et al*., 2018a, b). The Baltica Plate was located in the Southern Hemisphere and drifted northward during Early Palaeozoic times (Cocks and Torsvik, 2005; Golonka, 2009; Torsvik *et al*., 2012). The Gondwana, Laurentia, Baltica and Siberia continents were separated by large, oceanic domains that included the Iapetus Ocean and were subjected to advanced spreading (Figs 8, 9). The Vendian–early Cambrian rift documented by subsidence and magmatism (Nikishin *et al*., 1996; Šliaupa *et al*., 1997; Poprawa *et al*., 1999; Lassen *et al*., 2001; Poprawa and Pacześna, 2002; Poprawa, 2017; Krzywiec *et al*., 2018; Botor *et al*., 2019a, b) developed as a result of the break-up of Pannotia along the margin of the EEC. This margin was oriented SW–NE owing to the palaeoposition of Baltica. The rift developed into the Tornquist Sea, separating Baltica and Laurentia (Figs 8–11) and the EEC periphery turned into a passive continental margin

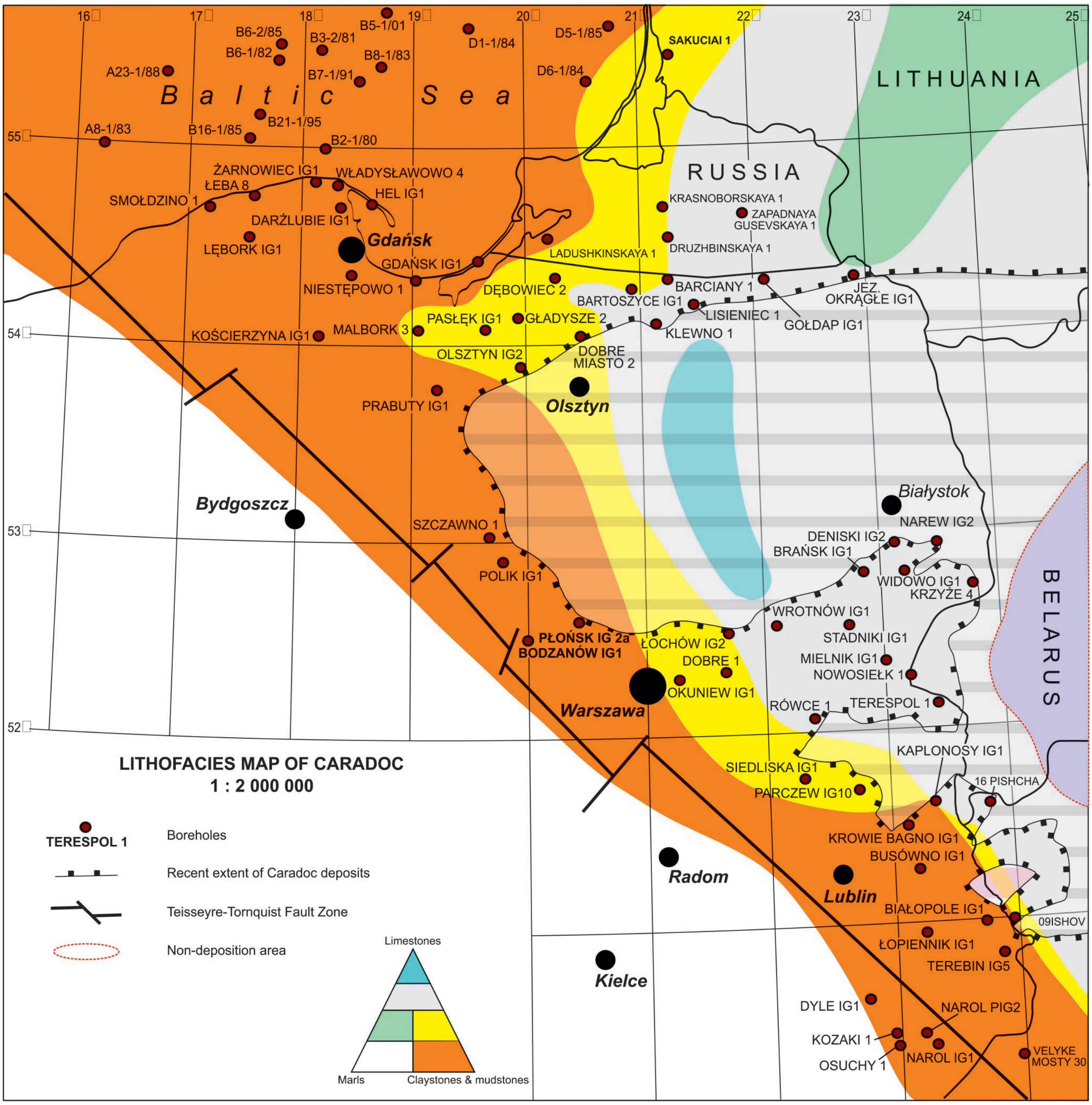


Fig. 5. Sample of palaeogeographic map (Caradoc–Late Ordovician) against background of present-day position of Poland from Modliński (2010).

(Nikishin *et al.*, 1996; Šliaupa *et al.*, 1997; Poprawa *et al.*, 1999, 2018; Poprawa, 2006a, b, 2017; Botor *et al.*, 2019a, b).

In the EEC, Cambrian strata are up to 900 m thick (Fig. 2) and onlap both the Ediacaran basaltic and volcanoclastics fills of rift valleys and the crystalline basement. These strata consist mainly of quartz arenites, quartzitic sandstones, thin-bedded sandstone/mudstone heteroliths and mudstones, which were deposited on a tide-dominated and wave-influenced shelf (Jaworowski, 1997; Stadnik *et al.*, 2017; Wendorff, 2017). Tongues of black, organic-rich mudstones are of late Cambrian (Słowiński and Piaśnica formations; Fig. 24) and Early Ordovician (Słuchowo Formation) age and form a good source rock for both conventional and shale-gas accumulations, which also continue along the Baltica margin into Denmark and Scania as well as to Ukraine (Pool *et al.*, 2012; Golonka *et al.*, 2017a, b; Poprawa, 2017; Radkovets, 2017; Schito *et al.*, 2017).

Ordovician

The Early Ordovician was the time of maximum dispersion of the continents and the existence of vast oceans between the Gondwana, Laurentia, Baltica and Siberia continents (Figs 12, 13). The amount of separation between Gondwana and Laurentia reached 5,000 km (Cocks and Torsvik, 2005; Golonka, 2009; Torsvik *et al.*, 2012; Golonka

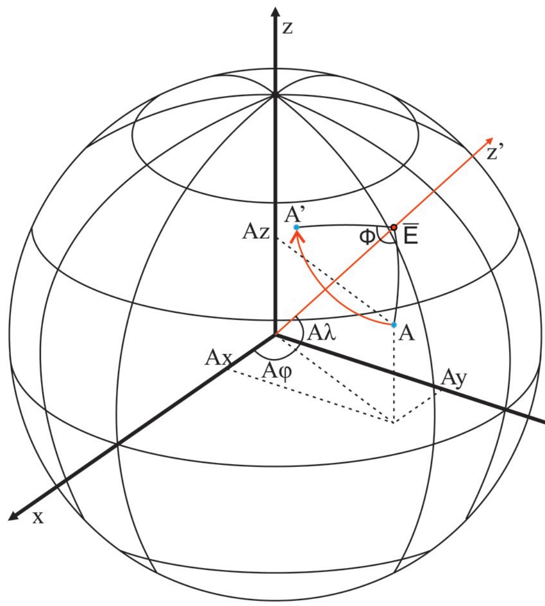


Fig. 6. Graphical representation of the Euler theorem. Ē – Euler pole; A – initial point position; A' – final point positon; Φ – rotation angle; z' – rotation axis; x, y, z – Cartesian coordinate axis; Ax, Ay, Az – coordinates of the point in Cartesian coordinates.

et al., 2017b). The separation of northern Gondwana and Avalonian terranes (part of Poland, northern Germany, Ardennes, England, Wales, south–eastern Ireland, much of Nova Scotia, southern New Brunswick and some coastal parts of New England) led to the origin of a new Rheic Ocean (Torsvik and Rehnström, 2003; Cocks and Torsvik, 2005; Golonka, 2009; Torsvik *et al.*, 2012; Golonka *et al.*, 2017b). Avalonia probably started to drift away from Gondwana and moved towards Baltica in the late Tremadocian and was in a drift stage by the Llanvirnian. The Rheic rifting and drift of Avalonia was related to the subduction zone, which developed along the central part of Gondwana (Figs 12–15). The Cambrian–Early Ordovician Iapetus Ocean began to narrow. The Brunovistulicum Terrane could constitute the eastern extension of Avalonia. The relationship between of the Perigondwanian and Avalonian terranes indicates an eastern extension of the Rheic Ocean. In the Central Western Carpathians, Late Ordovician–Early Silurian tonalitic gneisses of calc-alkaline character, associated with meta-gabbros, revealed the presence of magmatic episodes at 470–435 Ma (Janák *et al.*, 2002; Kohut *et al.*, 2008; Gawęda and Golonka, 2011; Gawęda *et al.*, 2017). These rocks record the docking of Avalonia to Baltica. Also, the intrusions of 459–470 Ma granitoids in the East Carpathians in Romania (Pana *et al.*, 2002; Munteanu and Tatu, 2003; Ballintoni *et al.*, 2010) document the collision-related tectono-magmatic effects of docking of eastern prolongation of Avalonia to Baltica. The Scythian Platform (southernmost Ukraine and SW Russia) comprises metamorphic sequences of age 470–410 Ma, covered by Devonian and Early Carboniferous rocks that were deformed during Carboniferous and Permian time (Zonenshain *et al.*, 1990; Golonka, 2009). Accreted terranes in the basement of the East Carpathian-Balkan area as well as in southernmost Ukraine and SW Russia could have constituted the eastern extension of Avalonia (Golonka, 2009; Golonka and Gawęda, 2012).

The Ordovician succession of the EEC records deposition on a N–S-trending (in the present-day position) carbonate-shelf ramp that developed along the landward (eastern side) of the basin and intertongued downdip with outer-shelf graptolitic mudstones (Modliński, 1982; Modliński and Szymański, 1997; Kędzior *et al.*, 2017; Skompski and Paszkowski, 2017). The succession is generally less than 100 m thick and reveals numerous diastemas, omission surfaces, hardgrounds and glauconite, all indicative of low sedimentation rates. Carbonates are represented by nodular and marly limestones, skeletal, commonly dolomitic packstones and wackestones, and locally oolitic grainstones. Mudrocks consist of black, silt-laminated mudstones, interbedded with green, often bioturbated mudstones and thin bentonite layers. Major mudstone tongues of a Floian (Słuchów Formation) and Late Darriwillian–Early Katian (Sasino Formation) age (Fig. 24) mark transgressions and early highstands, which were most likely driven by eustatic oscillations (Nielsen, 2004; Porębski and Podhalańska, 2017; Skompski and Paszkowski, 2017; Van der Meer *et al.*, 2017). With its basinwide extent, relatively high total organic carbon levels and appropriate thermal maturity levels, the Sasino Formation appears the best target for unconventional gas exploration in the Ordovician succession (Botor *et al.*, 2017a; Papiernik *et al.*, 2017).

Silurian

The part of Avalonia that included northwestern Poland and adjacent part of Germany probably was sutured to Baltica by the end of Ordovician or in the Early Silurian (Figs 16, 17). The convergence of these two plates is confirmed by palaeomagnetic data (e.g., Torsvik and Rehnström, 2003; Cocks and Torsvik, 2005; Torsvik *et al.*, 2012; Domeier and Torsvik, 2014; Domeier, 2016; Torsvik and Cocks, 2017). The Pomeranian segment of the EEC reflects the Caledonian collision. The system of NW–SE-striking, normal and strike slip faults, cutting the Precambrian basement as well as the Cambrian, Ordovician and Silurian deposits, developed during latest Silurian times (Golonka *et al.*, 2015, 2017b, c; Poprawa, 2017; Kasperska *et al.*, 2019). According to an interpretation of geophysical data (Krzywiec *et al.*, 2017, 2018; Mazur *et al.*, 2018a, b), the Caledonian tectonic suture, marking collision between Avalonia and Baltica, is located SW of the Teisseyre-Tornquist line. The EEC part of Baltica dips toward the SW below the accretionary prism located along the eastern margin of Avalonia (Poprawa, 2017; Mazur *et al.*, 2018a). The U-Pb dating of zircons in the Ordovician EEC bentonites indicates 455 Ma age (Anczkiewicz *et al.*, 2017). This age marks the docking of Avalonia to Baltica, the termination of subduction and the initiation of collision. Bentonites were generated in the magmatic arc at the northern margin of Avalonia. The Silurian bentonites are related to post-collisional magmatism (Anczkiewicz *et al.*, 2017). The Caledonian orogenic front is limited to NW Poland (Fig. 1). Toward the SE, the collisional process

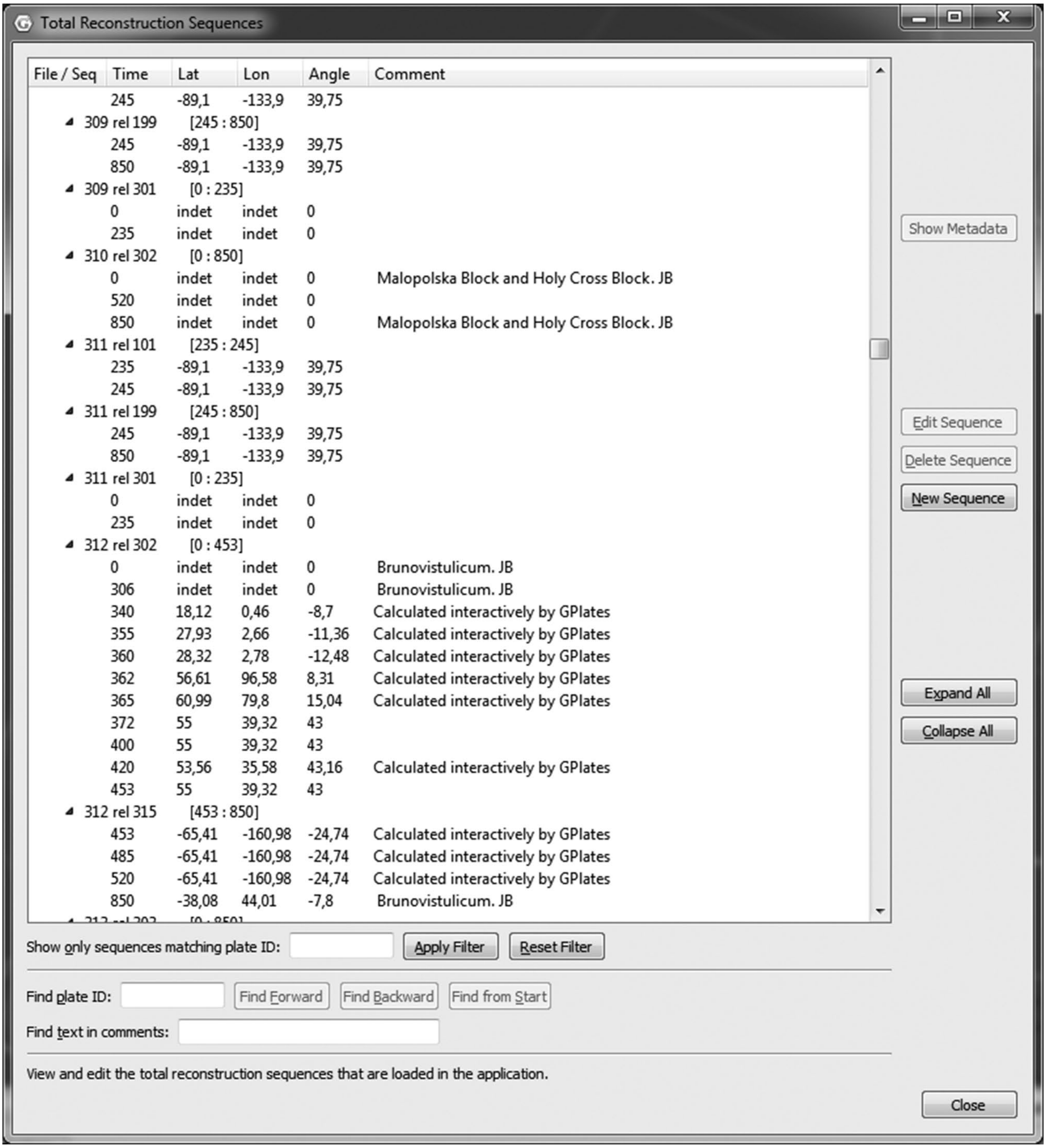


Fig. 7. An example of a rotation file displayed using GPlates software (Gurnis *et al.*, 2012; Müller and Seton, 2014). Each row describes the position of a tectonic plate at a certain time.

was dominated by a strike-slip suturing of the two continents, rather than by full-scale continent-continent collision (Erlström *et al.*, 1997; Poprawa and Pacześna, 2002; Torsvik and Rehnström, 2003; Golonka, 2007; Golonka *et al.*, 2017a, b; Poprawa, 2017). The Brunovistulicum and Małopolska terranes of southern Poland probably also belonged to Avalonia and joined Baltica along the Kraków-Lubliniec Fault (Fig. 1) together with northwestern Poland. As mentioned above, the Caledonian events were also noted in the Carpathian-Balkan area and in the Scythian platform in southernmost Ukraine and SW Russia (Zonenshain *et al.*, 1990; Janák *et al.*, 2002; Pana *et al.*, 2002; Munteanu and Tatu, 2003; Kohut *et al.*, 2008; Golonka, 2009; Gawęda and Golonka, 2011; Gawęda *et al.*, 2017). Ziegler (1989) mapped an orogenic belt at the southern border of Baltica, from Late Silurian to Permian time. Nikishin *et al.* (1996) displayed the Late Silurian accretion of terranes along the southeastern margin of Baltica. It is possible that part of the Scythian platform was accreted to Baltica together with the Avalonian terranes (Golonka, 2009).

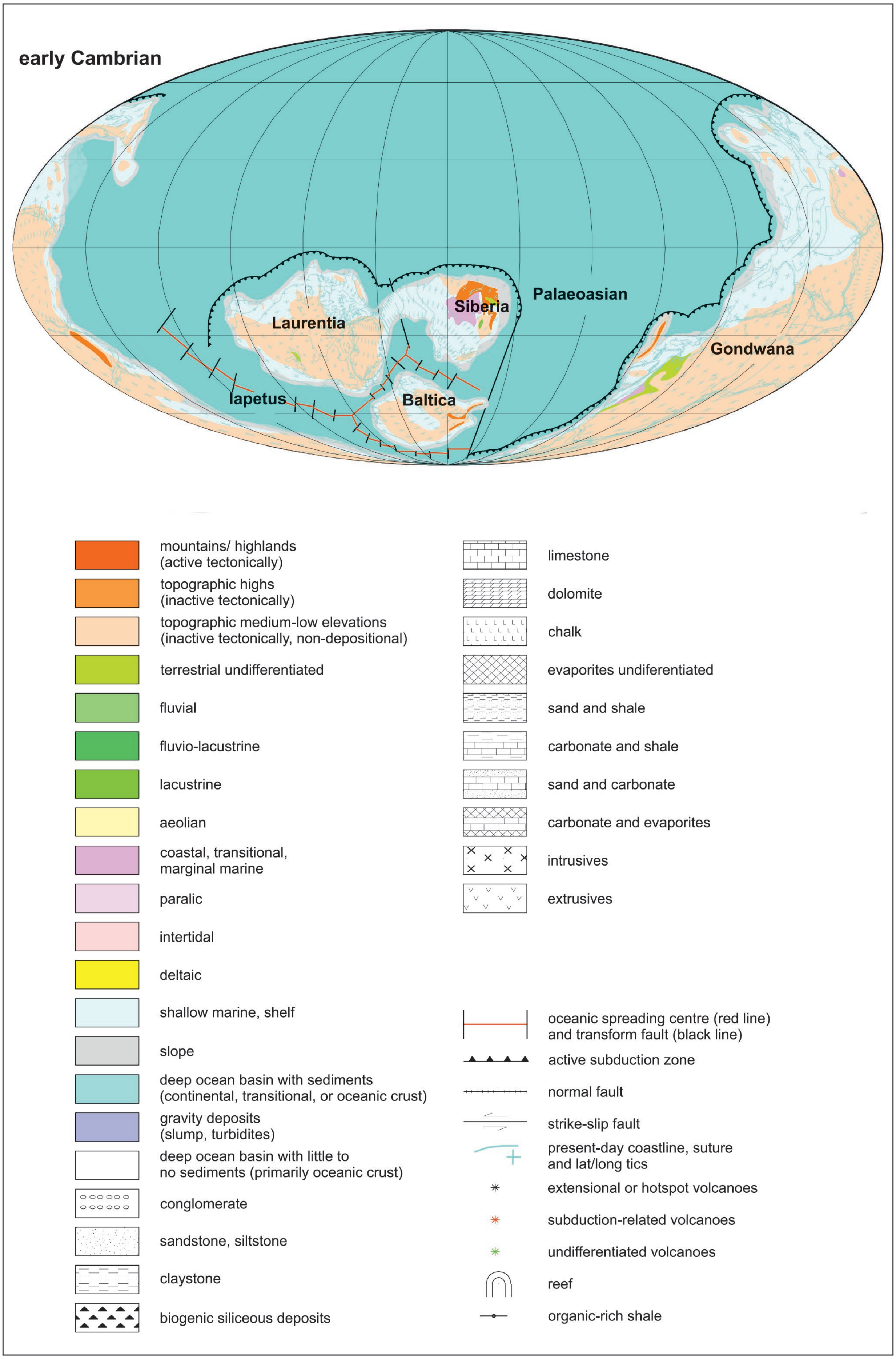


Fig. 8. Global palaeogeography during early Cambrian (modified from Golonka *et al.*, 2017a).

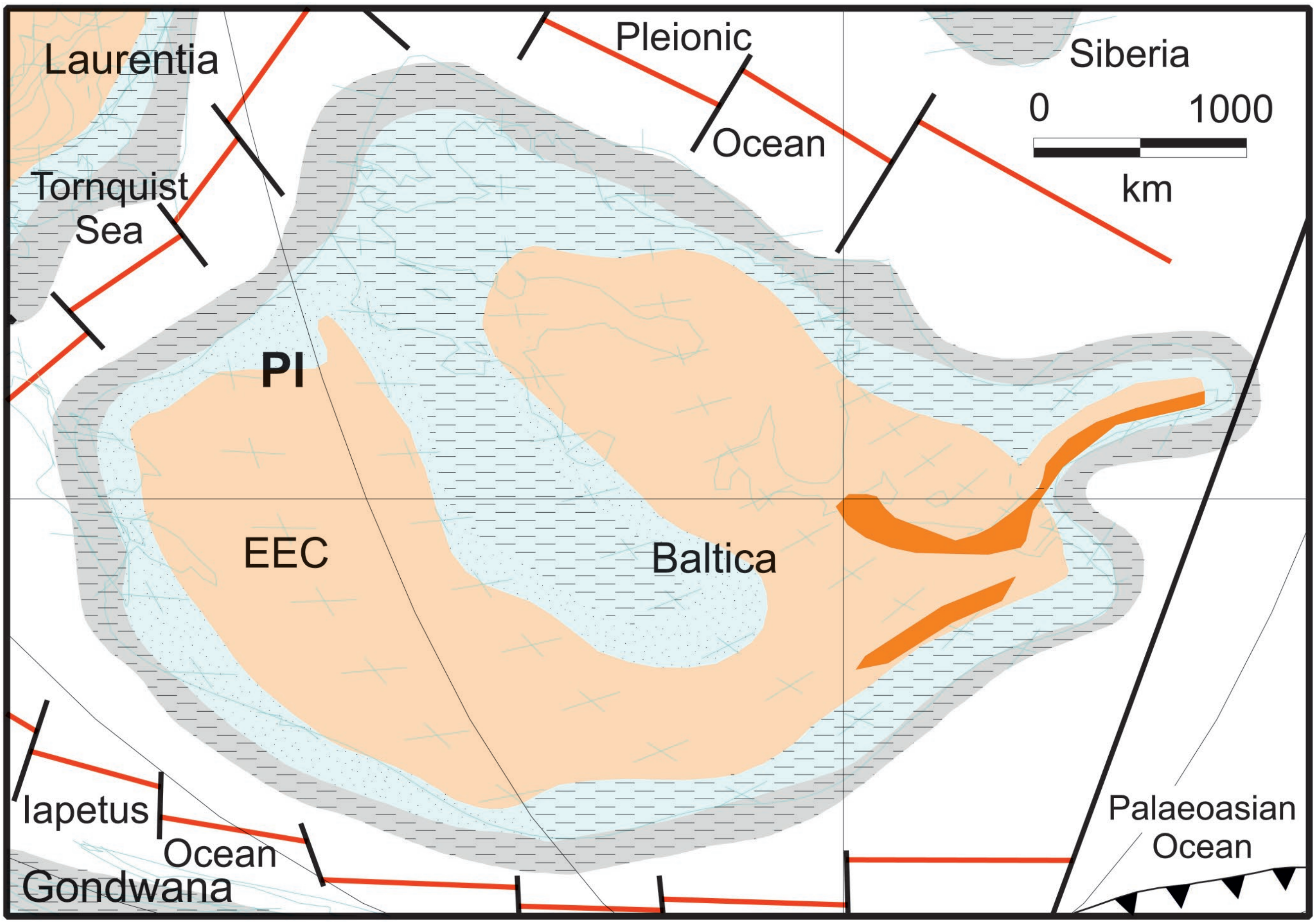


Fig. 9. Palaeogeography, palaeoenvironment and lithofacies map of Baltica and adjacent areas during early Cambrian. EEC – East European Craton (part of Baltica). Pl – Polish part of EEC. Legend as in Figure 8.

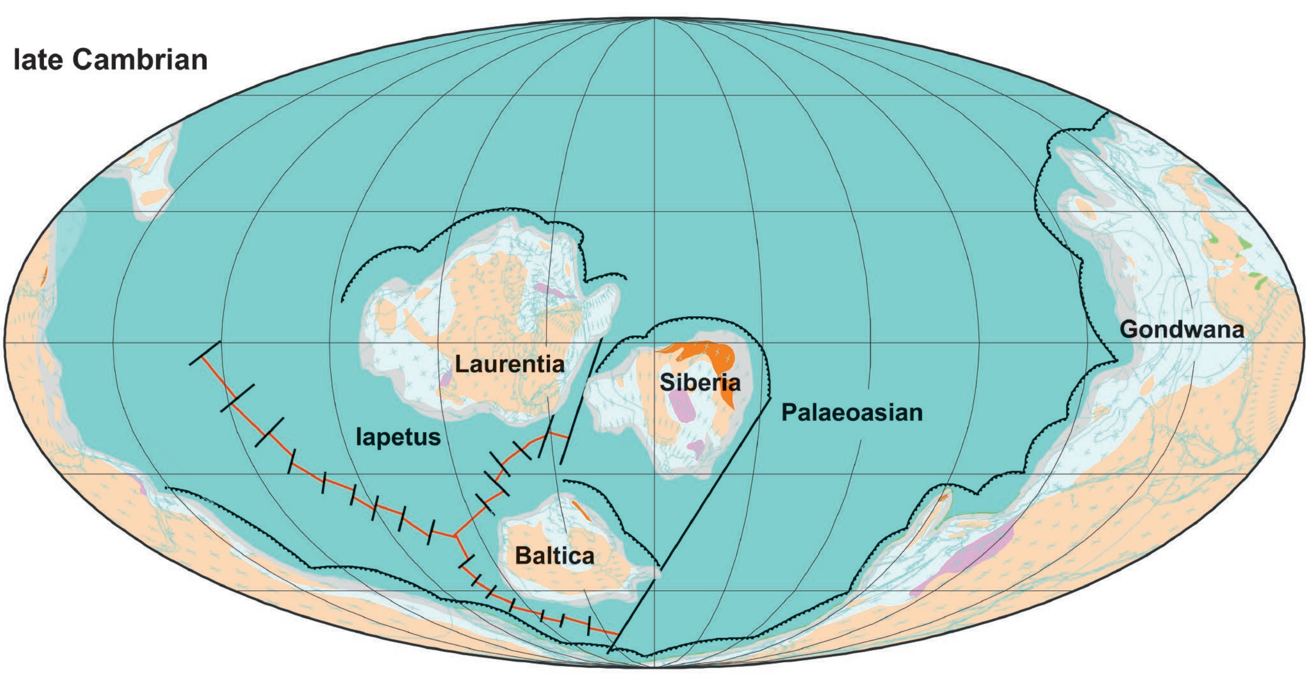


Fig. 10. Global palaeogeography during late Cambrian (modified from Golonka *et al*., 2017a). Legend as in Figure 8.

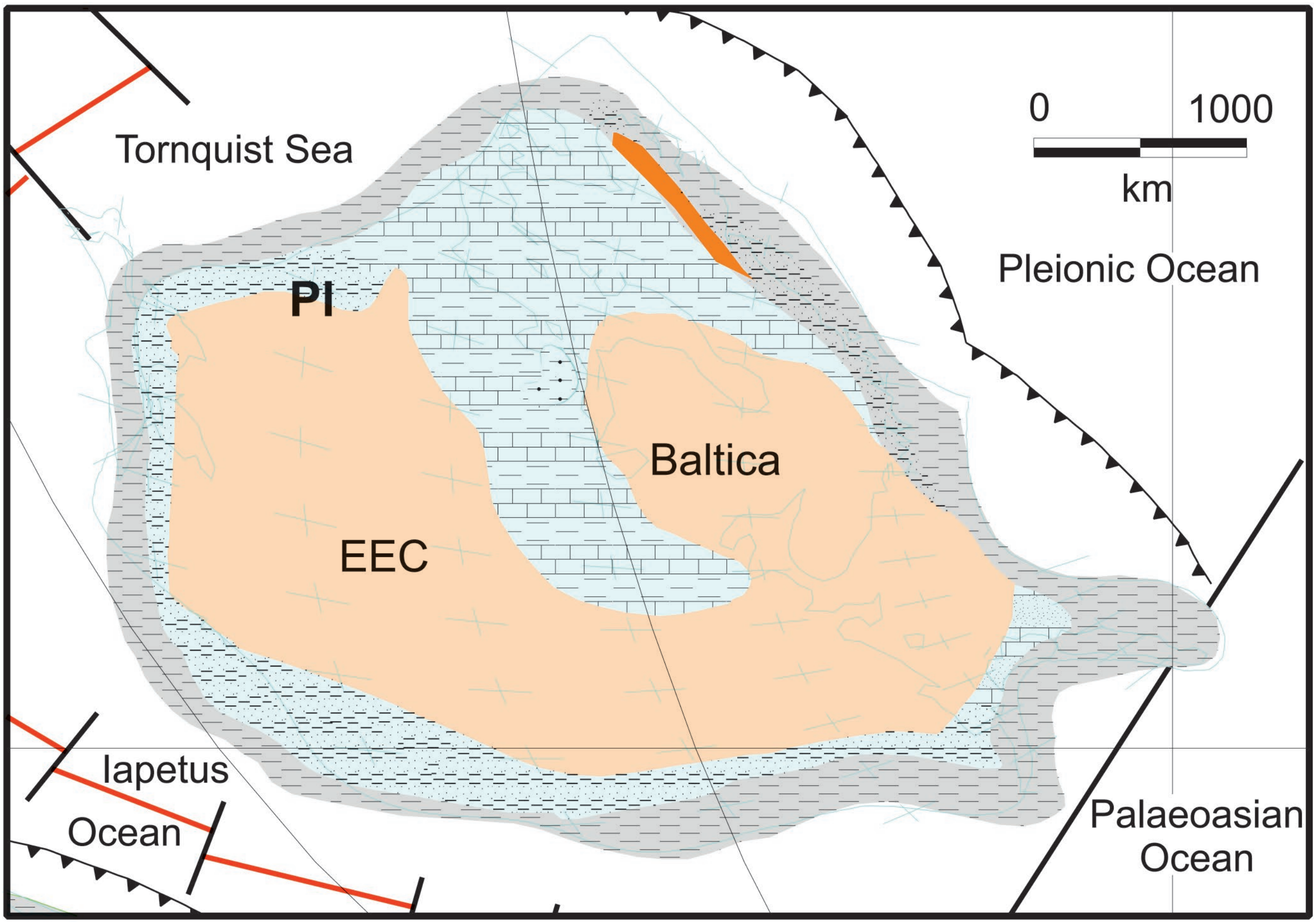


Fig. 11. Palaeogeography, palaeoenvironment and lithofacies map of Baltica and adjacent areas during late Cambrian. EEC – East European Craton (part of Baltica). Pl – Polish part of EEC. Legend as in Figure 8.

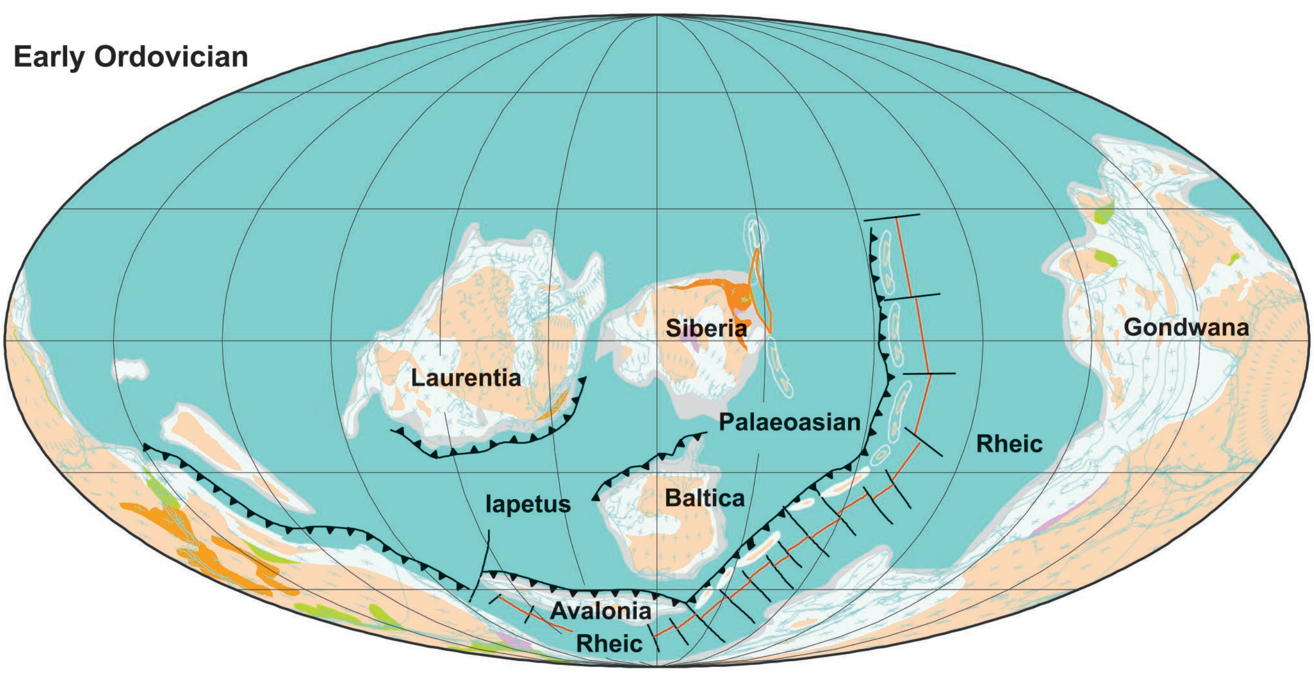


Fig. 12. Global palaeogeography during Early Ordovician (modified from Golonka *et al.*, 2017a). Legend as in Figure 8.

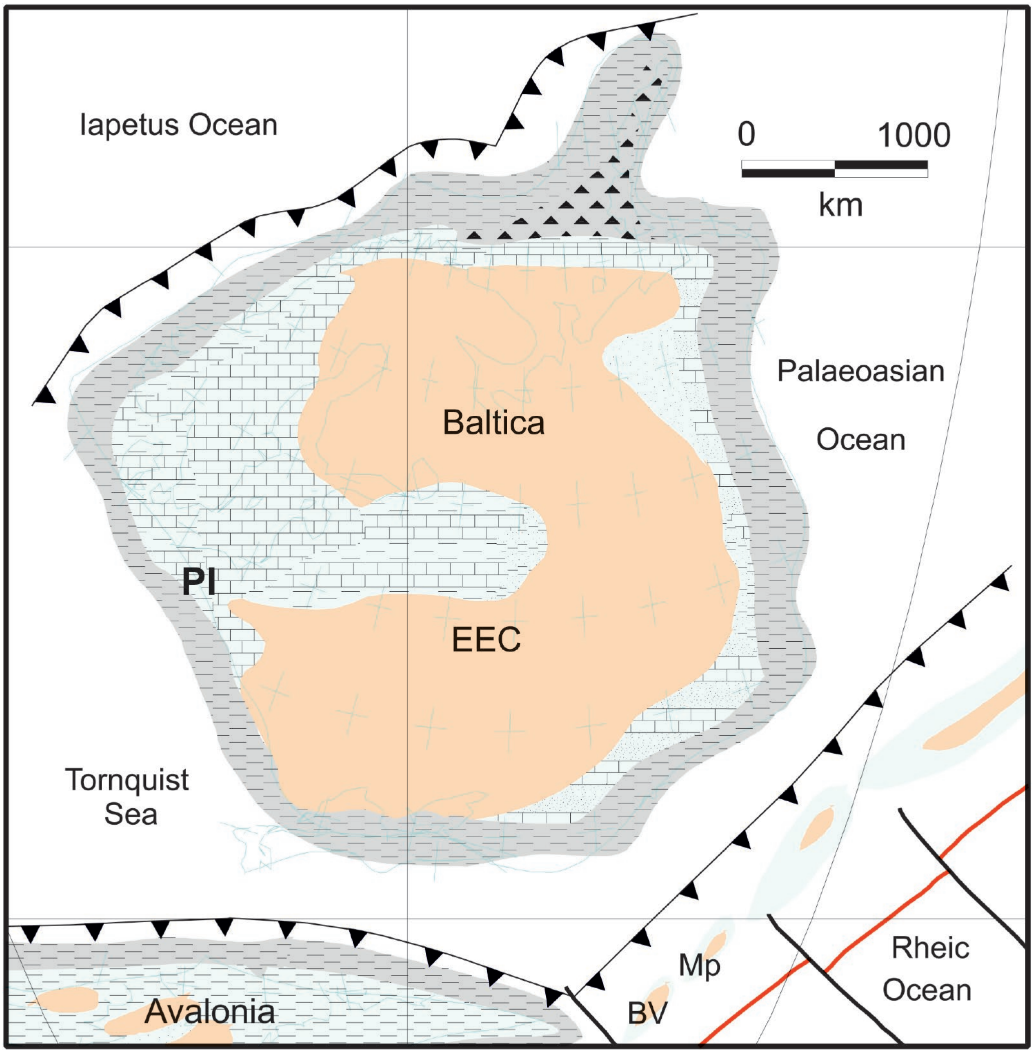


Fig. 13. Palaeogeography, palaeoenvironment and lithofacies map of Baltica and adjacent areas during Early Ordovician. EEC – East European Craton (part of Baltica), Pl – Polish part of EEC, BV – Brunovistulicum, Mp – Małopolska Block. Legend as in Figure 8.

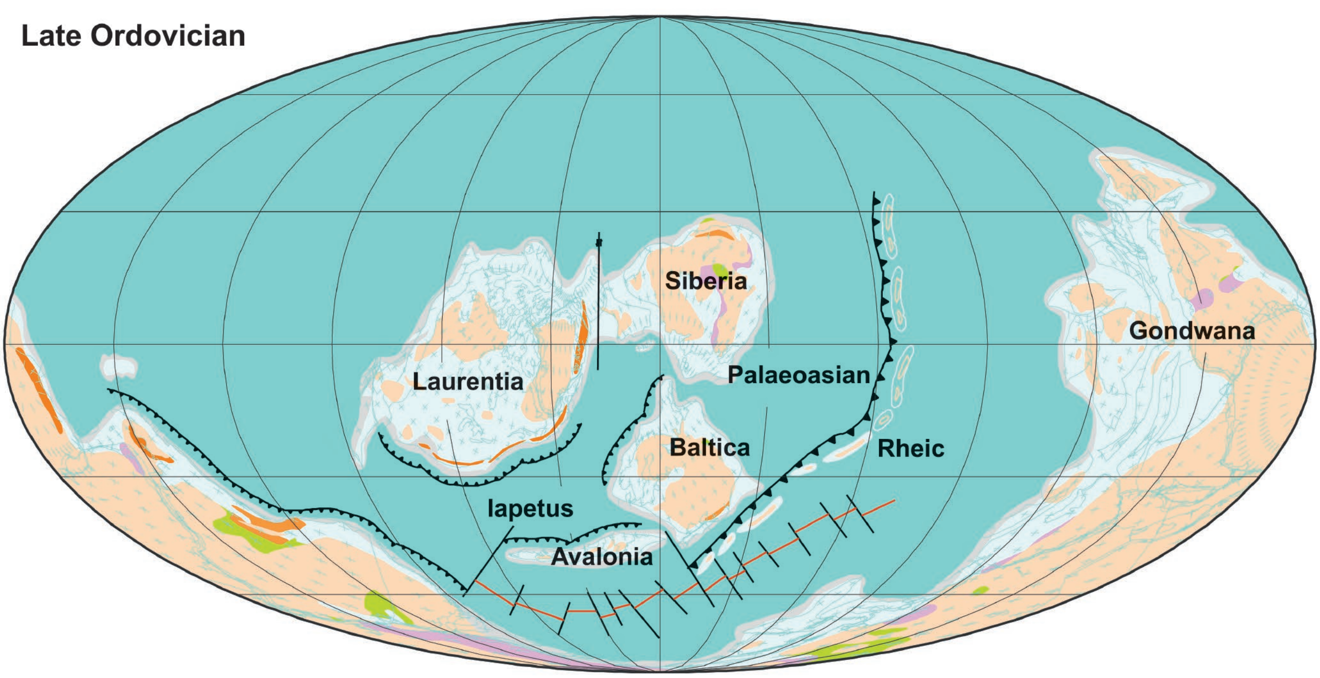


Fig. 14. Global palaeogeography during Late Ordovician (modified from Golonka *et al.*, 2017a). Legend as in Figure 8.

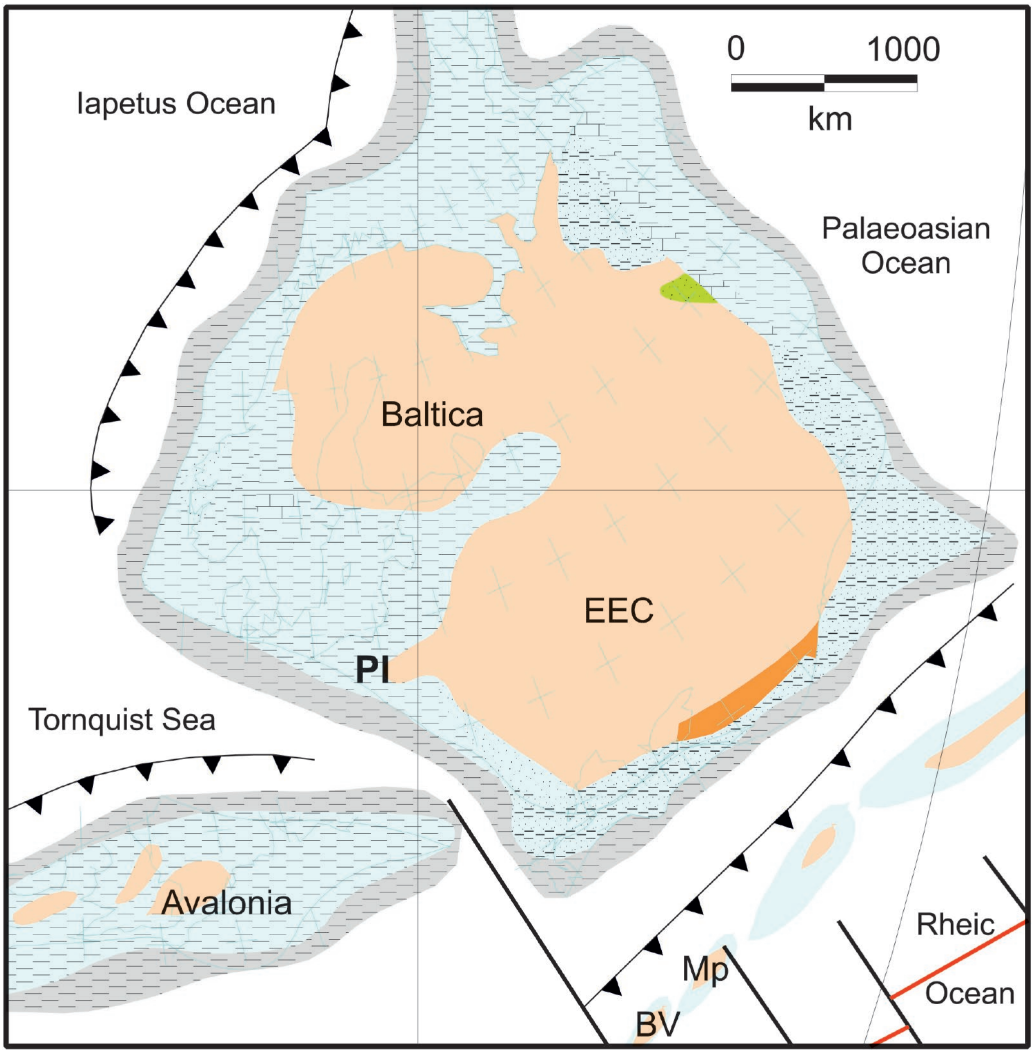


Fig. 15. Palaeogeography, palaeoenvironment and lithofacies map of Baltica and adjacent areas during Late Ordovician. EEC – East European Craton (part of Baltica), Pl – Polish part of EEC, BV – Brunovistulicum, Mp – Małopolska Block. Legend as in Figure 8.

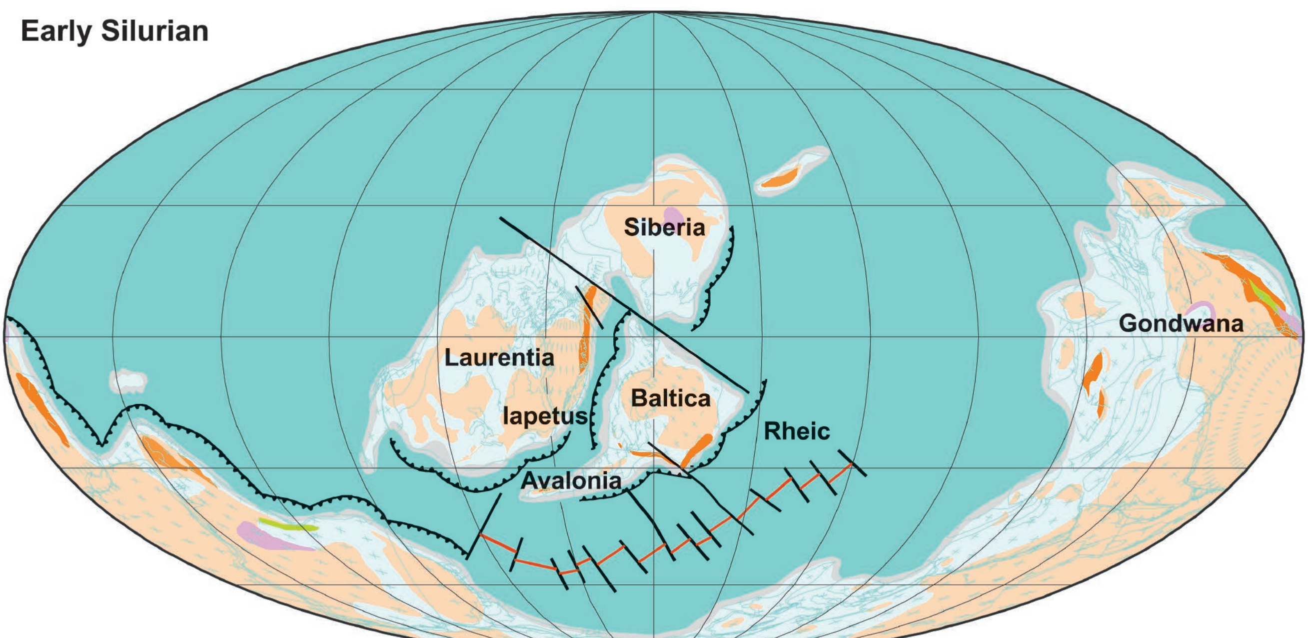


Fig. 16. Global palaeogeography during Early Silurian (modified from Golonka *et al.*, 2017a). Legend as in Figure 8.

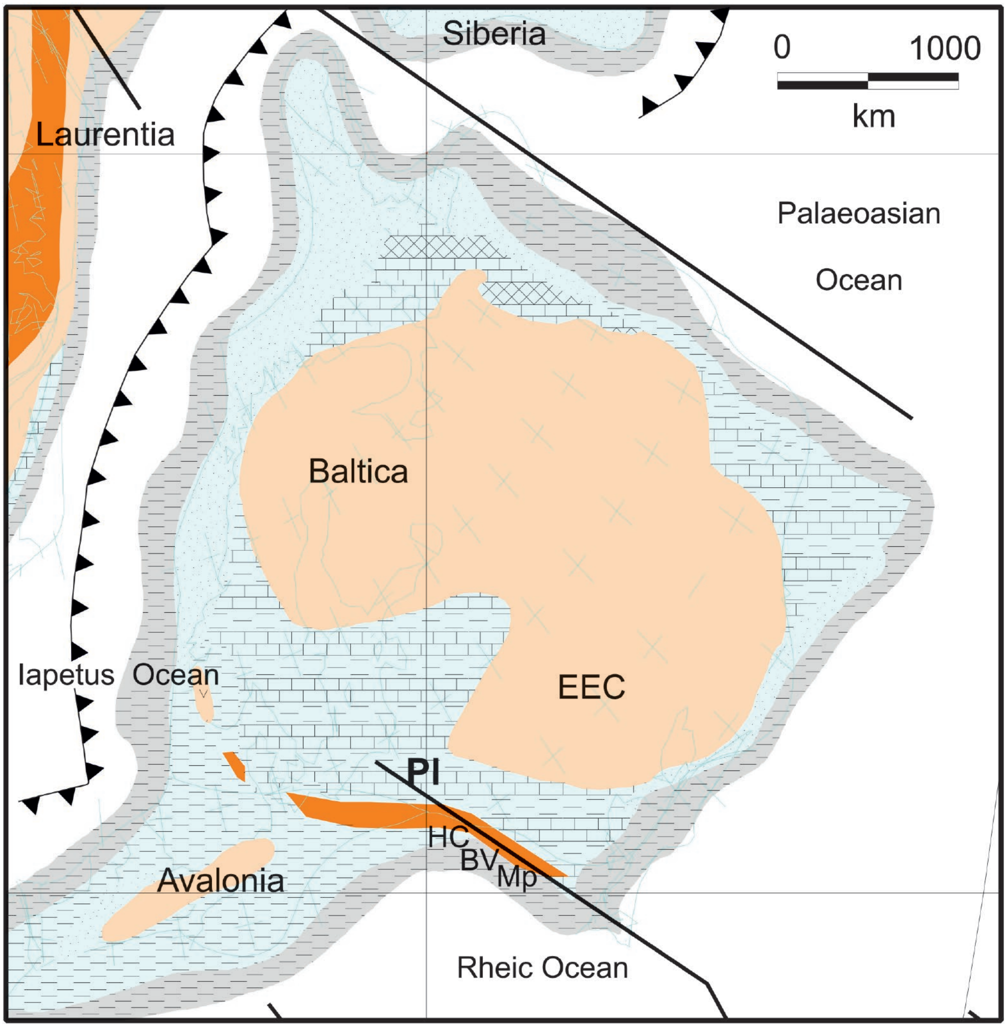


Fig. 17. Palaeogeography, palaeoenvironment and lithofacies map of Baltica and adjacent areas during Early Silurian. EEC – East European Craton (part of Baltica), Pl – Polish part of EEC, BV – Brunovistulicum, Mp – Małopolska Block, HC – Holy Cross Mts. Legend as in Figure 8.

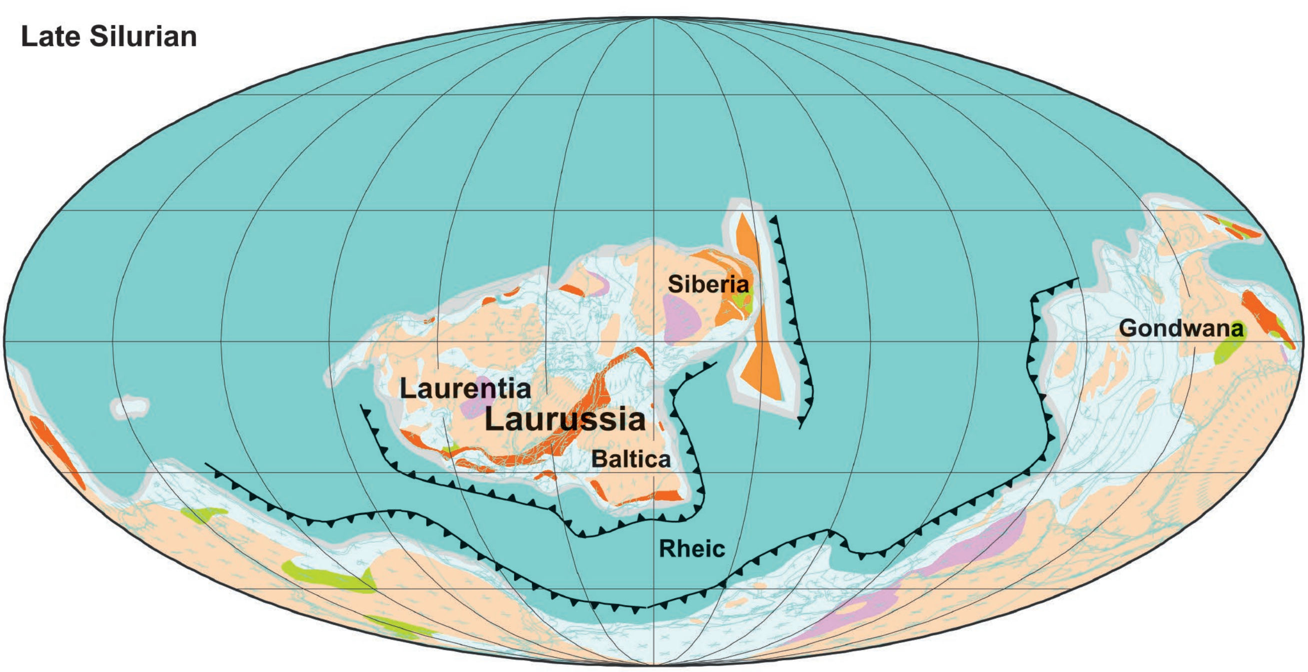


Fig. 18. Global palaeogeography during Late Silurian (modified from Golonka *et al.*, 2017a). Legend as in Figure 8.

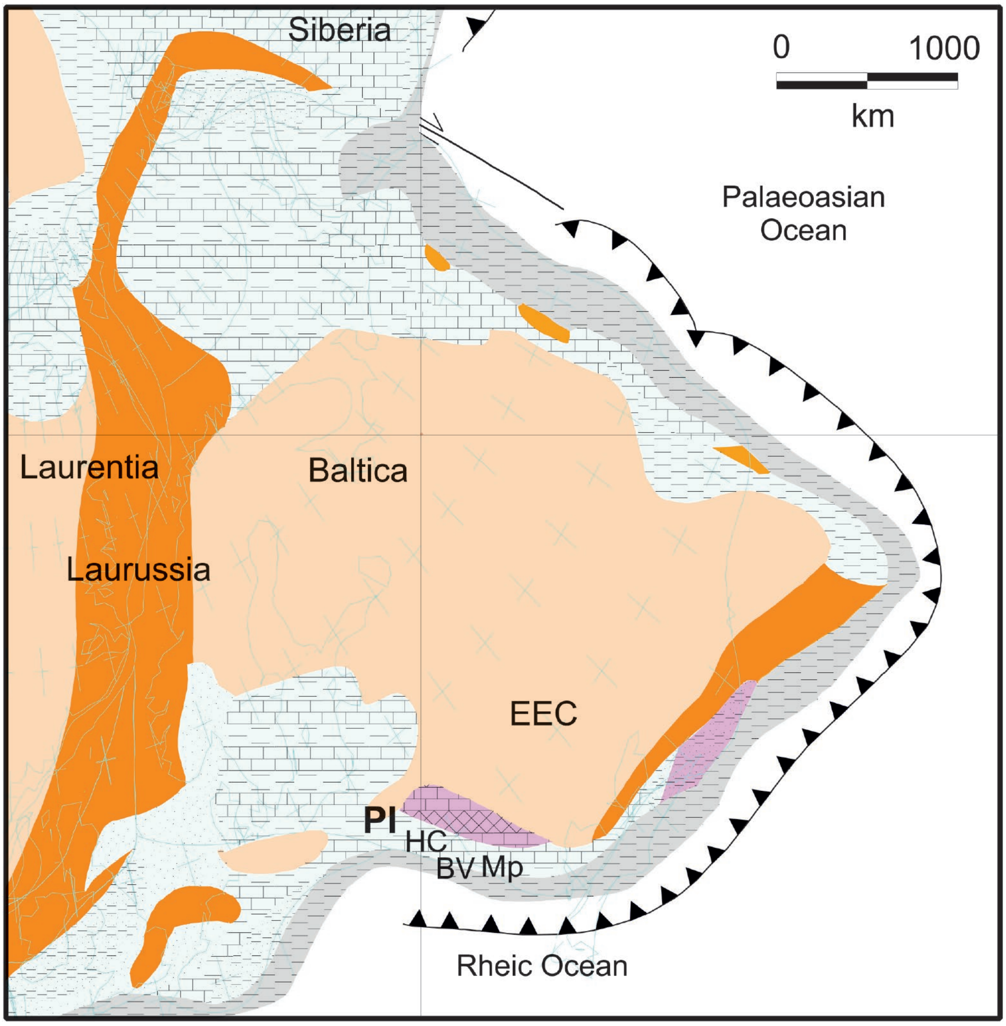


Fig. 19. Palaeogeography, palaeoenvironment and lithofacies map of Baltica and adjacent areas during Late Silurian. EEC – East European Craton (part of Baltica), Pl – Polish part of EEC, BV – Brunovistulicum, Mp – Małopolska Block, HC – Holy Cross Mts. Legend as in Figure 8.

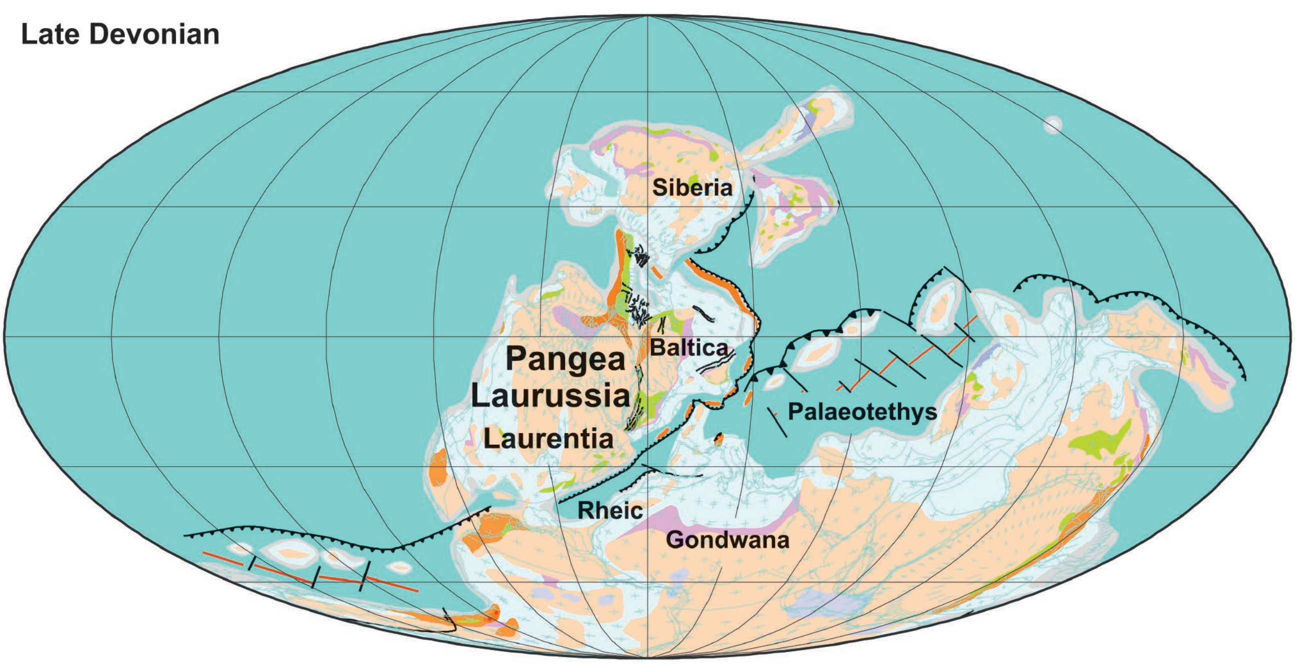


Fig. 20. Global palaeogeography during Late Devonian (modified from Golonka *et al.*, 2017a). Legend as in Figure 8.

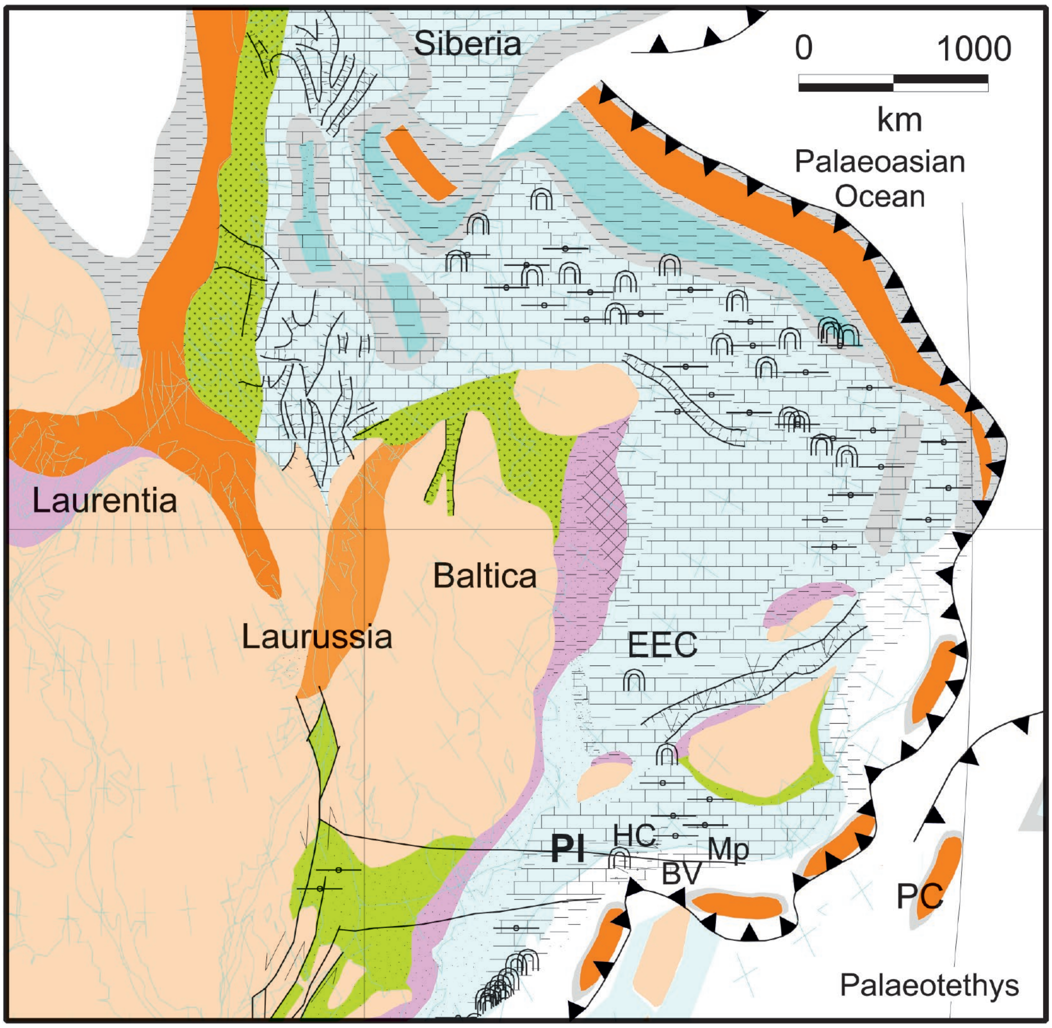


Fig. 21. Palaeogeography, palaeoenvironment and lithofacies map of Baltica and adjacent areas during Late Devonian. EEC – East European Craton (part of Baltica), Pl – Polish part of EEC, BV – Brunovistulicum, Mp – Małopolska Block, HC – Holy Cross Mts., PC – Protocarpathians. Legend as in Figure 8.

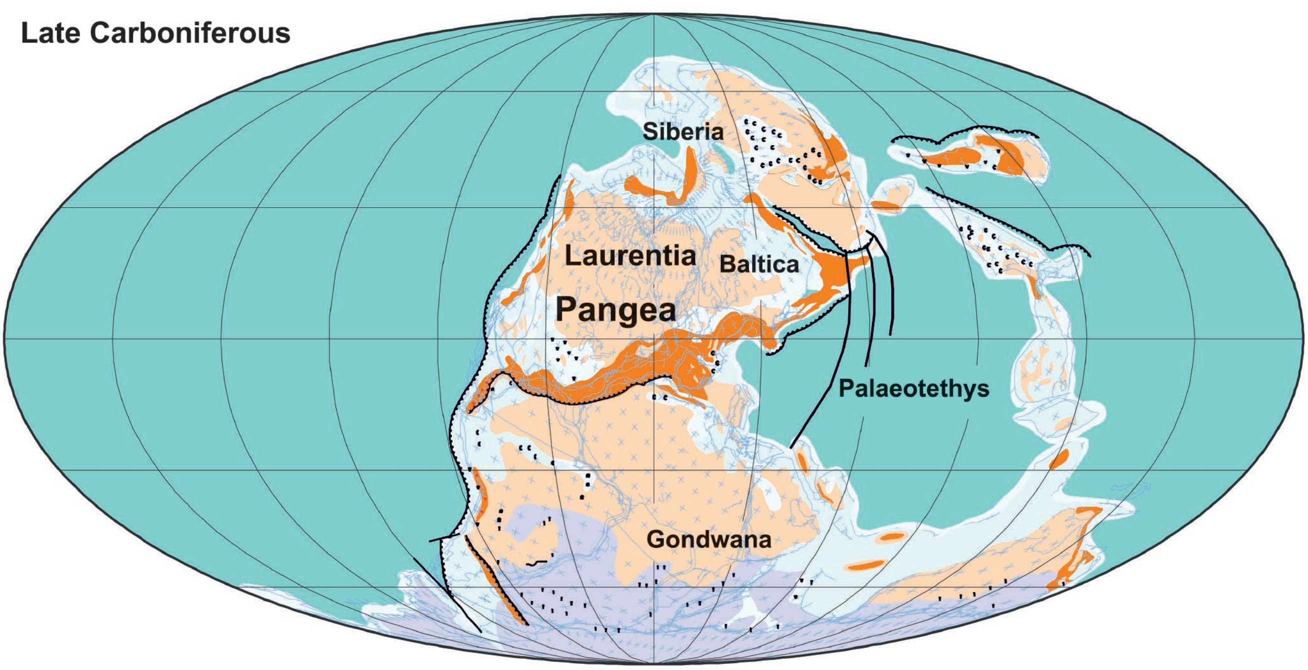


Fig. 22. Global palaeogeography during Late Carboniferous (modified from Golonka *et al.*, 2017a). Legend as in Figure 8.

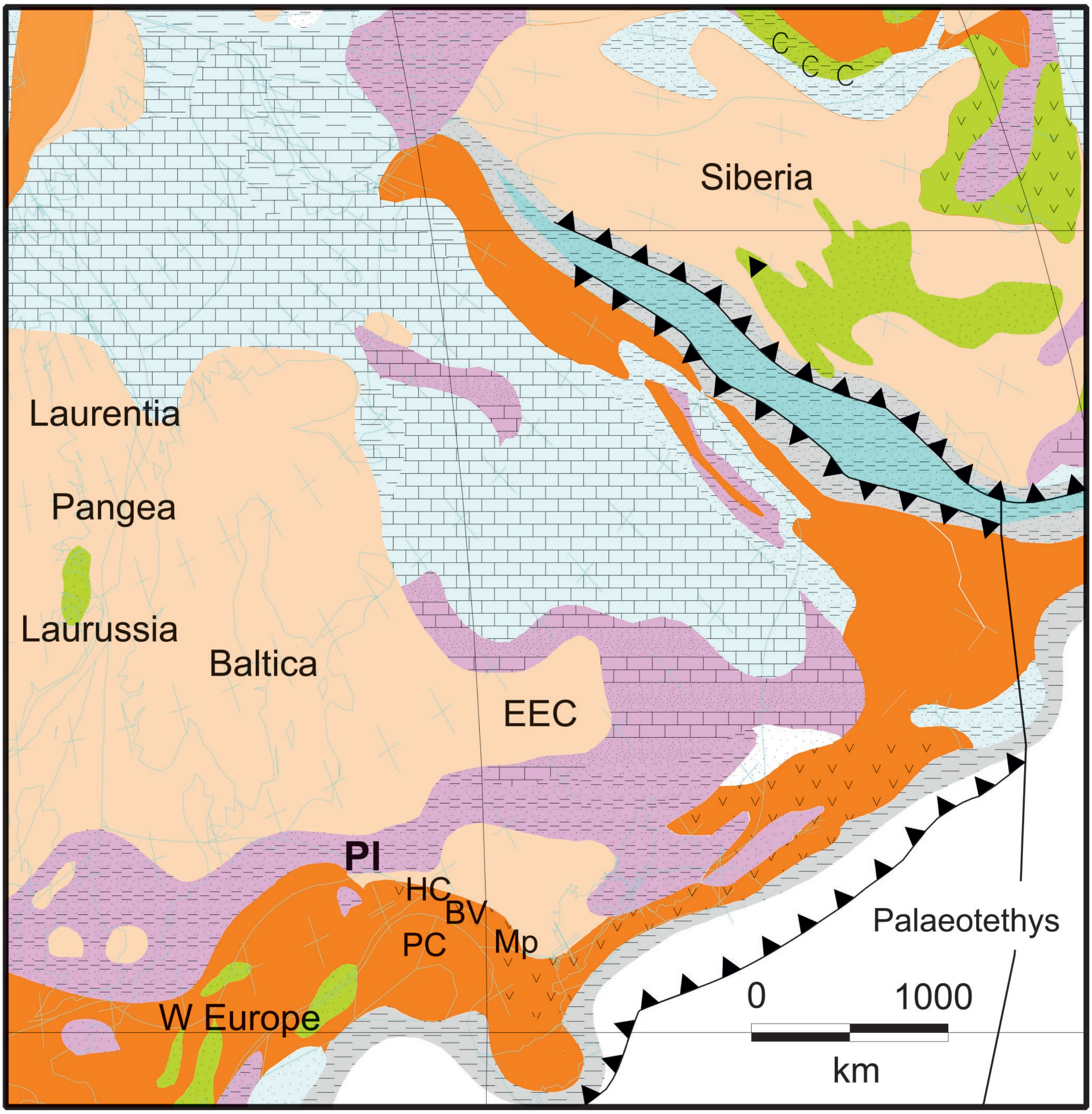
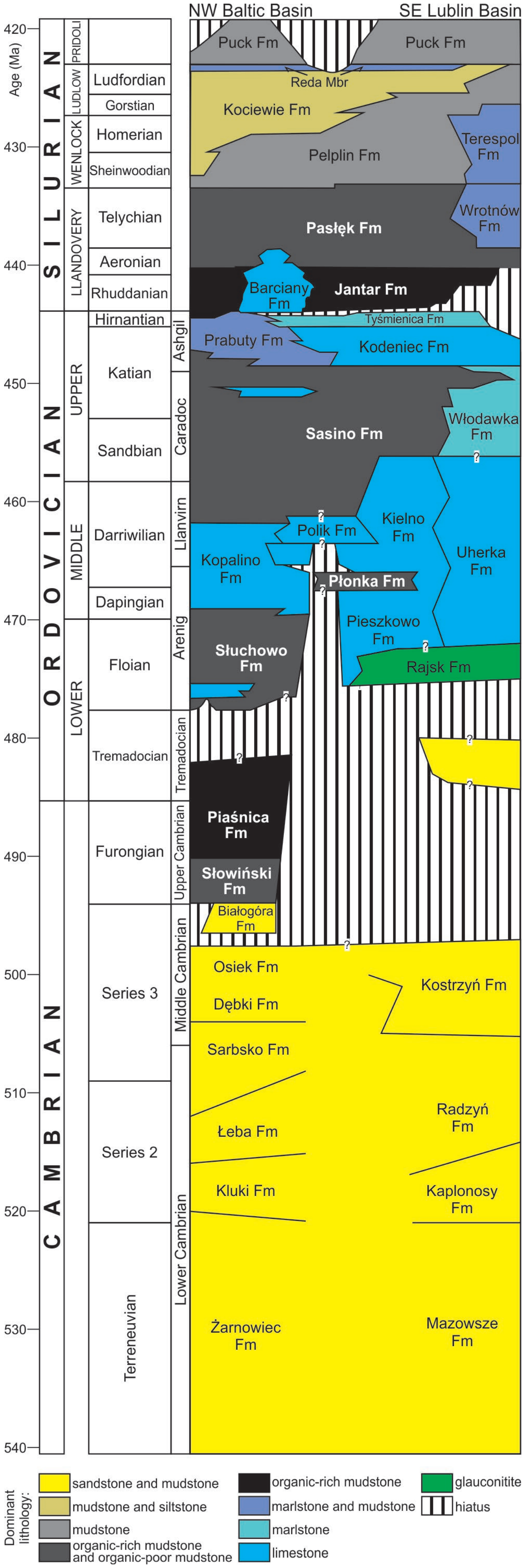


Fig. 23. Palaeogeography, palaeoenvironment and lithofacies map of Baltica and adjacent areas during Late Carboniferous. EEC – East European Craton (part of Baltica), Pl – Polish part of EEC, BV – Brunovistulicum, Mp – Małopolska Block, HC – Holy Cross Mts., PC – Protocarpathians, W. Europe – Western Europe. Legend as in Figure 8.

The Iapetus Ocean narrowed significantly during Early Silurian time, marking the onset of the Caledonian orogeny (Figs 18, 19), which was caused by collision of Baltica and Laurentia. After the complete closure of the Iapetus Ocean, the continents of Baltica, Avalonia and Laurentia formed the supercontinent Laurussia (Ziegler, 1989; Golonka, 2007; Golonka and Gawęda, 2012; Golonka *et al*., 2017a, b; Figs 17, 18).

The Caledonian foreland basin began to form during the earliest Silurian along the western margin of Baltica in Poland (Poprawa *et al*., 1999; Golonka *et al*., 2017a; Poprawa, 2017) and expanded diachronously southwards (Mazur *et al*., 2018b). The increase in flexural subsidence, superimposed on the post-Hirnantian global sea-level rise (Poprawa *et al*., 1999; Golonka and Kiessling, 2002; Lazauskiene *et al*., 2002; Haq and Shutter, 2008; Van der Meer *et al*., 2017), resulted in the transgressive expansion of shelfal mudstones onto cratonic areas (Dziadzio *et al*., 2017). According to Botor *et al*. (2017b, c), the rate of tectonic subsidence in the EEC margin exceeded 500 m/my and was accompanied by a high sediment influx (Poprawa *et al*., 1999; Poprawa, 2006a, b; 2017). The Silurian succession exceeds 3,500 m in thickness in the Pomeranian segment of the EEC (Fig. 4) and is dominated by mudrocks that pass eastwards



into shoreline carbonates (Modliński, 1982, 2010; Porębski and Podhalańska, 2017, 2019). The succession begins with black, organic-rich laminated mudstones of Rhuddanian–Aeronian age (Jantar Formation *sensu* Porębski and Podhalańska, 2017, 2019; Fig. 24). Upwards, this facies becomes interbedded on a centimetre scale with green, bioturbated mudstones in the Telychian (Pasłęk Formation) and both facies reflect deposition on a sediment-starved distal-shelf ramp that was subjected to fluctuating near-bottom oxygen levels (Dziadzio *et al.*, 2017). The overlying Wenlock strata consist of dark, less organic-rich argillaceous, dolomitic and calcareous, laminated mudstones, which are intercalated with very thin, bioclastic lag deposits as well as calcisiltite and calcarenite tempestites. Early diagenetic, carbonate concretions are common (Bojanowski *et al.*, 2019). The mudstones increasingly are interbedded upwards and basinwards with thin beds of quartz siltstone and rare sandstone (Kociewie Formation), which dominate the Ludlow strata (Fig. 24; Dziadzio *et al.*, 2017). This siliciclastic unit reflects copious sediment supply into rising, tectonically-driven accommodation settings and is believed to reflect a Caledonian synorogenic wedge that invaded the foredeep from the west and northwest (Jaworowski, 2000; Dziadzio *et al*., 2017). In this Silurian mudrock succession, only the Jantar Formation is a potential source for shale gas (Botor *et al*., 2017a, b; Papiernik *et al*., 2017, 2019).

Devonian–Carboniferous

The remnants of the Rheic Ocean still existed during Late Devonian time (Figs 20, 21). The final closure of this ocean occurred during the Variscan orogeny (Torsvik and Rehnström, 2003; Cocks and Torsvik, 2005; Golonka, 2009; Torsvik *et al*., 2012). The Pangea supercontinent originated during the Carboniferous (Figs 22, 23) as a result of the rotation of Gondwana and a series of orogenies (Variscan and Alleghenian) reflecting the collision of Gondwana and Laurussia. According to Golonka (2007), the Variscan orogeny in Europe was a result of the collision of several separate blocks, belonging to the Gondwanan promontory, with the Laurussia margin, followed by the involvement of the Gondwana continent. The Variscan orogeny in Poland was caused by the collision of the Bohemian Massif plates and the Protocarpathian terrane with Laurussia. The Protocarpathian terrane (Fig. 1) might have acted as an indentor that caused thrust tectonics in the Holy Cross Mountains and Lublin areas (Golonka, 2007; Golonka *et al*., 2015; Krzywiec *et al*., 2017). The Protocarpathian terrane was sutured to the northern (Laurussian) branch of Pangea after the Variscan orogeny (Golonka and Gawęda, 2012). The Palaeotethys Ocean was located south of this branch (Fig. 20).

Fig. 24. Lithostratigraphic subdivision of the Cambrian–Silurian deposits in the East European Craton (modified from Porębski and Podhalańska, 2017, 2019).

CONCLUSIONS

The EEC belonged to the Palaeozoic Baltica plate, which originated as a result of the disintegration of the supercontinent Pannotia during the early Cambrian. The Early Ordovician was the time of maximum dispersion of continents during the Palaeozoic. Avalonia was sutured to Baltica during the Caledonian orogeny and the assembly of the supercontinent Laurussia. The Variscan orogeny in Poland was caused by the collision of the Bohemian Massif plates and the Protocarpathian terrane with Laurussia. The Protocarpathian terrane acted as an indentor that caused thrust tectonics in the Lublin area of the EEC.

The reconstruction of the Palaeozoic evolution of the EEC broadens our knowledge about the origin of the Lower Palaeozoic shales rich in organic carbon and expands our knowledge concerning the facies context of the shale gas deposits. The Upper Ordovician (mainly Caradoc) and Lower Silurian (mainly Llandovery) graptolitic shales, characterized by relatively high total organic carbon contents within intervals of considerable thickness as well as thermal maturity high enough for hydrocarbon generation, display the greatest shale-gas potential.

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