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Development of Trans-European Suture Zone in Poland: from Ediacaran rifting to Early Palaeozoic accretion

Jerzy NAWROCKI and Paweł POPRAWA

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This contribution summarizes selected results of the "Palaeozoic Accretion of Poland" Project. Emphasis is placed on geochronological, geochemical and palaeomagnetic constraints on the Late Neoproterozoic to Early Palaeozoic development of the Trans-European Suture Zone (TESZ). During the Late Neoproterozoic break-up of Rodinia, a major rift developed in the area of the future TESZ along which Baltica was separated from peri-Gondwana and Laurentia, resulting in opening of the Tornquist Ocean and development of the southwestern Baltica passive margin. This was paralleled by the development of the Cadomian orogenic system along the margin of Gondwana and the eastern and southern margins of Baltica. Some tectonic units involved in the TESZ, such as the Brunovistulian Terrane and the Małopolska Massif characterized by Cadomian basement, were derived from the internal and external parts of the Cadomian Orogen, presumably somewhere at the SE or SW corners of Baltica. Determination of areas where these terrains were originally located depends strongly on the Ediacaran plate model that is adopted for Baltica. The Małopolska Massif was re-accreted to Baltica, presumably due to latest Ediacaran strike-slip tectonics, during the late Middle to Late Cambrian, causing at that time an interruption of its passive margin subsidence pattern and minor erosion. During Late Ordovician to Silurian times, the Caledonian collision of Gondwana-derived East Avalonia Terrane with Baltica gave rise to the development of a foredeep basin along the southwestern margin of Baltica. The proximal part of this foredeep corresponds to the Pomeranian region to the Koszalin-Chojnice Zone, and its distal parts to the Baltic Basin, both of which developed on Baltica basement. During Ordovician and Silurian times clastics were shed into the Koszalin-Chojnice Zone and the Baltic Basin from the evolving Caledonian orogenic wedge, consisting of a subduction-related volcanic arc, obducted ophiolites and accretionary prism, as well as crustal units that were detached from basement of Baltica and Avalonia. The Brunovistulian Terrane was accreted to the Małopolska Massif at the turn from the Silurian to the Devonian. Proximal terranes, such as the Pomerania and Łysogóry units remained after Late Neoproterozoic rifting in a position close to the relatively mobile SW margins of Baltica.

Jerzy Nawrocki and Paweł Poprawa, Polish Geological Institute, ul. Rakowiecka 4, PL-00-975 Warszawa, Poland, e-mails: jerzy.nawrocki@pgi.gov.pl; pawel.poprawa@pgi.gov.pl *(received: November 2, 2005; accepted: March 20, 2006).*

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INTRODUCTION

Despite extensive geophysical and geological studies the early stages of the tectonic evolution of the Trans-European Suture Zone (TESZ) that separates the East European Craton (EEC) from the Variscan and Alpine orogens (Fig. 1) has remained enigmatic. The provenance and accretionary history of crustal blocks involved in the TESZ is still under discussion and subject to contrasting interpretations, particularly concerning their derivation either from Baltica or Gondwana (see e.g. Pożaryski, 1991; Dadlez, 1995; Belka *et al*., 2002; Cocks, 2002). This pertains particularly to such crustal blocks as the Brunovistulicum (Brochwicz *et al*., 1986; Moczydłowska, 1997; Belka *et al*., 2002; Nawrocki *et al*., 2004*b*), the Małopolska Massif (Pożaryski, 1991; Lewandowski, 1993; Belka *et al*., 2002), the Łysogóry Unit (Pożaryski, 1991; Belka *et al*., 2002) and the Pomerania Unit (Pożaryski, 1991; Samuelsson *et al*., 2002), all of which are considered as potential allochthonous or exotic terranes, in the sense that they probably do not represent crustal fragments that were locally derived from the EEC.

Apart from the interpretation by Żelaźniewicz (1998), there is general agreement that the Brunovistulicum has an exotic origin, although its provenance and drift history remains a matter of controversy. For instance, Moczydłowska, (1997) proposed that it was derived from the Avalonian part of peri-Gondwana, whilst Nawrocki *et al*. (2004*b*) suggested it originated from its Arabian part. Taking into consideration the Late Neoproterozoic Baltica model presented by Nawrocki *et al*. (2004*a*), it is, however, more likely that this terrane was derived from the Cadomian belt that was located between peri-Gondwana and the southern margin of

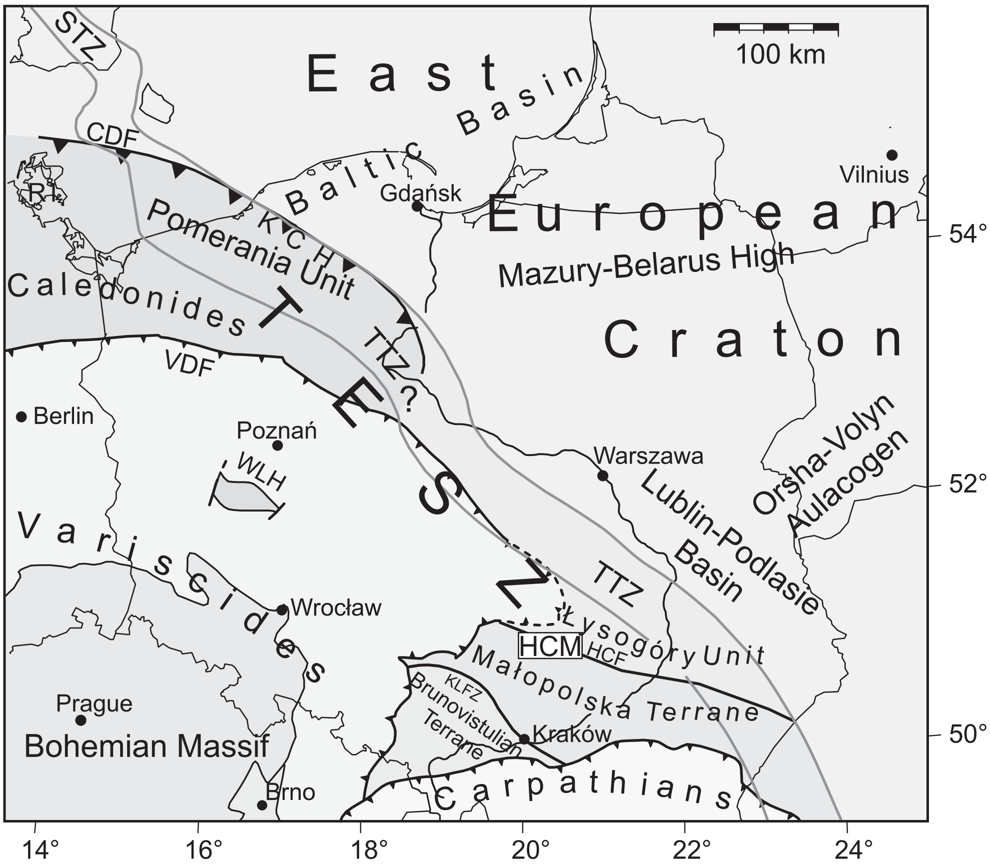

Fig. 1. Tectonic sketch map of Central Europe
(after Winchester and the PACE TMR Network Team 2002; Mazur and Jarosiński, 2006)

CDF — Caledonian Deformation Front; HCF — Holy Cross Fault; HCM — Holy Cross Mountains; KCH — Koszalin-Chojnice Zone; KLFZ — Kraków-Lubliniec Fault Zone; RI — Rügen Island; STZ — Sorgenfrei-Tornquist Zone; TESZ — Trans-European Suture Zone; TTZ — Teisseyre-Tornquist Zone; WLH — Wolsztyn-Leszno High; VDF — Variscan Deformation Front (after Pożaryski *et al.*, 1992)

the Baltica. Similarly, the origin of the Małopolska Massif is a matter of controversy. Many authors have questioned its exotic origin. According to Cocks (2002) and Cocks and Torsvik (2005), its Cambrian trilobite fauna (Orłowski, 1985) shows Baltic affinities. Dadlez *et al.* (1994) and Dadlez (1995) interpreted the Małopolska Massif at best as a proximal terrane that was detached from the EEC and later re-accreted to it. The postulate of an exotic origin for the Łysogóry and Pomerania units (Pożaryski, 1991; Belka *et al.* 2002; Samuelsson *et al.*, 2002) appears to be even more problematic.

The aim of this paper is to review problems related to Late Neoproterozoic rifting along the present-day SW margin of the East European Craton and the subsequent amalgamation of tectonic blocks forming now the TESZ in Poland. These processes cannot be analyzed without taking the Neoproterozoic-Early Palaeozoic palaeogeographic/palaeotectonic evolution of Baltica into consideration. This contribution summarizes the results of the project "Paleozoic Accretion of Poland" (no. PCZ-007-21), details of which are presented elsewhere (Nawrocki *et al.*, 2006; Poprawa *et al.*, 2006; Krzemiński and Poprawa, 2006)

THE BALTIC PLATE IN THE EDIACARAN — EARLY PALAEOZOIC

There is general agreement that continental Baltica had formed part of the putative Middle to Late Proterozoic megacontinent Rodinia that began to break-up around 750 Ma, resulting in the opening of the Palaeopacific Ocean, that was followed around 550 Ma by the opening of the Iapetus and Tornquist oceans (e.g. Torsvik *et al.*, 1996; Dalziel, 1997; Meert and Torsvik, 2003). However, the precise location and drift history of Baltica after its late Vendian (Ediacaran) separation from western Gondwana (Nance *et al.*, 2002) is still a matter of debate. In this respect, it should be noted that difficulties in reconstructing the Ediacaran palaeogeographic position of crustal blocks now involved in the Polish part of the TESZ are partly caused by the lack of an unequivocal setting of the Baltica at these times.

Based on palaeomagnetic poles obtained from the Fen complex of southern Norway (Piper, 1988; Meert *et al.*, 1998) only minor movements have been proposed for Baltica during the time span of 555–500 Ma (e.g. Hartz and Torsvik, 2002; Cocks

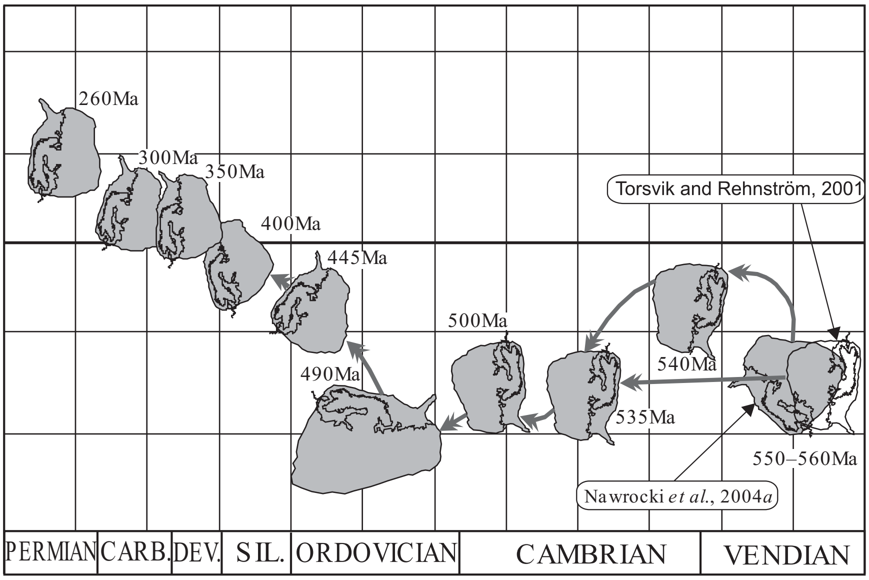

Fig. 2. Drift pattern of Baltica during late Vendian-Early Permian times based on palaeomagnetic data

The Early Ordovician to Early Permian positions are according to Torsvik *et al*. (1990, 1996); alternate models for the late Vendian-Late Cambrian setting of Baltica are based on Torsvik and Rehnström (2001) and Nawrocki *et al*. (2004*a*)

and Torsvik, 2005). In these reconstructions Baltica is located between 30 and 60 of southern latitude with its present SW margin facing north and its NE margin that includes the Baikalian Timanides Orogen facing the Cadomian NW part of peri-Gondwana (Fig. 2). This model does not explain, however, some tectonic problems such as the Cadomian-consolidated basement of the Brunovistulian Terrane and the partly metamorphosed Ediacaran flysch in the basement of the Małopolska Massif, assuming that these blocks were located initially near the present SW margin of Baltica (see Żelaźniewicz, 1998).

Lewandowski and Abrahamsen (2003) proposed a certain modification of the Baltica setting by locating it in a more equatorial position, at least during the Early Cambrian. On the other hand, Nawrocki *et al.* (2004*b*), taking into account palaeomagnetic data from the Ukrainian-Volynian basalts and Winter Coast sediments (NW Russia) (Popov *et al*., 2002), suggested that Baltica moved during late Ediacaran times (550–540 Ma) from moderate southern to equatorial latitudes while undergoing an anticlockwise rotation of about 120 (Fig. 2). Before these movements, the TESZ margin of Baltica faced western peri-Gondwana and partly Laurentia as proposed by Murphy *et al*. (2002). It should be stressed, however, that this model dramatically changes our understanding of the Timanides and the history of the Iapetus Ocean (see Nance *et al*., 2002; Cocks and Torsvik, 2005). According to the model by Cocks and Torsvik (2005), the Timanides Orogen developed within the mobile belt that was located between the present NE margin of Baltica and NW peri-Gondwana, and the Iapetus Ocean opened initially between Laurentia and western Gondwana.

The location of Baltica during the Cambrian appears to have been stable and similar to that proposed for the Ediacaran by Torsvik and Rehnström (2001). The occurrence of Late Cambrian eclogites (505–500 Ma) indicates that subduction of the Iapetus Ocean had commenced in the domain of the Scandinavian Caledonides marking the present-day western margin of Baltica (Andréasson, 1994; Gee, 2004). Collision between this part of Baltica and an intra-oceanic arc/trench system during the Finnmarkian orogeny led to a rapid 55 counter-clockwise rotation of Baltica at the turn from the Cambrian to the Ordovician within 20 Ma (Torsvik and Rehnström, 2001). During the Arenig the Avalonia Terrane was detached from the northern margin of Gondwana and drifted between 480 and 460 Ma rapidly northward to reach during the Caradoc palaeolatitudes comparable to those of Baltica (*ca*. 30 S) (Cocks and Torsvik, 2002). In the process of this, the crust of the Tornquist Ocean was subducted beneath Avalonia that collided with Baltica during the Ashgill (Torsvik and Rehnström, 2002). These combined landmasses collided during the Silurian (between 425 and 420 Ma) with Laurentia, giving rise to the to Scandian Orogeny that resulted in the suturing of the Laurussian megacontinent (Ziegler, 1989; Gee, 2004).

TRANS-EUROPEAN SUTURE ZONE IN POLAND DURING THE EDIACARAN TO EARLIEST CAMBRIAN

NEOPROTEROZOIC RIFTING AT THE WESTERN MARGIN OF THE EAST EUROPEAN CRATON

Relatively thick, undeformed Neoproterozoic and Phanerozoic sediments cover the SW marginal parts of the East European Craton (EEC). Ediacaran to Early Palaeozoic strata were deposited in multistage and polygenetic basins, development of which, at least partly, records tectonic processes that governed the development of the TESZ (e.g. Jaworowski, 1971, 1997; Pożaryski and Kotański, 1979; Garetsky *et al*., 1987; Modliński *et al*., 1994; Nikishin *et al*., 1996; Poprawa *et al*. 1999; Poprawa and Pacześna, 2002; Poprawa, 2006*a*).

The main Ediacaran to Early Palaeozoic depocentres developed along the western margin of the EEC in the Peri-Tornquist system of basins that is elongated in a NW–SE direction. This system interferes with NE–SW elongated depocentres and basins such as the Orsha-Volyn Aulacogen and Baltic Basin. Due to presence of Mazury-Belarus High, the sedimentary cover of the western EEC is subdivided into the Baltic and Lublin-Podlasie basins (Fig. 1). A distinct feature of basins associated with the

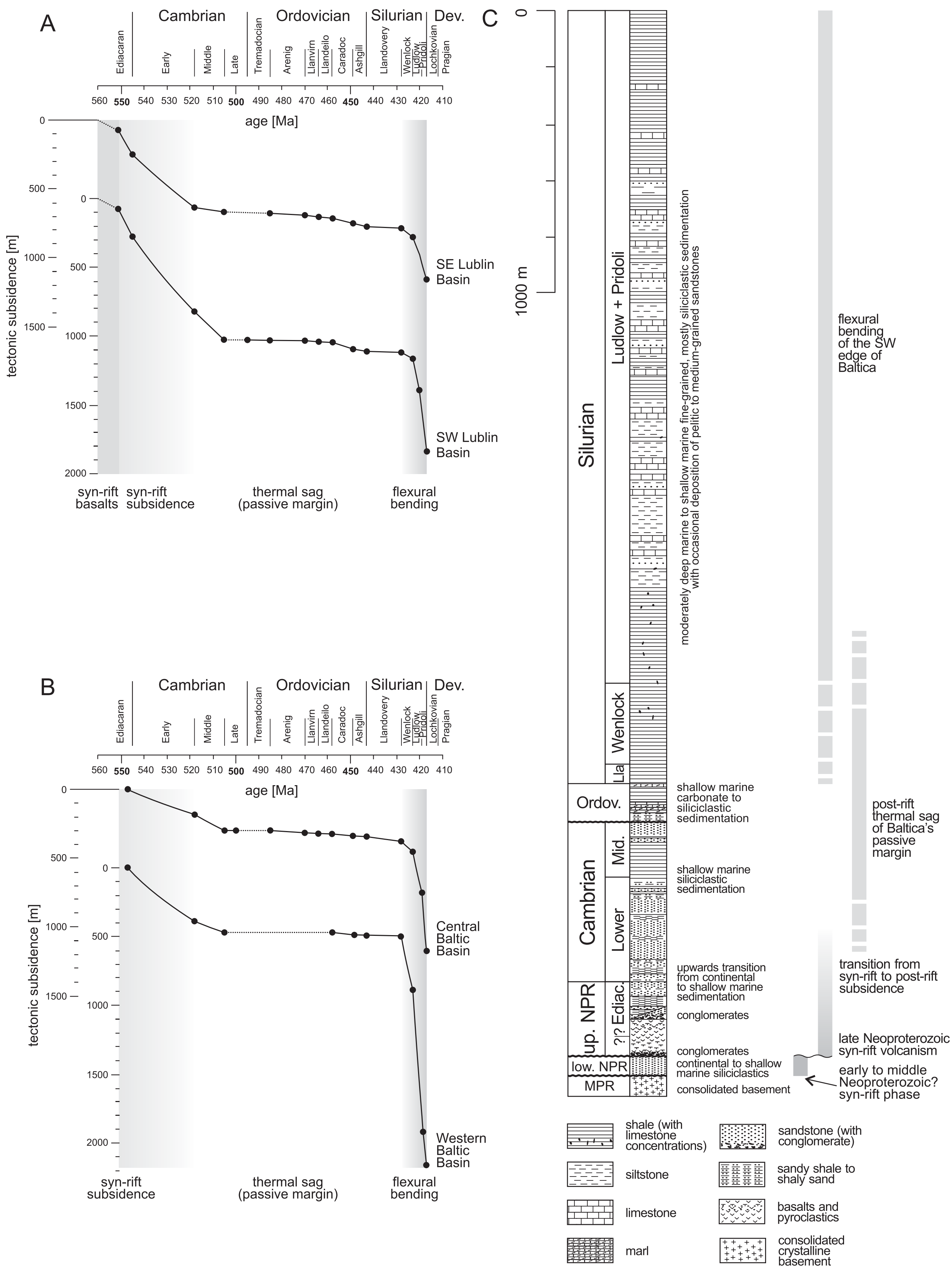

Fig. 3. Tectonic subsidence curves for representative well sections from (A) Lublin-Podlasie Basin and (B) Baltic Basin, and (C) correlation between main phases of basin evolution and development of the basin-fill (after Poprawa *et al.*, 1999; Poprawa and Pacześna, 2002)

NPR — Neoproterozoic; MPR — Mesoproterozoic western margin of the EEC is a virtually continuous Late Neoproterozoic to Silurian succession, except for an erosional gap comprising the upper Middle and Late Cambrian (Fig. 3C).

In the Lublin-Podlasie Basin the oldest sediments, covering the Palaeo- to Mesoproterozoic and older crystalline basement of the western EEC (e.g. Ryka, 1984; Bogdanova *et al*., 1997; 2001), are represented by the continental clastics of the Polesie Formation (Areń, 1982). To the east of the Lublin Basin, lateral equivalents of this succession reach thicknesses of up to 1000 m in grabens (Mahnatsch *et al*., 1976), such as the Orsha-Volyn Aulacogen. These developed during an early-middle Neoproterozoic rifting phase (Fig. 3C) that was associated with the Rodinia/Pannotia break-up (*cf*. Poprawa and Pacześna, 2002; Pacześna and Poprawa, 2005).

The time constrains for this phase of rifting are poor, as the sedimentary fill of these grabens lacks biostratigraphic control. However, these sediments, which contain detrital mica yielding K-Ar ages in the range of 700–770 Ma are unconformably covered by flood basalts ranging in age between 600 and 540 Ma (Semenenko, 1968; Emetz *et al*., 2004). Therefore, the development of these grabens and the related first rifting phase along the western margin of EEC can be roughly dated as Late Neoproterozoic (*c*. 700–600 Ma; Pacześna and Poprawa, 2005; Poprawa, 2006*a*). This contrasts with the assumption of a Mid-Riphean age of sediments contained in these grabens (e.g. Mahnatsch *et al*., 1976) and with previous models of Mesoproterozoic rifting underlying the development of the TESZ (Pożaryski and Kotański, 1979; Bogdanova *et al*., 1997; Żelaźniewicz, 1998). On the other hand, this is compatible with rift-related intrusion of dyke swarms along the Balto-Scandian margin, dated 750–650 Ma (Andréasson, 1994).

A major, second rifting event along the western margin of Baltica (Fig. 3C) is evidenced by the development of a large flood basalts province that extends from SE Poland, western Ukraine and Moldova through Belarus to Russia, and covers an area of roughly 140 000 km^2 (Ryka, 1984; Rozanov and Łydka, 1987; Bogdanowa *et al*., 1997; Emetz *et al*., 2004). Geochemical and petrological characteristics of these basalts, dykes and sills and associated pyroclastic rocks are clearly indicative for continental rifting (e.g. Białowolska *et al*., 2002; Emetz *et al*., 2004; Krzemińska, 2005). Volcanic activity was centered on the NE–SW trending Orsha-Volyn Aulacogen.

The youngest age for this volcanic activity was obtained by U-Pb dating of zircons from a tuff horizon at the top of the flood basalt succession yielding 551±4 Ma (Compston *et al*., 1995). K-Ar dating by Velicanov and Korenchuk (1997) indicates an age of *c*. 500–600 Ma for the flood basalts and *c*. 500–660 Ma for the gabbro-dolerite dikes and sills. Sokolov and Fedonkin (1990) obtained similar isotopic ages of 625–590 Ma on the Volyn basalts. The age for the basal part of this flood basalt succession is, however, poorly constrained by the essentially undated underlying sediments. Palaeomagnetic data on the Volyn basalts, acquired by Nawrocki *et al*. (2004*a*), confronted with the geochronological data of Popov *et al*. (2002) suggest that at least the upper part of the succession has a late Ediacaran age. Therefore it is reasonable to assign a late Ediacaran age to this second rifting event along the western margin of the EEC (Poprawa and Pacześna, 2002; Poprawa, 2006*a*). This timing is compatible with the rift-related intrusion of sheeted dykes and alkaline complexes along the Balto-Scandian margin, yielding ages in the range of 575–540 Ma (Andréasson, 1994), and with the onset of sea-floor spreading in the Iapetus Ocean commencing around 540–530 Ma (Gee, 2004).

Subsidence and facies analysis indicate, that this rifting phase, that preceded crustal separation between Baltica and Gondwana and the opening of the Tornquist Ocean, affected both the NW–SE trending Peri-Tornquist Zone and SW–NE trending Orsha-Volyn Zone (Poprawa and Pacześna, 2002). This led to development of a triple-junction south-west of the Lublin-Podlasie Basin, with the Orsha-Volyn Aulacogen representing the abandoned arm. This contradicts, however, the interpretations of Żelaźniewicz (1997), Żelaźniewicz *et al*. (1998) and Malinowski *et al*. (2005) that suggest Late Neoproterozoic convergence and collision along the western margin of Baltica. This model is based mainly on geological and geophysical data from the Cadomian deformed Brunovistulicum and Małopolska blocks. These contrasting interpretations of the Ediacaran megatectonic setting of SW Baltica can, however, be reconciled by invoking a post-Ediacaran strike-slip displacement of terranes involved in the TESZ (Poprawa and Pacześna, 2002; Poprawa, 2006*a*).

Late Ediacaran rifting along the SW margin of Baltica and subsequent opening of the Tornquist Ocean is confirmed by the Early Palaeozoic development of passive margin-type sedimentary basins. The late Ediacaran to Middle Ordovician subsidence history of the Lublin-Podlasie and Baltic basins and their progressive lateral expansion, as well as their facies development, are indicative of a latest Ediacaran to earliest Cambrian transition from syn-rift to post-rift subsidence and subsequent thermal subsidence of the passive continental margin (Fig. 3A, B) (Poprawa *et al*., 1999; Jaworowski, 2000*a*; Poprawa and Pacześna, 2002; Jaworowski and Sikorska, 2003; Poprawa, 2006*a*). Stratigraphic-sedimentological studies (Pacześna, 2005) document late syn-rift controls on the evolution of the latest Ediacaran to earliest Cambrian depocentre of the Lublin-Podlasie Basin. At the NW margin of Baltica a contemporaneous transition from syn- to post-rift subsidence at the onset of sea-floor spreading in the Iapetus Ocean is observed (Kumpulainen and Nystuen, 1985; Greiling *et al*., 1999; Gee, 2004).

Further evidence for Neoproterozoic rifting was obtained from reflection seismic data recorded in SW Baltic Sea that reveal the occurrence of presumably Neoproterozoic grabens along the western margin of Baltica (Lassen *et al*., 2001). Petrological, geochemical and geochronological studies on upper Ediacaran to Cambrian sediments in the German sector of the Baltic Sea (G 14 borehole) and in the basement of the Rügen Zone (Loissen 1 borehole) also indicate a passive margin setting for this basin (McCann, 1998; Giesse and Köppen, 2001; Giese *et al*., 2001).

CADOMIAN OROGEN IN SOUTHERN POLAND

THE BRUNOVISTULIAN TERRANE

The Brunovistulian Terrane* (BT) (e.g. Dudek, 1980; Pożaryski, 1991; Dadlez, 1995; Buła *et al*., 1997), located in SW Poland (Fig. 1), was one of the first tectonic units of Central Europe to be defined as a "terrane" (Ziegler, 1984; Brochwicz-Lewiński *et al*., 1986) and its exotic terrane nature is not questioned by most of the authors (e.g. Pożaryski, 1991; Dadlez, 1995; Franke, 1995; Pharaoh, 1999). An exotic Early Palaeozoic position of the BT with respect to EEC, as well as to the Małopolska and Bohemian massifs is suggested by its Cadomian consolidated basement (Dudek, 1980), palaeomagnetic data (Nawrocki *et al*., 2004*b*) and the development of its sedimentary cover (Buła *et al*., 1997; Buła, 2000), as well as by major wrench zones that delimit the BT, particularly to the north and east (Żaba, 1999, Buła, 2000, Malinowski *et al*., 2005). Authors postulating an allochthonous origin for the BT interpret it as a crustal fragment that was derived from the margin of Gondwana. This is based on its general geological framework (Unrug *et al*., 1999), faunal provinciality (Moczydłowska, 1997) and detrital mineral provenance studies (Belka *et al*., 2000), as well as on Nd model ages and the age of single zircon grains from the basement (Finger *et al*., 2000*a*, *b*; Hegner and Kröner 2000; Friedl *et al*., 2001). According to mobilistic interpretations, the BT was located during Neoproterozoic-Early Cambrian times in the Cadomian peri-Gondwana belt, either in its South American (Hegner and Kröner 2000; Friedl *et al*., 2001) or North African sector (Unrug *et al*., 1999; Leichman and Höck, 2001). A more stationary model was presented by Żelaźniewicz (1998) and Żelaźniewicz *et al*. (2001) according to which the BT and the Ediacaran (Vendian) foreland flysch basin of the neighbouring Małopolska Block were derived from a part of the Cadomian Orogen that was located adjacent to the future TESZ margin of Baltica.

The basement of the BT is composed of metamorphic and igneous rocks, mostly Cadomian (Neoproterozoic) in age (Dudek, 1980; Van Breemen *et al*., 1982; Finger *et al*., 2000*a*, *b*; Żelaźniewicz *et al*., 2001; Mazur *et al*., 2006). In some places these are covered by Vendian greenschist-grade metasediments (Żelaźniewicz *et al*., 2001). Gently deformed non-metamorphic Lower Cambrian to Ordovician sediments overlay the Cadomian basement of the BT (Fig. 4; Buła, 2000). The chronostratigraphy of Lower Cambrian clastic sediments, which in the northern part of the BT continue into the Middle Cambrian and Ordovician, is based on acritarch and trilobite faunas (Orłowski, 1975; Moczydłowska, 1995, 1997; Jachowicz and Přichystal, 1998). The Early Palaeozoic and basement rocks of the BT are unconformably covered by continental Early Devonian clastics that are followed by marine carbonates and shales (Konior and Turnau, 1973).

* Several authors use the term "Bruno-Silesian" instead of "Brunovistulian" which is intended at more precisely defining the crustal block underlying the Moravian and Upper Silesian parts of the terrane. In this volume, the editors decided to use the latter term for the sake of consistency.

Although the basement of the BT was clearly consolidated during the Cadomian Orogeny (*c*. 650–570 Ma; Dudek, 1980; Mazur *et al*., 2006), it is not an easy task to determine from which part of the Cadomian belt it was derived. The "autochthonous" BT model proposed by Żelaźniewicz (1998) does not fit the concept of Ediacaran Baltica presented by Cocks and Torsvik (2005), according to which the TESZ margin of Baltica was passive at the Ediacaran-Cambrian transition and located far away from the peri-Gondwana Cadomian belt. In the reconstruction of Nawrocki *et al*. (2004*a*), however, the SW corner of Baltica faced in late Ediacaran times a Cadomian belt. Correspondingly, the BT may have been separated around 555 Ma from this peri-Gonwana Cadomian domain at about the same time as the Tornquist Ocean began to open. In this respect, the BT was presumably started to translate during the late Ediacaran rotation of Baltica along its TESZ passive margin towards its present position (Fig. 2).

The palaeomagnetic pole obtained from Early Cambrian red beds of the BT (Nawrocki *et al*., 2004*b*) is strongly rotated and as such does not fit the Cambrian part of the Baltic apparent polar wander path (APWP). Nevertheless, it gives a palaeolatitude that fits the Early Cambrian position of the TESZ margin of Baltica or the Arabian part of peri-Gondwana. The latter location of the BT is rather less likely owing to differences in the Early Cambrian trilobite fauna. Cambrian trilobites from the BT, if diagnostic, indicate rather Baltica than Gondwana affinities. The endemic taxon *Schmidtiellus panowi* (Samsonowicz) occurs only in the Małopolska Massif and on the BT (see Nawrocki *et al*., 2004*b*), and therefore points to their Early Cambrian proximity and possibly their location close to the TESZ margin of Baltica; this pertains particularly to the Małopolska Massif, at least from Mid-Cambrian times onward (see below). However, the record of latest Cambrian rifting processes in the western part of the BT (Hegner and Kröner, 2000) casts some doubts on this interpretation since there is extensive evidence for Cambrian rifting in the northern peri-Gondwana Cadomian belt (see e.g. Nance *et al*., 2002). This may suggest a Cambrian peri-Gondwana setting for the BT, that is however not compatible with its faunal affinities.

THE MAŁOPOLSKA MASSIF

The Małopolska Massif (Block) and the Łysogóry Unit, both of which crop out in the Holy Cross Mts. (HCM), are regarded by some authors (e.g. Belka *et al*., 2002) as the first Gondwana-derived terranes that were accreted to the TESZ margin of Baltica during the Middle Cambrian-Early Ordovician or the Late Silurian (Pożaryski, 1991). A peri-Gondwana origin of the Małopolska Massif is inferred mainly from the isotopic age (*c*. 540–560 Ma) of detrital micas and zircons contained in Cambrian sediments and the biogeographic affinity of Early Cambrian brachiopods (Fig. 4; Belka *et al*., 2002). Similarly, Winchester *et al*. (2002) took the presence of a Cadomian-deformed basement, combined with the Gondwana-affinity of the Early Cambrian brachiopod faunas, as evidence for the Gondwana derivation of the Małopolska Massif. On the other hand, Żelaźniewicz (1998) suggested that the Ediacaran (Neoproterozoic) flysch sequences (foreland basin deposits) of the Małopolska Massif and the adjacent

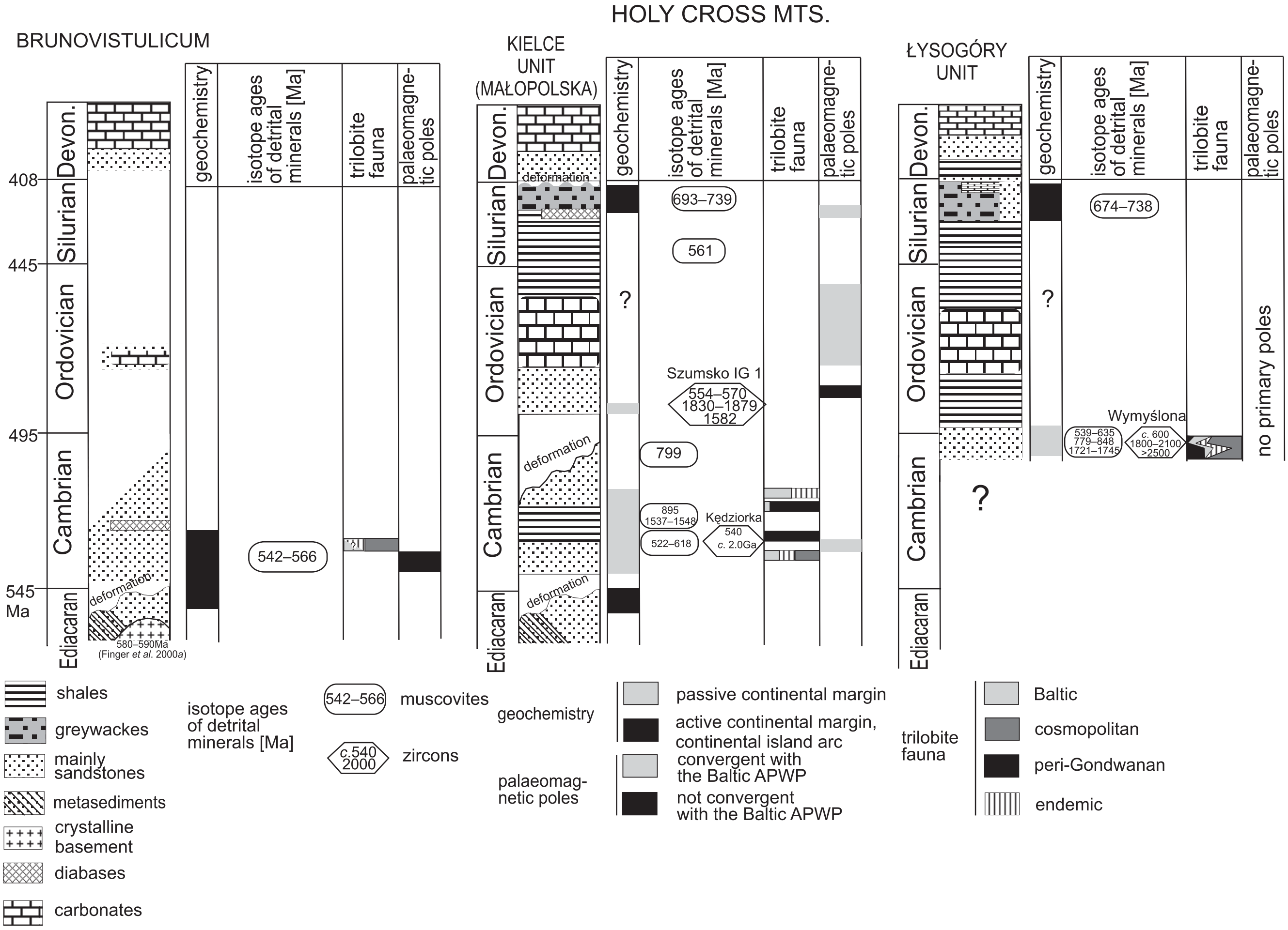

Fig. 4. Diagrammatic stratigraphic columns for main crustal units involved in the TESZ of southern Poland and selected provenance data obtained for their sedimentary successions

Isotope ages of detrital minerals are presented according to Belka *et al.* (2002) and Nawrocki *et al.* (2006); geochemical features are based on Nawrocki *et al.* (2006) and Kozłowski *et al.* (2004); Sc-Th-Zr/10 discriminant plot (after Bhatia and Crook, 1986) was used for interpretation of a tectonic setting; palaeomagnetic data are adopted from Nawrocki (2000), Nawrocki *et al.* (2004*b*, 2006), Lewandowski (1993) and Schätz *et al.* (2002); palaeogeographic interpretation of trilobite fauna is according to Żylińska (2002), and Nawrocki *et al.* (2004*b*, 2006); time scale after Gradstein *et al.* (2004)

Brunovistulian Terrane were initially located close to the future TESZ margin of Baltica. Cocks (2002) and Cocks and Torsvik (2005), postulated a Baltica affiliation of the HCM, emphasizing the Baltica affinity of Cambrian trilobites, which occur in the southern Kielce Unit of the Małopolska Massif.

Discrepancies between the different derivation models for the HCM arise not only from uncertainties concerning the palaeogeography of Baltica, but above all from a lack of credible provenance constraints, such as isotopic ages of detrital minerals, whole-rock geochemistry and palaeomagnetic data. Moreover, the Cambrian trilobite faunas of the HCM required verification. To address these deficiencies, a new study of the Ediacaran to Early Palaeozoic rocks of Małopolska Massif was undertaken (Nawrocki *et al.*, 2006), the results of which are summarized in Figure 4.

New geochemical data indicate that the Ediacaran sediments of the Małopolska Massif were derived from the continental basement of an orogenically active domain whilst the Lower Cambrian clastics were deposited under a passive margin setting on the flanks of a stable craton.

The palaeomagnetic pole isolated from the Early/Middle Cambrian Kamieniec Shale Formation (Małopolska part of the HCM) coincides with the Early Cambrian segment of the Baltic APWP constructed on the basis of Scandinavian poles (Torsvik and Rehnström, 2001; Lewandowski and Abrahamsen, 2003).

Although most of the trilobite taxa of the both units of HCM are endemic species, some parts of the Cambrian succession yielded nevertheless taxa diagnostic for other biogeographic areas, thus indicating possible palaeogeographic links of the HCM basin to Baltica and/or peri-Gondwana (Nawrocki *et al.*, 2006). A significant contribution of Baltica trilobites is evident in the lowermost and uppermost parts of the Early-Middle Cambrian succession of the Kielce region and in the uppermost part of the Late Cambrian sequence of the Łysogóry region. However, peri-Gondwana trilobites dominate in the Kamieniec and Słowiec formations (Early to Middle Cambrian, Kielce region) and in the Late Cambrian (Furongian) Wiśniówka Fm. (Łysogóry region). Taken at face value, these trilobite faunal affinities suggest a very "dynamic" palaeogeography for the HCM. However, this is difficult to explain in terms of the relative position of Baltica and Gondwana that did not change substantially in the course of the Cambrian. As the different Cambrian trilobite faunas of the HCM may actually be related to particular lithofacies, their biogeographic significance is presumably limited. As such, they do not permit to arrive at an unequivocal palaeogeographic solution.

New isotope age estimates (Nawrocki *et al*., 2005) indicate that the Cambrian sediments of the Małopolska part of the HCM contain muscovites derived not only from a late Cadomian source, as defined by Belka *et al*. (2002), but also from sources with an igneous-metamorphic overprint dated at *c*. 0.8–0.9 Ga and 1.5 Ga. The Cadomian ages of detrital minerals in Cambrian sediments of the HCM area point to its proximity to the Cadomian orogenic belt. Part of these minerals may have been derived from the metamorphosed foreland flysch of the southern Małopolska Massif. On the other hand, detrital muscovites yielding a 1.5 Ga age were most probably derived from the contact zones of Rapakivi type granites of the EEC. Detrital zircons in the Tremadocian sandstones of the Szumsko borehole yielded ages of 1.83–1.88 Ga (Fig. 4) that can point to a Fennoscandian source as well.

A possible Cambrian proximity of the Małopolska Massif and the TESZ Baltica margin is also inferred from the similarity of the palaeomagnetic pole isolated from the Kamieniec Fm. and coeval Baltica poles. Although the geochemical record does not point to an Early Cambrian separation, Middle Cambrian convergence and subsequent collision of the Małopolska Massif with the TESZ Baltica margin, as postulated by Belka *et al.* (2002), the deformed and metamorphosed Ediacaran foreland flysch and the contrasting geochemical signature of Ediacaran and Cambrian sediments indicate that at the end of the Neoproterozoic the Małopolska Massif was located in an area characterized by intense orogenic activity. A location of the Małopolska Massif within the Cadomian belt and its transfer to the Polish part of the TESZ at the Ediacaran-Cambrian turn is, however, not compatible with the plate reconstruction of Cocks and Torsvik (2005) that assumes at that time no major plate boundary reorganization and postulates passive southern and western Baltica margins (in present coordinates). Nawrocki *et al.* (2004*b*) proposed an alternate Ediacaran plate reconstruction that is more compatible with the available data, according to which the southern and southwestern margins of Baltica faced a Cadomian belt. In this reconstruction the Małopolska Massif formed the foreland of the Cadomian Orogen near the present southeastern corner of Baltica, and was translated in latest Ediacaran to Late Cambrian times along TESZ Baltica margin close to its present position. This model resembles the reconstructions proposed by Lewandowski (1993) and Narkiewicz (2002), but differs in the derivation and tectonic transport timing of the Małopolska Block. An "in situ" Ediacaran evolution of the Małopolska Block is less likely as the Polish segment of Baltica was at these times affected by rifting and not by compressional tectonics (see Poprawa *et al*., 1999).

Middle Neoproterozoic detrital muscovites, as contained in the Cambrian sediments of both HCM units, are not known from the Cambrian series of the SW margin of the EEC (Baltica), but occur also in the Avalonian part of peri-Gondwana where they are linked to the early development stages of mature oceanic arcs (Nance *et al*., 2002). Correspondingly, the occurrence of Middle Neoproterozoic detrital muscovites in the Cambrian sediments of the HCM is taken as an indication that at least since the Cambrian some crustal unit with such a peri-Gondwana basement was located in its vicinity.

EARLY PALAEOZOIC DEVELOPMENT OF THE TESZ IN POLAND

PERSPECTIVE FROM THE EAST EUROPEAN CRATON MARGIN

As a consequence of Ediacaran rifting, the western slope of the Baltica developed during the late Early Cambrian to Ordovician as a passive continental margin (Poprawa *et al*., 1999; Giese and Köppen, 2001; Lassen *et al*., 2001; Poprawa and Pacześna, 2002). Subsidence rates of the Peri-Tornquist Zone systematically decreased with time, reflecting progressive cooling and contraction of the lithosphere (Fig. 3). Moreover, basin margins were progressively overstepped, particularly during the Ordovician (comp. Modliński, 1982), thus confirming post-rift subsidence mechanisms. This suggests that after Ediacaran rifting and crustal separation between Baltica and peri-Gondwana, oceanic crust (Tornquist Ocean) was accreted to the thinned continental crust of the distal TESZ Baltica margin, at least during parts of the Cambrian (e.g. Poprawa, 2006*a*).

However, a characteristic feature of the Cambrian evolution of the Peri-Tornquist basins is the occurrence of a late Middle Cambrian and/or Late Cambrian erosional hiatus (Fig. 5) that cannot be explained by a eustatic sea level low-stand and therefore requires tectonic controls (Poprawa *et al*., 1999; Pacześna and Poprawa, 2005; Jaworowski and Sikorska, 2006). Development of this hiatus is in all likelihood related to soft docking of the Małopolska Block at the TESZ Baltica margin close to its present position in response to its Middle to Late Cambrian strike-slip displacement (Poprawa, 2006*a*). From the Late Ordovician onward, a systematic increase in subsidence rates is observed along the western margin of Baltica that reached a maximum during the Late Silurian (Poprawa *et al*., 1997, 1999; Poprawa and Pacześna, 2002). Overall the Silurian subsidence pattern of the Peri-Tornquist basins system, both spatial and 1D, is typical for thrust- and slab-loaded flexural bending of the lithosphere, thus supporting the interpretation of this stage of basin evolution in terms of Caledonian foredeep basin development (*op. cit*.). This indicates that by Late Ordovician times the previously passive TESZ Baltica margin had changed into convergent plate boundary in response to the collision of the continental East Avalonia Terrane with allochthonous crustal fragments contained in the TESZ and Baltica (e.g. Beier *et al*., 2000; Cooks, 2000, 2002; Samuelsson *et al*., 2002; Torsvik and Rehnström, 2003).

Facies analyses of the Ordovician and Silurian sediments of the Baltic Basin (Jaworowski, 1971, 2000*b*; Beier *et al*., 2000) show that fine-grained flysch-type siliciclastics derived from the exposed part of the North German-Polish Caledonides were shed into the Peri-Tornquist basins mainly during the Late Silurian (*cf*. Ziegler, 1990). Close to the Caledonian deformation front, in the German and the Danish sector of Baltic Basin, terrigenous material derived from North German-Polish Caledonides is well developed and facies analyses clearly suggest a foredeep setting for this part of the basin (Vejbaek *et al*., 1994; Maletz *et al*., 1997; Beier *et al*., 2000).

THE POMERANIA AND OTHER RELATED UNITS

Attempts to reconstruct the pre-Variscan evolution of the Pomeranian sector (northern Poland) of the TESZ require analysis of the development of the Koszalin-Chojnice and Rügen zones (*cf.* e.g. Dadlez, 1978, 2000; Znosko, 1986; Katzung, 2001), as well as of provenance areas supplying sediments to these zones and the eastward adjacent Baltic Basin (e.g. Giese *et al.*, 1994, 2001; McCann, 1998; Giese and Köppen, 2001; Jaworowski and Sikorska, 2003; Schovsbo, 2003; Krzemiński and Poprawa, 2006; Poprawa, 2006*b*; Poprawa *et al.*, 2006). At the present stage of knowledge, geochemical, petrologic and geochronologic constraints permit to advance a realistic model for the palaeogeographic and tectonic evolution of this area.

In the Baltic Basin, Late Ordovician and Silurian shales, derived from western sources, show predominantly the geochemical characteristics of a stable cratonic source (Fig. 5; Krzemiński and Poprawa, 2006). An identical geochemical signature characterizes also the Middle Ordovician to Early Silurian sediments of the Koszalin-Chojnice Zone (*op. cit.*). In addition, U-Pb SHRIMP analyses on single zircon grains collected from sediments of the Baltic Basin and Koszalin-Chojnice Zone, which are derived from approximately western sources (*cf.* Jaworowski, 2000*b*; Schovsbo, 2003), show a consistent and clear dominance of zircon of an EEC provenance over few "Cadomian" and "Caledonian" zircons (Poprawa *et al.*, 2006).

This suggests that during Middle Ordovician to Silurian times the basement of the EEC extended further westward into the source area of these clastics (*op. cit.*), where it was exposed to erosion in response to tectonics related to convergence and subsequent collision. Consequently it is likely that the Late Ordovician-Early Silurian sediments of the Koszalin-Chojnice Zone were deposited on Baltica basement (*op. cit.*). This concept is also based on the occurrence of slightly metamorphosed late Ediacaran-Early Cambrian (?) sediments south of the Rügen Zone (i.e. Loissin 1/70 borehole), thought to represent the sedimentary cover of western Baltica (Dallmeyer *et al.*, 1999; Giese *et al.*, 2001). Furthermore, results of geochemical and geochronological studies on detrital material from the Koszalin-Chojnice Zone and the Baltic Basin indicate that these domains were palaeogeographically closely related and probably formed the proximal and more distal parts of the same basin, respectively (Poprawa, 2006*b*).

For such a model palynomorph analyses on Ordovician and Silurian series of the Pomeranian region provide, however, no straightforward palaeogeographic constraints. Szczepanik (2000) and Jachowicz (2000), who studied acritarchs from the Ordovician and Silurian succession both of the Koszalin-Chojnice Zone and the western parts of the Baltic Basin argued for similarities between both the domains (Fig. 5), and suggested also that some forms thought to be indicative for Gondwana are in fact cosmopolitan (M. Jachowicz, pers. com.). However, according to Samuelsson *et al.* (2002) Middle to Late Ordovician chitinozoa assemblages from Pomerania (Koszalin-Chojnice Zone) and Avalonia demonstrate a high level of similarity (Fig. 5), but both show greater similarity to Baltoscandia than to North Gondwana (comp. Wrona *et al.*, 2001). Moreover, Samuelsson *et al.* (2001) demonstrated the first appearance of clear Gondwana fossil associations in Ashgill deposits from the borehole G 14, north of the Caledonian deformation front close to Rügen, thus testifying to collisional uplift of the accretionary prism at that time. These interpretations do not contradict the concept of Middle to Late Ordovician collision of the East Avalonia Terrane with Baltica (*cf.* Winchester *et al.*, 2002; Torsvik and Rehnström, 2003). Therefore, this data does not exclude a reconstruction according to which the Koszalin-Chojnice succession was deposited in a foredeep on the westernmost slope of Baltica.

In the northwestern sector of the Baltic Basin, Ordovician and Silurian sediments were partly supplied from a source area in which subduction-related volcanic arcs were present (Fig. 5) (Schovsbo, 2003). This is coherent with a NW-ward thickness increase of the Middle to Late Ordovician K-bentonite (Bergström *et al.*, 1995), pointing to the location of major Plinian eruptions, related to subduction of the Iapetus and Tornquist oceans during the convergence of Avalonia with Laurentia and Baltica (Huff *et al.*, 1992; Torsvik and Rehnström, 2003).

The Late Ordovician greywackes of the Rügen Zone contain a significant amount of detrital clasts that were derived from volcanic island arc and ultramafic-mafic ophiolitic sources, representing an active margin, whereas in their upper parts contributions from a cratonic source become more significant (Fig. 5; Giese *et al.*, 1994, 2001; McCann, 1998; Giese and Köppen, 2001). According to Giese *et al.* (1994) and Tschernoster *et al.* (1997) some detrital minerals from the Rügen Ordovician, such as zircons, are characteristic for an Avalonian provenance. Dallmeyer *et al.* (1999) came to a similar conclusion, based on ^{40}Ar-^{39}Ar analyses of detrital mica yielding an average age of 610 Ma (Fig. 5). Correspondingly, it is concluded that the Late Ordovician greywacke flysch of Rügen Island was deposited in the accretionary wedge that was associated with the active, convergent margin of Avalonia and that was ultimately thrust onto the margin of Baltica (Fig. 5) (e.g. Giese *et al.*, 1994).

Furthermore, the Late Silurian sediments of the Baltic Basin contain detrital micas that, based on K-Ar dating, were derived from a source area that included muscovites reset during Middle Ordovician to earliest Silurian times (Fig. 5; Poprawa *et al.*, 2006). Taking into account the presence of roughly coeval metamorphism in the North German Caledonides (Frost *et al.*, 1981; Ziegler, 1978, 1982, 1984, 1990; Katzung, 2001) and a tectono-thermal event in the Rügen Zone (Fig. 5) (Dallmeyer *et al.*, 1999; Giese *et al.*, 2001), it is likely that during Late Silurian times the external parts of the North German-Polish Caledonian Orogen were exposed and eroded in response to ongoing thrusting. This thrust belt contained basement elements that were detached from the margin of Baltica and from the Avalonia Terrane, as well as subduction-related volcanic island arc rocks and sediments of the accretionary prism. Clastics derived from this orogenic belt were deposited in its N- and NE-ward adjacent flexural foreland basin that broadly overstepped the margin of Baltica, the proximal part of which is represented by Koszalin-Chojnice Zone (Poprawa, 2006*b*).

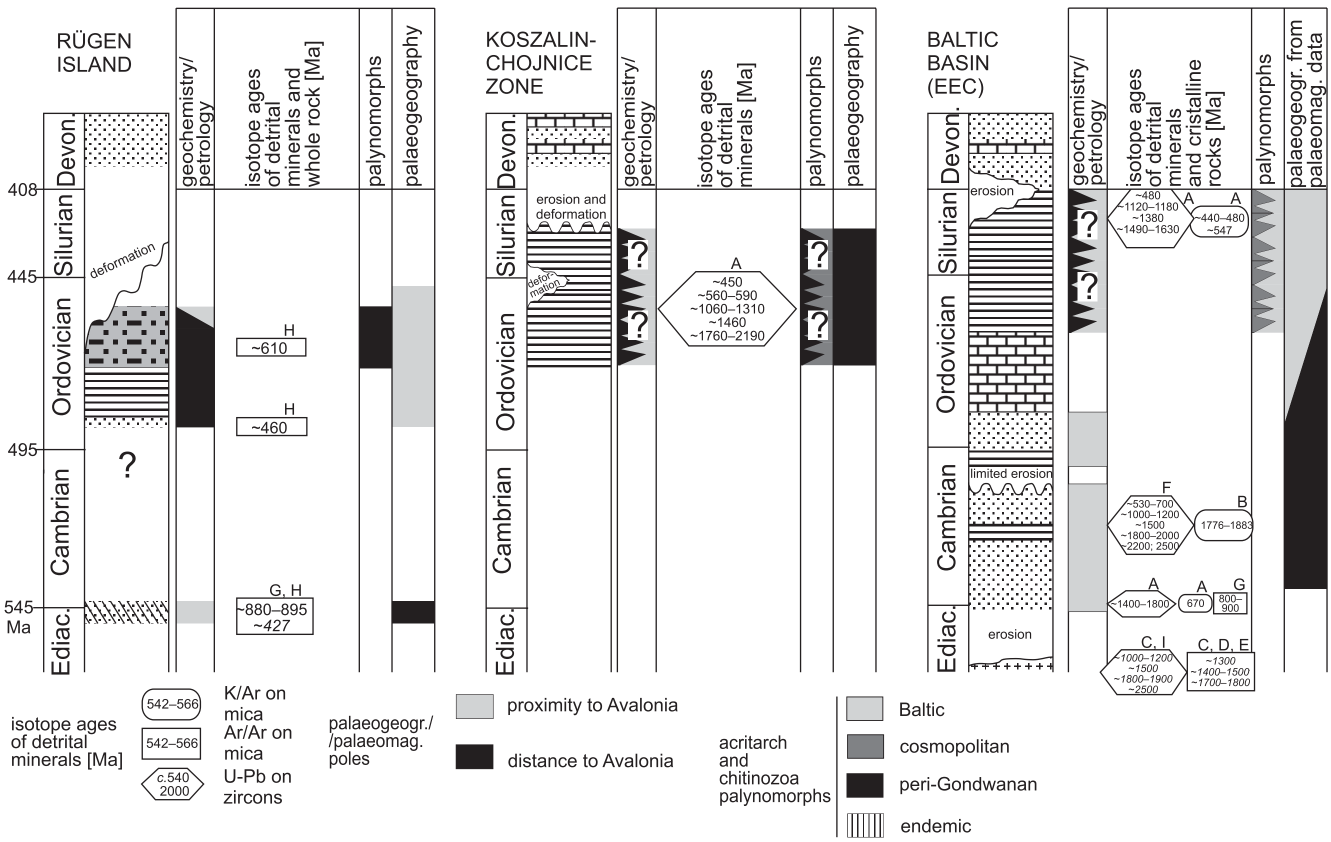

Fig. 5. Diagrammatic stratigraphic columns for the sedimentary cover of units involved in the Pomeranian segment of the TESZ (N Poland and NE Germany) and selected provenance data obtained from their sedimentary successions

Geochemical and petrological data for the Baltic Basin after McCann (1998), Sikorska (1998, 2000), Jaworowski and Sikorska (2003), Schovsbo (2003), Krzemiński and Poprawa (2006), for the Koszalin-Chojnice Zone after Krzemiński and Poprawa (2006), and for the Rügen area after Giese *et al*. (1994, 2001), McCann (1998) and Giese and Köppen (2001); isotope ages according to: **A** — Poprawa *et al*. (2006); **B** — Belka *et al*. (2000); **C** — Dörr *et al*. (2002); **D** — Marheine and Valverde-Vaquero (2002); **E** — Bogdanova *et al*. (2001); **F** — Valverde-Vaquero *et al*. (2000); **G** — Giese *et al*. (2001); **H** — Dallmeyer *et al*. (1999); **I** — Bogdanova (2005); isotope ages for whole rocks or minerals from crystalline rocks are given in italics; data on palynomorphs for the Baltic Basin and Koszalin-Chojnice Zone after Jachowicz (2000), Szczepanik (2000) and Samuelsson *et al*. (2002), and for the Rügen area after Samuelsson *et al*. (2000) and Vecoli and Samuelsson (2001); palaeomagnetic data after Torsvik and Rehnström (2003); time scale after Gradstein *et al*. (2004); other explanations as on Figure 4

THE MAŁOPOLSKA MASSIF

Palaeomagnetic data obtained from Cambrian (Nawrocki *et al*., 2006), Ordovician (Schätz *et al*., 2002) and Silurian (Nawrocki, 2000) rocks (Fig. 6) indicate that since the Middle Cambrian no large-scale strike-slip movements of the Małopolska Massif relative to the SW margin of Baltica have occurred. However, a certain tectonic mobility of this unit at the Cambrian-Ordovician transition is evidenced in the HCM by the deformation of Cambrian strata that are involved in several thrust and fold structures, attributed to the pre-late Tremadocian Sandomirian Orogeny (Fig. 4; Gągała, 2005). This deformation phase may be related to the palaeomagnetically documented 60° anticlockwise rotation of Baltica between 500 and 490 Ma (Fig. 2; Torsvik *et al*., 1996).

The geochemical signature and the spectrum of isotope ages of detrital mica significantly changed in the Late Silurian. Geochemical studies on Late Silurian greywackes of both HCM units (i.e. southern Kielce, and northern Łysogóry) indicate a continental island arc provenance of the detritus (Kozłowski *et al*., 2004). The cooling ages of mica contained in Late Silurian sediments of both regions range between 674 and 739 Ma (Nawrocki *et al*., 2005). Input from a Late Cadomian source, documented by a cooling age of 560 Ma, was recognised only in samples of Early Silurian mudstones (Fig. 4). The Middle Neoproterozoic detrital muscovite contained in the Late Silurian greywackes was derived from a crustal unit located to the west of the Małopolska Massif, as indicated by sedimentological data (see Kozłowski *et al*., 2004). It cannot be excluded that it was the same unit that had supplied Neoproterozoic detrital mica to the Cambrian sediments of the Małopolska Massif.

The late stages of the Avalonia-Baltica collision, and their subsequent collision with Laurentia, are recorded in different ways in the Silurian sedimentary basins of the TESZ area (Poprawa *et al*., 1999; Narkiewicz, 2002; Poprawa and Pacześna, 2002). During the Late Silurian (late Ludlow-Pridoli) and earliest Devonian (early Lochkovian), an extensional tectonic regime dominated the Kielce region of the HCM where diabase dykes and sills of this age were intruded (Nawrocki *et al*., 2006). During the subsequent Late Caledonian (Lochkovian-Pragian?; see Malec, 1993) tectonic pulse, the Palaeozoic strata of the Kielce region were deformed during the final amalgamation of the BT and the Małopolska Massif.

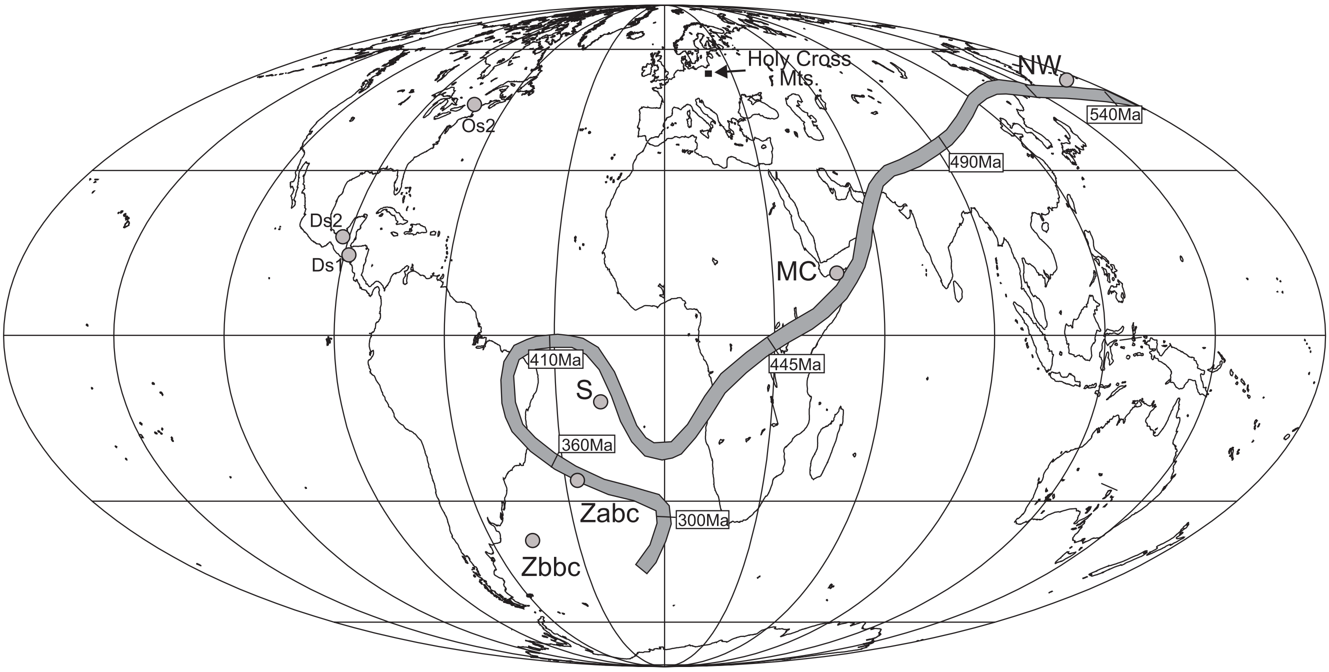

Fig. 6. Southern APWP for Baltica (after Torsvik *et al.*, 1990, 1996; Torsvik and Rehnström, 2001) and selected palaeopoles obtained from Early Palaeozoic rocks of the Holy Cross Mts.

NW — Early/Middle Cambrian pole obtained from the Kamieniec Shale Fm. (Nawrocki *et al.*, 2006); MC — Middle Ordovician pole isolated from the Mójcza Limestone by Schätz *et al.* (2002); S — Late Silurian pole isolated from the Bardo diabase by Nawrocki (2000); Zabc, Zbbc — Early Carboniferous secondary pole isolated from the Bardo diabase (southern limb of syncline) calculated after and before bedding correction respectively (*op. cit.*); Os2 — pole obtained from Tremadocian clastic rocks of the Kielce Unit (Lewandowski, 1993); Ds1, Ds2 — poles isolated from Early Devonian rocks of the Kielce Unit (*op.cit*); note that the secondary pole Zabc from the Bardo diabase fits the APWP after full restoration of the southern limb of Bardo syncline; this indicates that the Silurian strata of the southern limb of Bardo syncline were not deformed before the Carboniferous

The amplitude and range of this deformation was, however, very limited. A palaeomagnetic pole of secondary origin isolated from a diabase on the southern limb of Bardo syncline (Nawrocki, 2000) falls on the Early Carboniferous segment of the Baltic APWP after restoration of the Silurian strata (Fig. 6), suggesting that the southern limb of the Bardo syncline was not significantly inclined prior to the Variscan deformations (Fig. 7). By contrast, the Lublin-Podlasie Basin, which encroaches on the margin of the EEC, developed during the Late Silurian into a typical flexural foreland basin (Poprawa and Pacześna, 2002) in which clastics shed from western sources were deposited, including some distal flysch-type sediments (*cf*. Jaworowski, 1971). This indirectly points to Late Caledonian deformation of the area at the Łysogóry-Małopolska transition.

THE ŁYSOGÓRY UNIT

The Palaeozoic rocks of the Łysogóry Unit are exposed in the northern part of the HCM (Fig. 1). The Holy Cross Fault separates this unit from the Małopolska part of the HCM (i.e. the Kielce region). By contrast to the Kraków-Lubliniec Fault Zone, which separates the Małopolska and the BT blocks, this fault is not expressed in deep seismic data, according to the interpretation of Malinowski *et al*. (2005). The main differences in the sedimentary succession of the Łysogóry Unit and the adjacent Małopolska Massif is the lack of angular unconformities at the contact between Cambrian and Ordovician, and between Silurian and Devonian successions (Fig. 4). These features should, however, not be overestimated in terms of palaeogeography as the Małopolska Massif took in a proximal position relative to the EEC margin, at least from the Middle Cambrian onward. Detrital zircon and muscovite data obtained from the Late Cambrian sediments of the Łysogóry Unit (Belka *et al*., 2002; Nawrocki *et al*., 2006; Fig. 4) reveal a complex provenance pattern of clastic material that, in all likelihood, was derived from Cadomian and Baltic sources. The Cambrian and Silurian series of the Łysogóry Unit contain, apart from Late Neoproterozoic and Early Proterozoic micas, also detrital Middle Neoproterozoic muscovites. Interestingly, the age spectrum of muscovite separated from Upper Silurian greywackes of the Łysogóry Unit and the Małopolska Massif is exactly the same (Fig. 4). Moreover, also the geochemistry of these rocks is identical and indicates a continental island arc detrital provenance (Kozłowski *et al*., 2004). The Middle Neoproterozoic detrital muscovites found in these sediments suggest the presence of a Silurian island arc that surrounded a crustal unit metamorphosed about 730 Ma ago. This unit, named here the Wielkopolska Terrane, was located to the west of the HCM, as can be inferred from the directions of transport of clastic material (see Kozłowski *et al*., 2004). This arc moved to the west at the Silurian-Devonian transition (see next chapters).

Belka *et al*. (2002) consider the Łysogóry Unit as an exotic terrane that was derived from the Gondwana margin and brought closer to Baltica during the Late Cambrian. In our views, there is insufficient data to support such an interpreta-

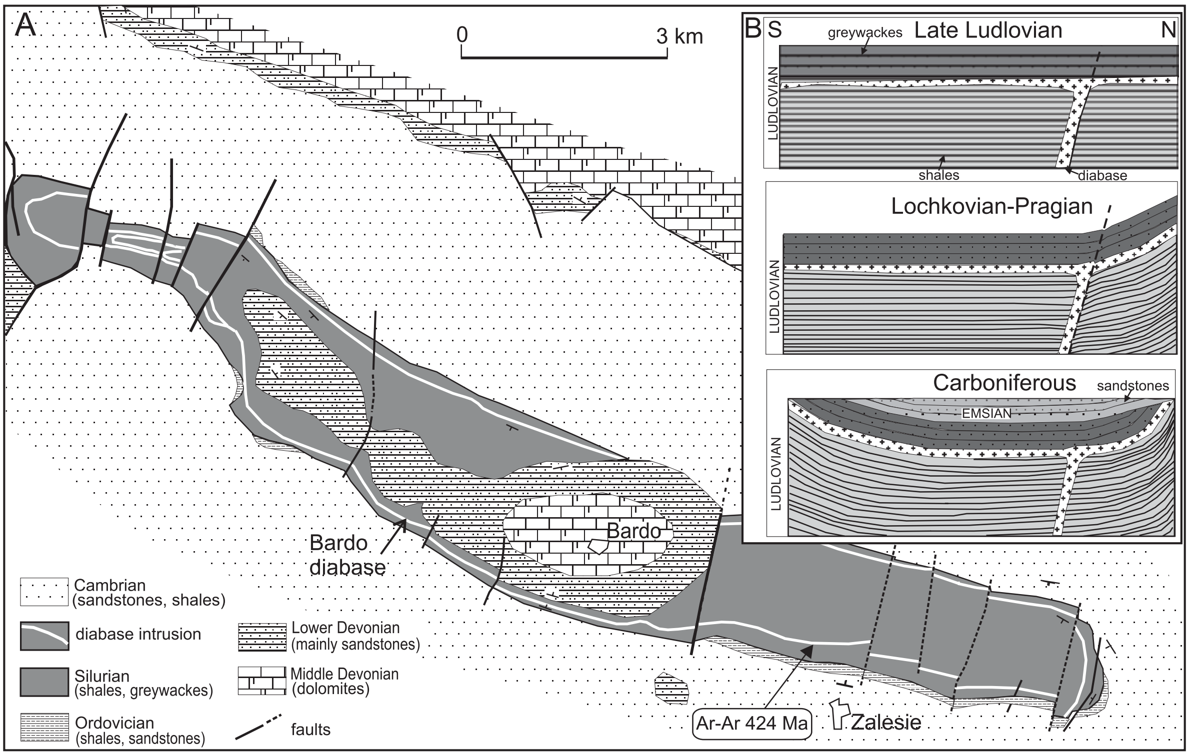

Fig. 7. A — geological sketch map of the Bardo syncline (after Czarnocki, 1958); diabase Ar-Ar age according to Nawrocki *et al.* (2006); B — deformation stages of Silurian rocks forming the Bardo syncline according to palaeomagnetic data obtained from the Bardo diabase (Nawrocki, 2000)

tion. A partly Baltica source of detrital minerals in Cambrian sediments, and a crustal structure similar to that of the East European Craton, as defined by the deep seismic data (Malinowski *et al*., 2005), point rather to stationary model for the Łysogóry Unit and its close link with the mobile margin of the East European Craton, as postulated by some authors (e.g. Dadlez *et al*., 1994; Dadlez, 1995).

BRUNOVISTULIAN TERRANE

As discussed above, the BT was probably translated dextrally along the present-day SW margin of Baltica during the late Ediacaran-Early Cambrian (550–510 Ma) rotation of the latter (Fig. 8). By Cambrian times the BT had, however, not yet reached its present position in the TESZ, as evidenced by its Cambrian palaeomagnetic pole that does not fit the Baltic APWP (Nawrocki *et al*., 2004*b*). Nevertheless, by Middle Ordovician times the BT was clearly separated from the peri-Gondwana domain and located in the vicinity of the SW Baltica margin, as evidenced by the Baltica conodont faunas of its Middle-Late Ordovician carbonates (Belka *et al*., 2002). The BT was brought into the immediate vicinity of the Małopolska Massif after the Ludlow and prior to the deposition of the Lower Devonian "Old Red" type sandstones. The Ludlow sediments of the Małopolska Massif were not derived from the BT but from an island arc located to the west of it, in the place now occupied by the BT (Kozłowski *et al*., 2004). The Early Devonian proximity of the BT and the Małopolska Massif can be inferred from facies boundaries of the Early Devonian sandstones (Pajchlowa and Miłaczewski, 1974) that cross cut the Kraków-Lubliniec Fault Zone that forms the boundary between these two crustal blocks (*cf*. Buła *et al*., 1997; Żaba, 1999; Buła, 2000).

SUMMARY OF PALAEOGEOGRAPHY

Figures 8 and 9 give two contrasting versions of the late Ediacaran plate reconstruction of Baltica and Gondwana. In the model of Figure 8A, that is based on Torsvik and Rehnström (2001) and Cocks and Torsvik (2005), the TESZ Baltica margin faces N-ward. This model does not adequately explain the occurrence of tectonic blocks characterized by Cadomian deformation and magmatism, here referred to as the Teisseyre Terrane Assemblage (TTA), near the present SW margin of Baltica during the Early Cambrian. According to this model, the TTA was derived from the Uralian margin of Baltica (Fig. 8A) and moved during the latest Ediacaran-Cambrian along this margin towards the present-day SW corner of Baltica (Fig. 8B). However, palaeomagnetic data, common Early Cambrian trilobite *Smidtiellus panowi*, and some cooling ages of detrital mica indicate that the Małopolska Massif and the BT were located not far from each other and close to the present SW margin of Baltica, at least since the Middle Cambrian (Fig. 9B).

As there is no recognizable source area for detrital mica with cooling ages of about 1.5 Ga in the Avalonian part of peri-Gondwana or the Volgo-Uralian part of Baltica, preference is given to the late Ediacaran plate reconstruction shown in Figure 9A that corresponds to the modified Late

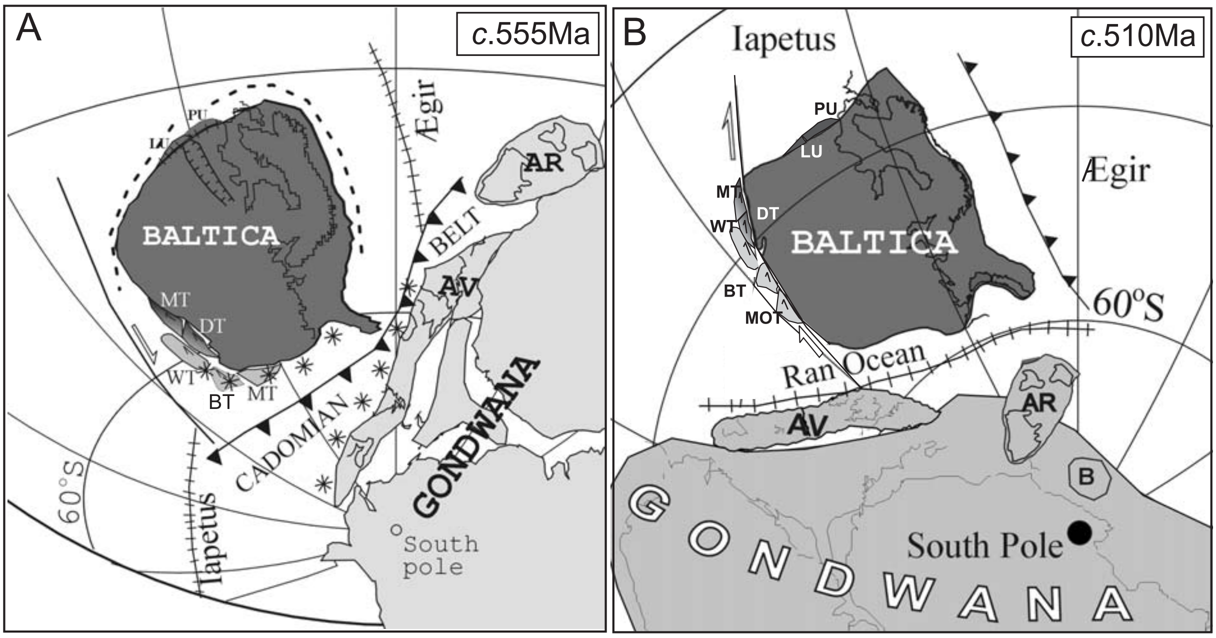

Fig. 8. The Gondwana megacontinent and Baltica with adjacent tectonic units in the late Ediacaran (A) and latest Middle Cambrian (B)

The location of Baltica and Gondwana is adapted from Torsvik and Rehnström (2001), and Cocks and Torsvik (2005); AV — Avalonia; AR — Armorica; B — Bohemia; LU — Łysogóry Unit; PU — Pomerania Unit; Tornquist Terrane Assemblage: BT — Brunovistulian Terrane; DT — Dobrogea Terrane; MOT — Moesia Terrane; MT — Małopolska Terrane; WT — Wielkopolska Terrane

Vendian-Early Cambrian APWP of Baltica (Fig. 6; Nawrocki *et al*., 2004*a*). In this model Baltica moved during 555–540 Ma from moderate southern to equatorial latitudes and rotated anticlockwise by about 120 (Fig. 2). The late Ediacaran position of Baltica, as given in Figure 9A, explains the location of the BT near the present-day SW Baltica margin. This is compatible with the Cadomian basement of the BT and its Early Cambrian trilobite fauna that shows Baltica or Małopolska Massif affinities (Finger *et al*., 2000*a*; Orłowski, 1985; Żelaźniewicz, 1998; Nawrocki *et al*., 2004*b*). Moreover, this model can also explain why Cambrian sediments of present SW Baltica contain some Cadomian age detrital zircon grains (Valverde-Vaquero *et al*., 2000) and why detrital micas from the Middle Cambrian of the Małopolska Terrane show cooling ages of about 1.5 Ga.

Our preferred model of late Ediacaran palaeogeography shows the TTA located near the present SW corner of Baltica (Fig. 9A). The Pomerania and Łysogóry units remained at the SW margin of Baltica, or near it, after late Ediacaran rifting. As Palaeozoic sequences covering these units were deposited on Baltica basement, the Pomerania and Łysogóry units are here not defined as true terranes. By contrast, the Małopolska and Brunovistulicum crustal blocks were located during late Ediacaran times in the SE part of the TESZ Baltica margin that was involved in the Cadomian Orogen. The Małopolska and Dobrogea blocks presumably represent proximal terranes that were detached from the SE corner of Baltica and moved dextrally along its margin during the Ediacaran-Cambrian transition while Baltica rotated. The Brunovistulian and Moesia terranes have an exotic origin. They most probably were derived from the Cadomian part of peri-Gondwana during late Ediacaran rifting that resulted in the separation of SW Baltica from the Avalonian part of peri-Gondwana (Fig. 9A).

The list of TTA needs to be supplemented by the Wielkopolska Terrane that supplied the Early Palaeozoic basins of the HCM with detrital muscovites characterized by Middle Neoproterozoic cooling ages (Fig. 9). These Middle Proterozoic cooling ages can be related to the breakup of Rodinia and the development of mature oceanic arcs, vestiges of which are found in the basement of Avalonia (Nance *et al*., 2002).

At the turn from the Cambrian to the Ordovician Baltica rotated anticlockwise (Fig. 2; Torsvik *et al*., 1996). This implied further dextral movement of the TTA along its SW margin. Transpressional movements between the Wielkopolska and Małopolska terranes underlay the Sandomirian deformation phase that is clearly evident in the Kielce region of the HCM (Gągała, 2005). Whilst during the Early Ordovician the TESZ area was relatively stable, this tectonically quiescent period ended in the Middle to Late Ordovician, depending on the zone of TESZ, when island arcs started to grow west of Baltica in conjunction with the progressive closure of the Tornquist Ocean (Torsvik and Rehnström, 2003) and narrowing of the Rheic Ocean (Tait *et al*., 2000; Franke, 2000). Following end-Ordovician collision of the East Avalonia Terrane with Baltica, the Caledonian orogenic wedge was thrust on the Baltica margin during the Silurian, involving deformation of the TTA. In the process of this, the Brunovistulian terrane moved to its present position near the Małopolska Massif and the Wielkopolska Terrane was relocated to the west. However, owing to subsequent deformation of crustal units involved into TESZ, the present position of the Wielkopolska Terrane is unknown.

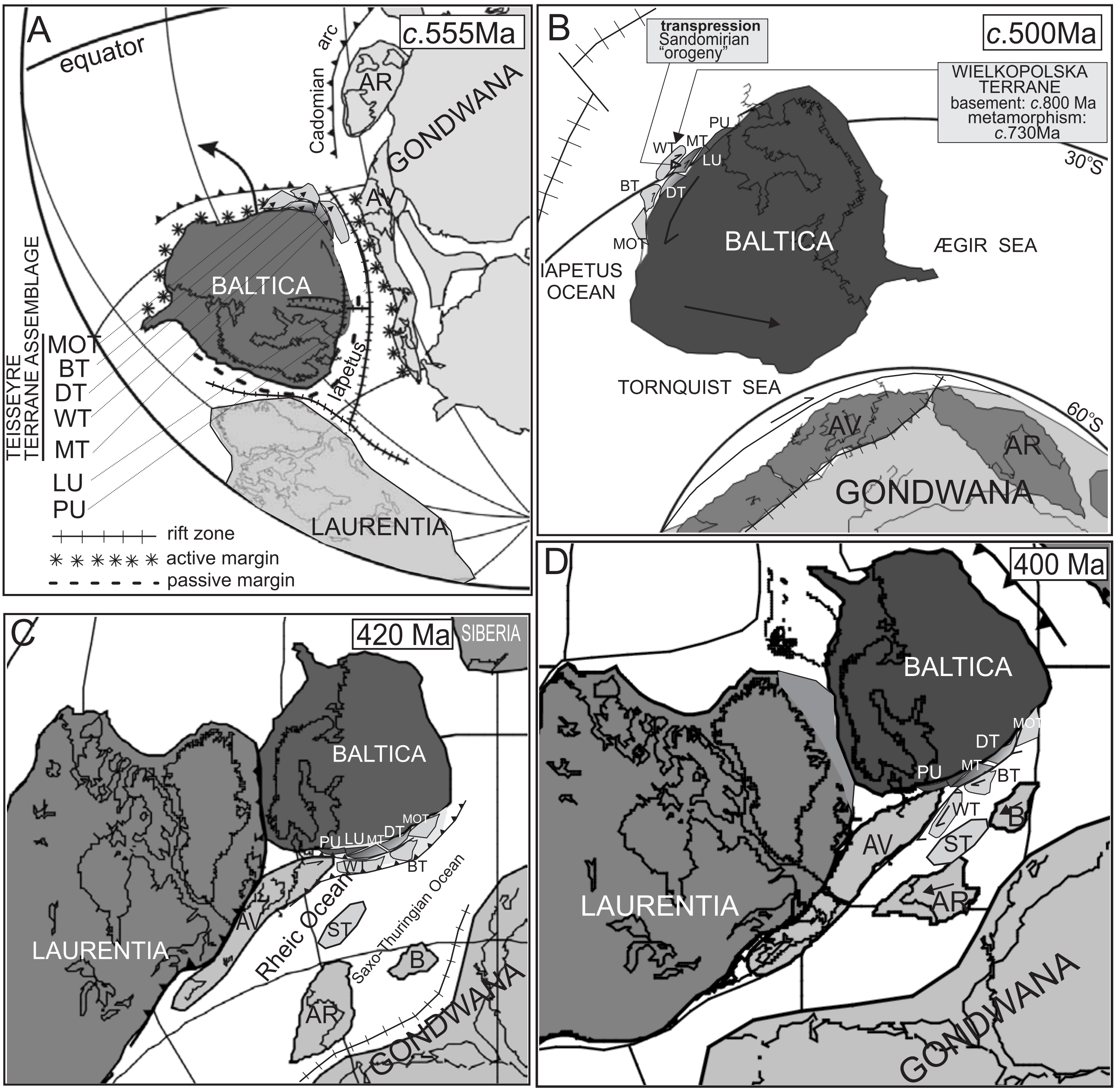

Fig. 9. Simplified plate reconstructions showing the Gondwana megacontinent and Baltica (adapted from Torsvik and Rehnström, 2001 and Torsvik *et al*., 1996) with adjacent tectonic units

A — late Ediacaran (555 Ma) reconstruction with Baltica positioned according to Nawrocki *et al*. (2004*a*); **B** — Late Cambrian (500 Ma) reconstruction showing next development stage of model A according to Nawrocki *et al*. (2004*b*); **C** — Late Silurian (420 Ma) reconstruction, after Tait *et al*. (2000); **D** — Early Devonian (400 Ma) reconstruction adapted from Cocks and Torsvik (2002); other explanations as on Figure 8

CONCLUSIONS

During Late Neoproterozoic times a major rifting along the trace of the future Trans-European Suture Zone culminated in crustal separation between Baltica and peri-Gondwana, leading to the development of the SW passive margin of Baltica.

The Brunovistulian Terrane and the Małopolska Massif were involved in the Cadomian Orogen and were derived from near the S margin of Baltica. Determination of the exact place of derivation of these units essentially depends on which Ediacaran plate reconstruction model for Baltica is adopted.

In response to strike-slip movements, the Małopolska Massif was finally docked at the TESZ margin of Baltica presumably during the late Middle to Late Cambrian, causing an interruption of its post-rift subsidence and minor erosion. Major parts of this strike-slip movement and tectonic transport of the Małopolska Massif in the vicinity of the Baltica occurred at the turn of Ediacaran and the Cambrian.

Brunovistulian Terrane ended its large-scale strike slip movement at the turn from the Silurian to the Devonian when it was accreted to the Małopolska Massif.

During Late Ordovician and Silurian times, the Caledonian collision of East Avalonia with Baltica and the intervening

Teisseyre Terrane Assembly caused the development of a foredeep basin along the SW margin of Baltica. In Pomerania, the Koszalin-Chojnice Zone that is floored by Baltica basement forms the proximal part of this foredeep. Its distal parts correspond to the Baltic Basin.

During the Late Ordovician and Silurian, the Baltic Basin and the Koszalin-Chojnice Zone were supplied with clastics from the west by a collisional source area composed of crustal elements that were detached from the basement of Baltica and East Avalonia, as well as a subduction-related volcanic arc, obducted ophiolites and an accretionary prism.

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