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New Late Vendian palaeogeography of Baltica and the TESZ

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New palaeomagnetic poles obtained from the Vendian tuffs and basalts of western Ukraine indicate the necessity of a substantial revision of the Late Vendian–Early Cambrian palaeogeography of the Baltic plate. The palaeopole calculated for the most stable component isolated from the Vendian tuffs and basalts is far away from the Vendian–Cambrian apparent polar wander path (APWP), constructed on the basis of Scandinavian poles but is very close to the pole recently isolated from the Vendian sediments of the White Sea Region. Depending on the polarity of the newly-determined Late Vendian pole, two palaeogeographic models of the Baltic plate in the Late Vendian–Early Cambrian are possible. In our preferred model the Baltic plate moved at that time from the moderate southern latitudes to the equator rotating anticlockwise of *ca*. 120°. This reconstruction explains the geological structures of the marginal zones of Baltica better than the previously proposed stationary model of the Late Vendian–Cambrian Baltica. According to the new late Vendian palaeogeographic scenario, the European, passive margin of Baltica was separated from an active, Avalonian margin of Gondwana. The Late Neoproterozoic tectonic structures of the Brunovistulian Terrane and the Małopolska Block were developed near the present day southwestern corner of Baltica that was tectonically active at that time. Alternative reconstruction shows the Baltic plate moving from the moderate northern latitudes in the Vendian, crossing palaeoequator in the latest Vendian, and reaching moderate southern palaeolatitudes in the Late Cambrian. This model, however, would have required exceptionally high plate velocity (*ca.* 33 cm/year).

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INTRODUCTION

Since the new palaeomagnetic poles for 535 and 500 Ma were reported, the drift history of Baltica in the Late Vendian–Cambrian has appeared to be well recognized (Torsvik and Rehnström, 2001). On the basis of this data and the Vendian palaeopoles from the Fen complex (Piper, 1988; Meert *et al*., 1998), only a minor mobility of the Baltic plate for 555 to 500 Ma timespan has been proposed (e.g. Hartz and Torsvik, 2002). In the reconstruction by Hartz and Torsvik (2002), Baltica is located between 30° and 60° of southern latitude, with its present SW edge facing to the north. This model does not explain, however, some tectonic problems like the presence of a Cadomian orogen in the basement of the tectonic blocks situated near the present SW edge of Baltica.

The present SW margin of Baltica is bordered by a crustal domain, named the Trans-European Suture Zone (TESZ), which separates the Precambrian crust of this plate from the Variscan and Alpine mobile belts of western Europe. In Southern Poland, this domain consists of at least three fault-bounded crustal units. From the margin of Baltica outwards, these are the Łysogóry, the Małopolska and the Brunovistulian (Fig. 1). The Brunovistulian was one of the first tectonic units of Central Europe to be defined as a "terrane" (Brochwicz-Lewiński *et al*., 1986) and still remains the best-documented terrane of the central part of TESZ (Pożaryski, 1991; Dadlez, 1995; Franke, 1995; Pharaoh, 1999). The basement of this terrane is composed of metamorphic and igneous rocks, mostly Cadomian (Neoproterozoic) in age (Dudek, 1980; Van Breemen *et al*., 1982; Finger *et al*., 2000; Żelaźniewicz *et al*., 2001). In some places they are covered by the Vendian flysh sequences metamorphosed in a greenschist grade (Żelaźniewicz *et al*., 2001). The Late Vendian metamorphosed flysh sequences cover also the Małopolska Tectonic Block (Żelaźniewicz, 1998). Because of these orogenic features, it is difficult to accept any Neoprotorozoic palaeogeography with the Małopolska and Brunovistulian in the passive margin of Baltica as is presented by Hartz and Torsvik (2002). Lewandowski (1993) locates the Małopolska Block near the present southern margin of Baltica

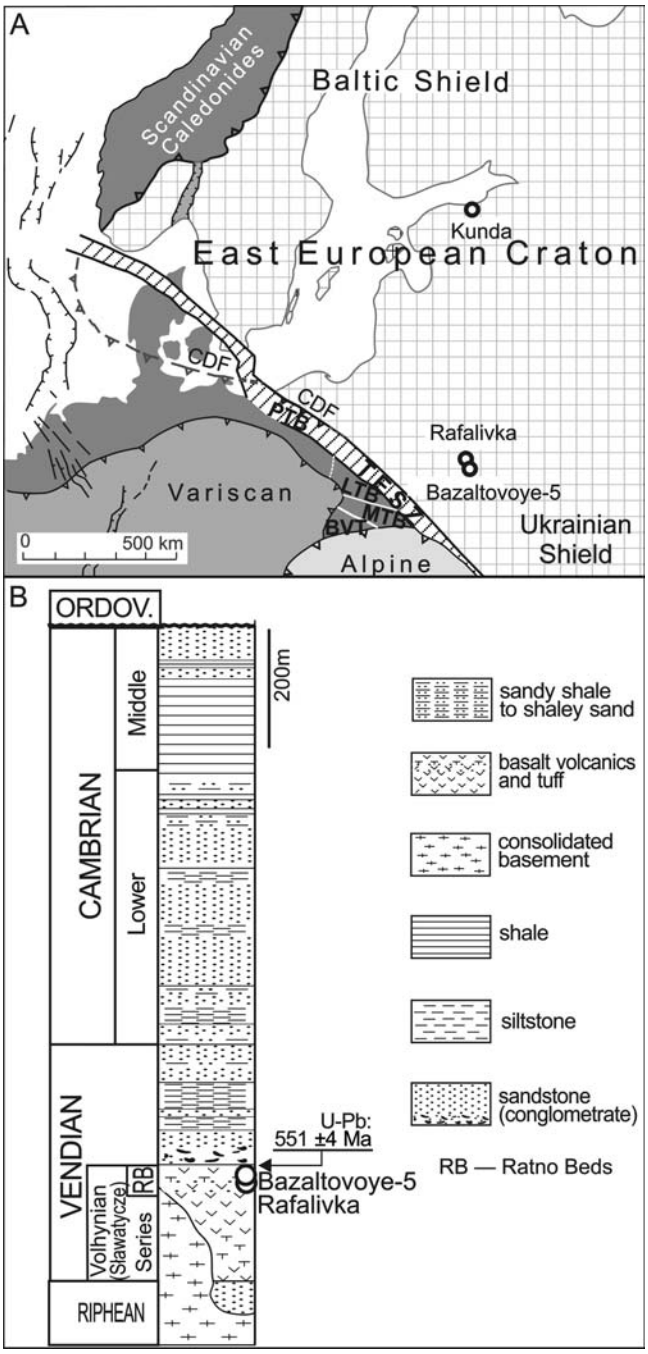

Fig. 1. A — location of the studied outcrops within a tectonic sketch map of the Central Europe (CDF — Caledonian deformation front, PTB — Pomerania Tectonic Block, LTB — Łysogóry Tectonic Block, MTB — Małopolska Tectonic Block, BVT — Brunovistulian Terrane); B — stratigraphic subdivision of Vendian–Cambrian sediments from the Lublin–Volhyn part of the East European Craton (after Poprawa and Pacześna, 2002); location of studied exposures Bazaltovoye-5 and Rafalivka is marked with circles

in the Early Palaeozoic. He postulates a large-scale tectonic transport of the Małopolska to its present position during the Variscan orogeny. However, the palaeomagnetic pole obtained from the Bardo diabase (S part of the Holy Cross Mts., Małopolska Block) indicates that such a movement could not take place after the Silurian (Nawrocki, 2000).

A certain modification of Baltica palaeogeography has been recently proposed by Lewandowski and Abrahamsen (2003), who situated this continent in the more equatorial position in the Early Cambrian. New palaeomagnetic studies concerning the Vendian sediments of White Sea Region (Popov *et al.*, 2002) disclosed a new palaeopole that is not concordant with the coeval Scandinavian palaeopoles. Any new palaeomagnetic pole may, therefore, potentially clarify the problem of palaeogeography of Baltica at the turn of the Vendian and Cambrian. For this reason we decided to undertake a palaeomagnetic study of Late Vendian and Early Cambrian rocks from Ukraine and Estonia.

NEW PALAEOMAGNETIC RESULTS

MATERIAL AND METHODS

Two exposures of the Vendian extrusives from the Volhynia region of the Western Ukraine were sampled for palaeomagnetic investigations. The samples were drilled from the doleritic parts of two lava flows of the pillar basalts croping out in the Bazaltovoye-5 quarry (25 samples), and from doleritic parts of the layered basalts and underlaing tuffs in the Rafalivka quarry (35 samples, see Fig. 1). Sampling was constrained to three lava flows and one layer of tuffs. All sampled rocks are attributed to the Ratno Beds that compose the uppermost part of the volcanogenic Volhynian Series (Białowolska *et al.*, 2002). The Ratno Beds extend as far as SE Poland, where they form uppermost part of the Sławatycze Series (a counterpart of the Volhynian Series). Compston *et al.* (1995) obtained U-Pb age of 551 ± 4 Ma from the uppermost tuffs of the Sławatycze Series (Fig. 1B). Hence, basalts and tuffs from Bazaltovoye-5 and Rafalivka should be very close to this age. It is unlikely that they are much older than 551 Ma. The Lower Cambrian red mudstones of the Baltija Group were sampled in Kunda quarry (NE Estonia), where 15 hand samples were taken. These rocks are correlated with the Manykayan stage (Paskievicius, 1997). The Vendian sediment, adjanced to the studied Volhynian intrusives dips 3° to the west. The Lower Cambrian sediments from Kunda quarry dip 2° to SW.

Vendian samples were subjected to both alternating field (AF) and thermal demagnetization experiments. For Early Cambrian red beds we used thermal demagnetization only. Demagnetization results were analysed using orthogonal vector plots (Zijderveld, 1967), and the directions of the linear segments were calculated using principal component analysis (Kirschvink, 1980). Magnetic mineralogy was determined with the use of isothermal remanent magnetization (IRM) techniques and thermomagnetic analyses.

RESULTS OF DEMAGNETIZATION

Most of the samples from the Volhynia revealed a low-coercivity natural remanent magnetization (NRM) component, removed by alternating fields up to 20 mT and temperatures of about 350°C (Fig. 2). In the samples from Rafalivka this component was strongly dispersed and therefore was not

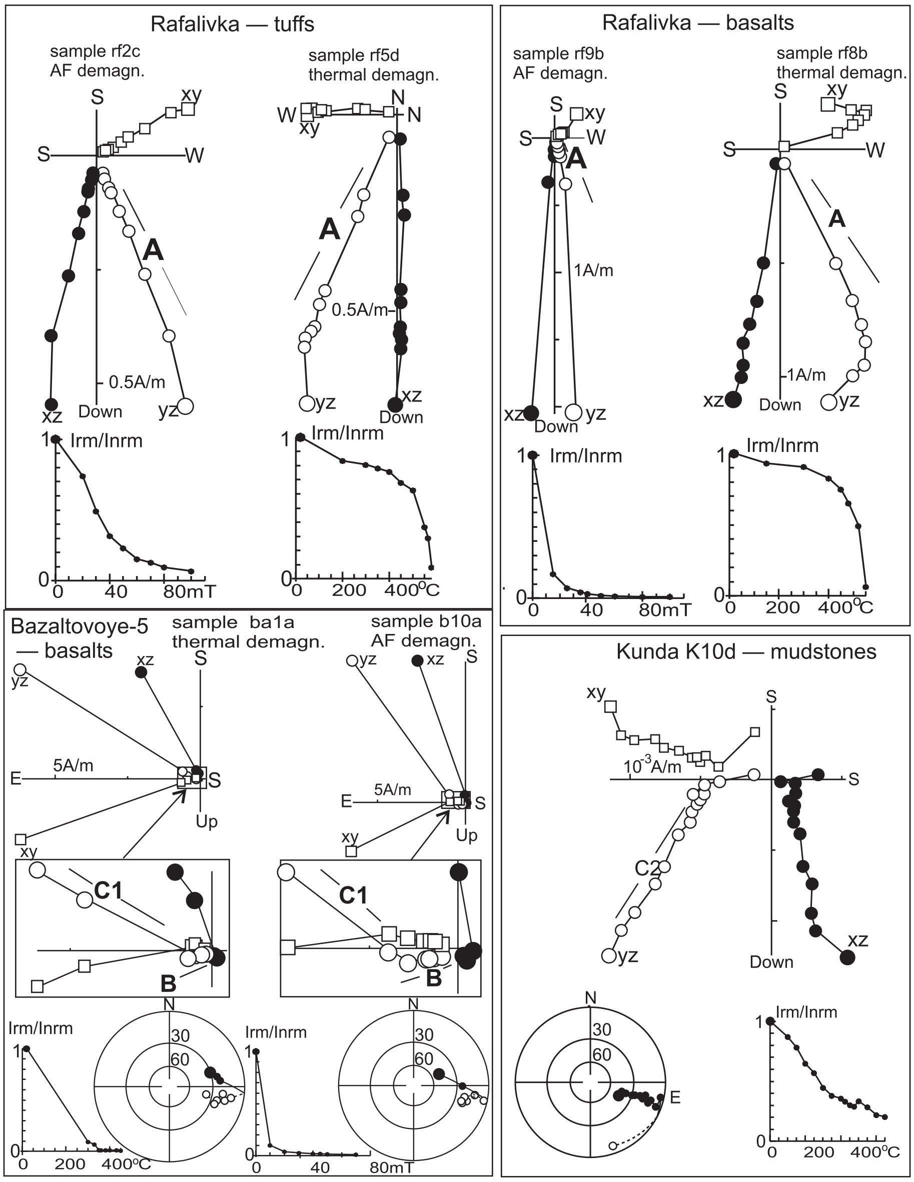

Fig. 2. Typical demagnetization characteristics (orthogonal plots, intensity decay curves and demagnetization directional tracks) of Vendian basalts and tuffs from Rafalivka and Bazaltovoye-5 quarries, and Lower Cambrian mudstones from Kunda quarry

Circles in the orthogonal plots represent vertical projections, squares represent horizontal projections; the characteristic components "A", "B", "C1" and "C2" are marked on the orthogonal plots; Irm — intensity of remanent magnetization, Inrm — initial intensity of natural remanent magnetization

evaluated statistically. Samples from Bazaltowoye-5 contained a very large low-coercivity component "C1" (Fig. 2). This quickly removed component is not well documented because the number of demagnetization levels was not sufficient. Nevertheless, the directions defined for particular samples by the best-fitted lines group in the first quarter of the hemisphere (Fig. 3). After the removal of the low-coercivity overprint above 20 mT or 350°C, a high-coercivity component "A" with unblocking temperatures of about 570°C can be identified in the samples from tuffs and basalts of Rafalivka quarry. The "A" magnetization is isolated as a straight-line segment directed towards the origin in an orthogonal projection.

In the samples from Bazaltowoye-5, a second component was also isolated. This component defined as "B", was demagnetized in the field of about 80 mT and temperatures not exceeding 450°C (Figs. 2 and 3). It is poorly documented in particular samples because of a very large overprint of "C1" component. Associated with no more than 2% of initial NRM intesity, "B" magnetization usually fluctuated at the last levels of demagnetization.

Samples from the Lower Cambrian red mudstones revealed the presence of a one distinct component "C2". This magnetization was defined in temperatures up to 550°C, as a straight-line segment not directed towards the origin in orthogonal projection (Fig. 2). These rocks also contained a high temperature component. Its credible definition was impossible because of a substantial increase of the magnetic susceptibility at temperatures higher than 550°C.

MAGNETIC CARRIERS

IRM experiments and the subsequent thermal demagnetization of the saturation magnetization confirm the predominance of magnetic carriers from an ulvospinel-magnetite solid solution series in the basaltic samples (Fig. 4). The structure of NRM indicates the presence of two magnetic phases, differing in coercivity and unblocking temperatures. Thermal and AF demagnetization of NRM indicate that the "A" component is carried by moderately high-coercivity minerals with unblocking temperature of about 570°C (Fig. 2). This demagnetization behaviour is typical for basaltic lava containing deuterically-oxidised titanomagnetite (e.g. Buchan and Halls, 1990). The component "B" is carried by a medium-coercivity mineral with unblocking temperature of about 450°C, most probably titanomagnetite. The component "C1" could be recorded by maghemite because of its unblocking temperature of about 350°C and a certain decrease of magnetic susceptibility at temperatures 350–450°C, caused by a mineral transformation from maghemite into hematite. A mineral with unblocking temperature of about 550°C, such as magnetite is a carrier of component "C2", isolated from the Cambrian red beds. IRM experiment indicates also the presence of hematite in these rocks (Fig.4).

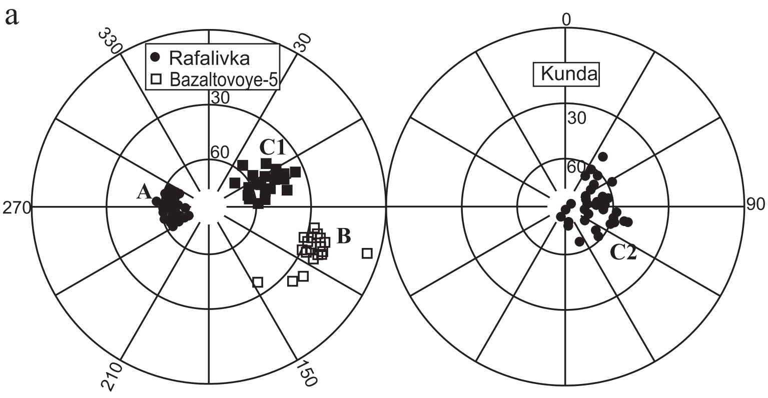

Fig. 3. a — stereographic projections of line-fit palaeomagnetic directions from the studied Vendian and Early Cambrian rocks; open (closed) symbols denote upward (downward) pointing inclinations; the stereographic plots are presented in tilt-corrected coordinates; b — table with characteristic directions and palaeopoles isolated from Vendian basalts and tuffs of Volhynia and Early Cambrian mudstones from Estonia; N — number of samples used in calculations, *D*/*I* — declination/inclination, *K* — precision parameter (after Fisher, 1953), α_{95}— semi-angle of the cone of 95% confidence, Plat. — latitude of south palaeomagnetic pole, Plong. — longitude of south palaeomagnetic pole, dp — error of the distance between site and palaeopole, dm — palaeodeclination error

b

Locality	Component	N	*D*	*I*	α_{95}	K	Plat.	Plong.	dp	dm
Rafalivka	A	29	269°	66°	2.4°	117.3	36°S	153°E	3°	4°
Bazaltovoye-5	B	21	114°	-26°	3.9°	68.3	26°S	102°E	2°	4°
	C1	21	67°	55°	3.9°	66.7	40°N	102°E	4°	6°
Kunda	C2	35	89°	72°	4.7°	27.7	46°N	74°E	7°	8°

DISCUSSION

PALAEOMAGNETIC DATA

The directions were converted into the palaeomagnetic poles that were compared with the apparent polar wander path (APWP) for Baltica (Fig. 5). “A” and “B” palaeopoles are far away from the Late Vendian–Cambrian segment of the path constructed on the basis of Scandinavian poles (see Torsvik and Rehnström, 2001). They correspond to the Late Vendian palaeopole from the White Sea Region (Popov *et al.*, 2002). It should be stressed, however, that component “A” has about 40° higher value of inclination than “B” component. Hence, they cannot be coeval. The component (and palaeopole) “A” is most probably nearly primary connected with the emplacement of tuffs and basalts (c. 560–550 Ma ago). It is carried by a fine-grained magnetite that was demagnetized only in a high amplitude alternating field and moderate to high temperatures. Much more lower values of unblocking temperatures and coercivites of “B” component can indicate its secondary origin. It may be linked with the migration of post-magmatic brines along the pillar structures of basalts. However, “B” palaeopole does not correspond to the post-Vendian part of the Baltic APWP (Fig. 5) being located between the palaeopole from the White Sea Region (Popov *et al.*, 2002) and the Early Cambrian palaeopole from the Nekso Formation (Lewandowski and Abrahamsen, 2003). Because of this, it should be also considered as a Late Vendian one, being, however, younger than “A” palaeopole and secondary in origin. Due to insufficient documentation, “B” palaeopole was not considered in the construction of a revised APWP for Baltica.

The modified Late Vendian-Early Cambrian APWP for Baltica (Fig. 5) is based on the assumption that “A” component is of reversed polarity. Normal polarity is assigned to a characteristic component isolated from the Nekso sandstones (Lewandowski and Abrahamsen, 2003). The polarity of the direction from the White Sea Region is regarded as opposite to that assumed by Popov *et al.* (2002). Our results make APWP for Baltica much longer in the time concerned than that proposed by Torsvik and Rehnström (2001). Palaeomagnetic poles from the Volhynia and White Sea Region are far away from the palaeopoles isolated from the Fen complex (Piper, 1988; Meert *et al.*, 1998). It should be stressed, however, that the Fen com-

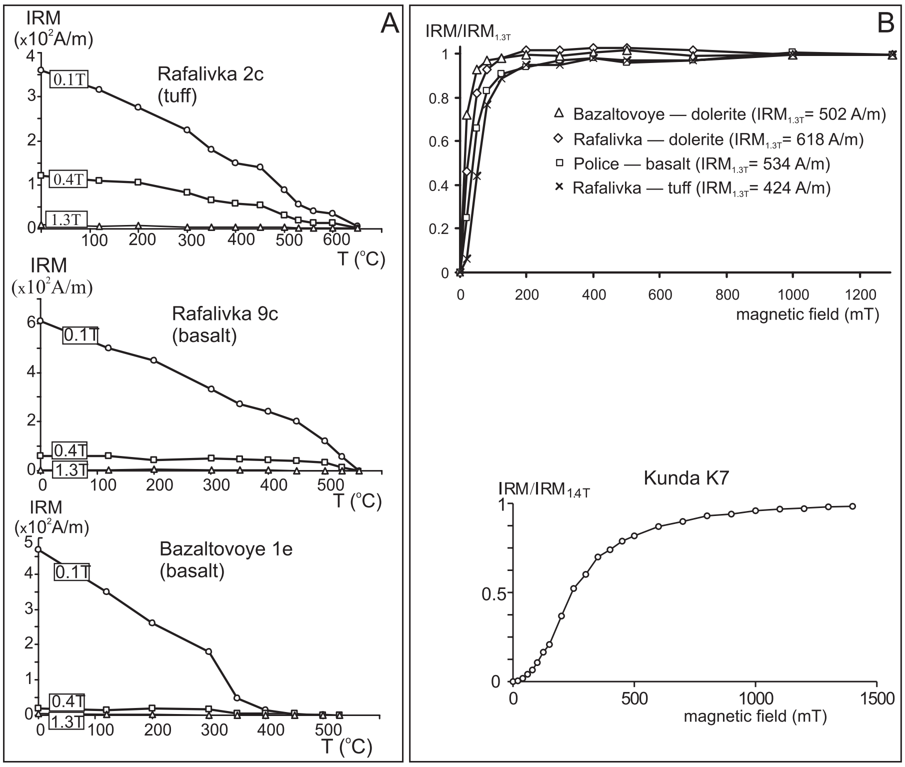

Fig. 4. a — thermal demagnetization of orthogonal-axis IRM curves obtained for tuffs and basalts from Rafalivka and Bazaltovoye-5; b — IRM acquisition curves prepared for the same samples and for the Lower Cambrian mudstone from Kunda quarry

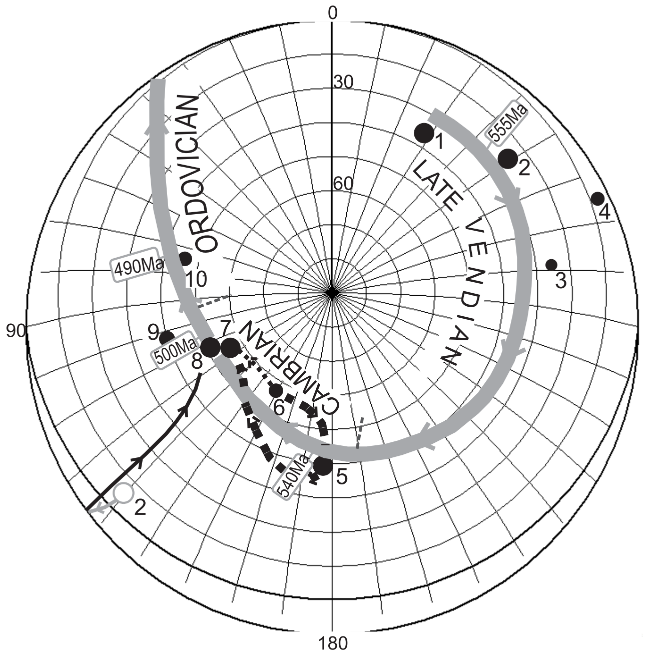

Fig. 5. Southern APWP for Baltica (thick grey line) and selected palaeopoles obtained from Vendian–Cambrian rocks of Baltica. The Late Cambrian–Ordovician segment of the path is presented after Torsvik *et al.* (1990, 1996) and Torsvik and Rehnström (2001). Three other versions of the Late Vendian–Early Cambrian segment of the Baltic APWP are also presented. The thin black line demonstrates the version according to Popov *et al.* (2002), the thin broken line — according to Torsvik and Rehnstrom (2001) and the thick broken line has been drawn according to Lewandowski and Abrahamsen (2003). 1 — palaeopole "A" from Rafalivka (this paper), 2 — palaeopole from Vendian sediments of White Sea Region (Popov *et al.*, 2002), 3— palaeopole "B" from Bazaltovoye-5 (this paper), 4 — palaeopole from the Lower Cambrian red beds of the Brunovistulian Terrane (Nawrocki *et al.*, 2004), 5 — palaeopole from Nekso Formation (Lewandowski and Abrahamsen, 2003), 6 — palaeopole from Fen Complex (Meert *et al.*, 1998), 7 and 8 — palaeopoles from Tronetrask Formation and Alum Shale respectively (Torsvik and Rehnström, 2001), 9 — palaeopole "C1" from Bazaltovoye-5 (this paper), 10— palaeopole "C2" from Kunda (this paper). In the construction of the Late Vendian segment of the new Baltic APWP the palaeopoles number 1 and 2 were used only. The poorly-documented palaeopole number 3 was not taken into consideration

plex is most probably older than the Volhynian basalts. Its age was estimated to be 568–598 Ma (Meert *et al.*, 1998). The palaeopole "C1" is convergent with the Cambrian segment of the Baltic APWP. The palaeopole "C2" corresponds to its Late Cambrian/Early Ordovician part (Fig. 5). This indicates their secondary origin. Palaeomagnetic pole number 4 (Fig. 5), obtained from the Early Cambrian red beds of the Brunovistulian Terrane (Nawrocki *et al.*, 2004) corresponds to the area of stereonet with the Late Vendian poles number 1, 2 and 3. This departure of pole number 4 from the Early Cambrian segment of the new APWP can be explained (see next chapter) by a significant (c. 80°) tectonic rotation of this terrane in the Early Palaeozoic.

NEW LATE VENDIAN-CAMBRIAN PALAEOGEOGRAPHY OF BALTICA AND THE TESZ AREA

Since an unequivocal polarity interpretation of palaeomagnetic directions from Volhynia and White Sea Region is not possible, two versions of palaeogeographic reconstruction of Baltica in the Late Vendian–Early Cambrian should be discussed (Fig. 6A). Model "X", which we prefer, corresponds to the modified Late Vendian-Early Cambrian APWP for Baltica (Fig. 5). It presents the Baltic plate moving at that time from moderate southern latitudes to the equator and rotating anticlockwise of *ca*. 120°. This model, apart from a fast (*ca*. 16 cm/year) plate drift, needs a relatively high rotation rate (c. 6°/Ma). Alternative reconstruction of Baltica presented as model "Y" (Fig. 6A) shows the Baltic plate moving from the Vendian position at moderately northern latitudes, crossing the palaeoequator in the latest Vendian and reaching moderate southern palaeolatitudes during the Cambrian (Fig. 6A). This model, discussed by Nawrocki *et al.* (2004), would have required an exceptionallyhigh plate velocity (*ca*. 33 cm/year).

The existence, near the present eastern and southwestern edges of Baltica, of crustal blocks containing a very distinct record of the Neoproterozoic orogeny, like the Brunovistulian Terrane (Żelaźniewicz, 1998; Finger *et al.*, 2000) can be justified by the model of the Late Vendian Baltica "X". In this reconstruction, the present-day SW margin of Baltica was separated from the Neoproterozoic structures of the Avalonian parts of peri-Gondwana (Fig. 6B). The present-day southern and eastern margins of this plate were tectonically active during its drift to nearly equatorial position in the Late Vendian–Early Cambrian. The Baltoscandian margin of Baltica was passive at that time. This interpretation is in agreement with the existing geological evidence (see e.g. Svenningsen, 1995; Poprawa *et al.*, 1999; Willner *et al.*, 2001; Scarrow *et al.*, 2001; Roberts and Siedlecka, 2002; Kalvoda *et al.*, 2002, 2003; Jaworowski and Sikorska, 2003). Moreover, our reconstruction can also explain why some detrital zircon grains from the Cambrian sediments of the present SW slope of Baltica have Cadomian ages (Valverde-Vaquero *et al.*, 2000).

The Neoproterozoic orogenic sequence of the Brunovistulian terrane was developed in the peri-Gondwana area. This terrane was separated from the Avalonian part of peri-Gonwana together with Baltica in the Late Vendian. The youngest Neoproterozoic structures of the Brunovistulian Terrane were developed when this unit was located near a tectonically active, present-day SW corner of Baltica. The Grenvilian Nd model ages and the same age of single zircon grains from the basement of Brunovistulian (Finger *et al.*, 2000; Hegner and Kröner, 2000) can be explained if this unit had been located in the proximity of the Avalonian and south American margin of Gondwana. Cambrian trilobite fauna from the Brunovistulian Terrane, if diagnostic, indicate rather Baltic links (Orłowski, 1985; Nawrocki *et al.*, 2004). Early Cambrian palaeolatitude (*ca*. 7°) obtained from palaeomagnetic studies (Nawrocki *et al.*, 2004) matches the Early Cambrian location of the TESZ margin of Baltica or the Arabian part of peri-Gondwana. This second location of the Brunovistulian Terrane in the Early Cambrian is rather impossible because of the Baltic links of the trilobite fauna and the Grenvilian ages noted in its basement. The Brunovistulian Terrane was probably dextrally translated along the present day SW edge of Baltica while

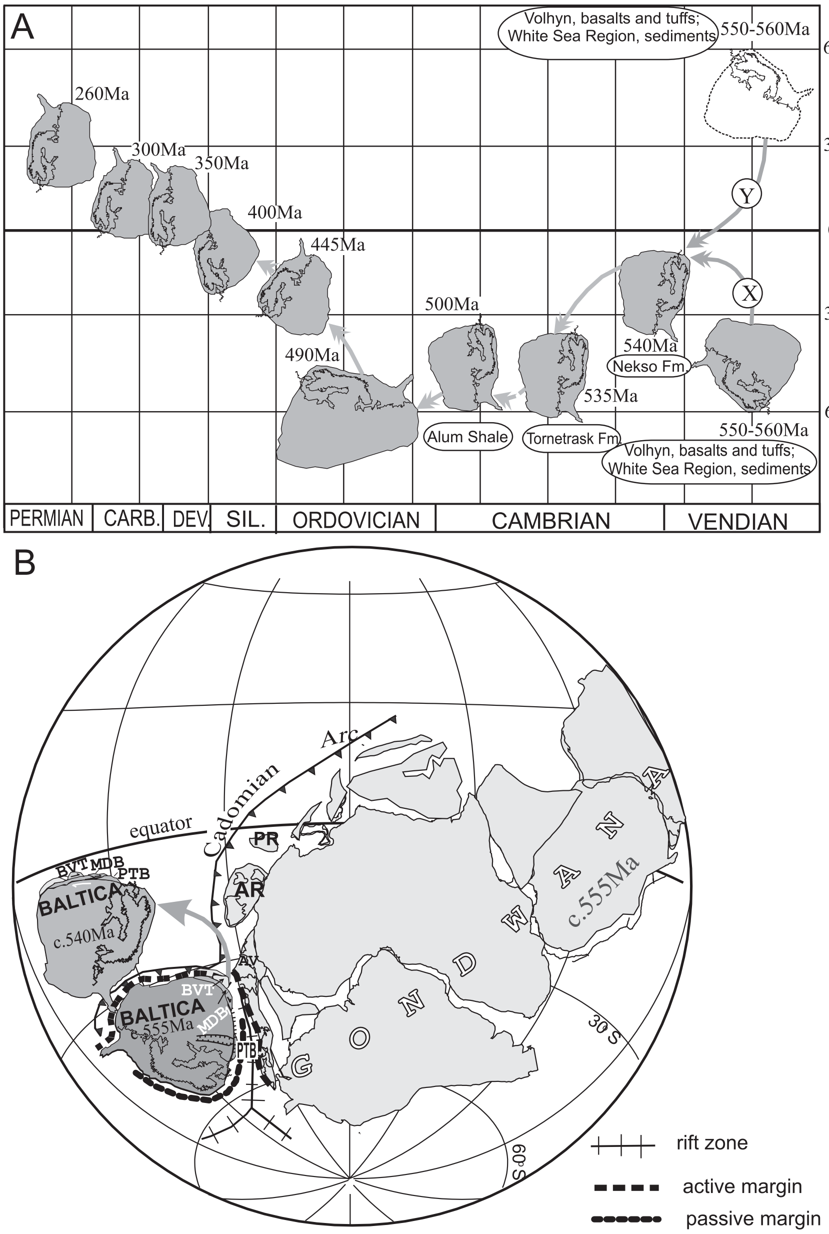

Fig. 6. A — palaeogeographic reconstruction of Baltica for the Late Vendian–Early Permian time span. The Early Ordovician–Early Permian location is quoted after Torsvik *et al.* (1990, 1996). The Late Vendian–Late Cambrian setting corresponds to palaeomagnetic poles and paths presented in Figure 5. Baltica "X" (grey in colour) has been drawn according to the new APWP presented in this paper. The white-coloured Baltica "Y" is in compliance with the APWP of Popov *et al*. (2002); B — simplified palaeogeographic reconstructions showing Gondwana megacontinent (adopted from Torsvik and Rehnström (2001), Torsvik *et al.* (1996) and the position of the Baltica in the Late Vendian and Early Cambrian; PR — Perunica, AV — Avalonia, AR — Armorica, BVT, — Brunovistulian Terrane, MDB — Małopolska-Dobrogea Tectonic Block, PTB — Pomerania Tectonic Block. The nearly equatorial position of the Brunovistulian Terrane at *ca.* 540 Ma is presented according to palaeomagnetic data of Nawrocki *et al*. (2004)

Baltica rotated in the Late Vendian time. It should be stressed, hovewer, that this terrane could not then reach its present position in the TESZ because the Cambrian palaeomagnetic pole characteristic for this unit (Nawrocki *et al*., 2004), being strongly rotated, does not fit the Baltic APWP (Fig. 5). The final stage of the tectonic transport of the Brunovistulian Terrane in the vicinity of the Małopolska Block took place after the Ludlovian, but before the sedimentation of the Lower Devonian sandstones of the "old red" type. The Ludlovian sediments of the Małopolska Block were not derived from the Brunovistulian Terrane but from the island arc located west of the Małopolska, in the place occupied now by the Brunovistulian Terrane (Kozłowski *et al*., 2004). The Early Devonian proximity of the Brunovistulian and the Małopolska can be inferred from the distribution of the boundaries of particular "old red" facies (Pajchlowa and Miłaczewski, 1974). These boundaries cut the Kraków-Lubliniec fault zone that separates both units.

The palaeogeography of the Małopolska Block in the Late Vendian is not clear. This unit could form a marginal part of Baltica, being always located near its present position. Then the partly metamorphosed Late Vendian flysh sequences covering the Małopolska (Żelaźniewicz, 1998) could be related to the collision of any Cadomian tectonic block with this part of Baltica. It should be stressed, however, that this solution does not match the results of subsidence analysis where the Late Vendian–Cambrian extension at the SW edge of Baltica is postulated (Poprawa *et al*., 1999). Because of this, another setting of the Małopolska in the Late Vendian should be taken into consideration. This unit could form an external part of the area with the Late Neoproterozoic deformations, occupying the active southern margin of Baltica. It was moved as a proximal terrane to the present position during the Late Vendian rotation of Baltica. This model corresponds to the reconstructions proposed by Lewandowski (1993) and Narkiewicz (2002). However, in our proposition, the time and source of the tectonic transport of Małopolska Block are different.

The geological structure, lithology and geochronology of the Brunovistulian Terrane show a broad fit with the crystalline basement of the Istanbul Zone (Kalvoda *et al*., 2002). The Vendian and Cambrian sequences of the central Małopolska Block and Brunovistulian Terrane correlate well with the Scythian Platform (Kalvoda *et al*., 2003). This supports our interpretation, in which the Bunovistulian Terrane and the Małopolska Block could form, in the latest Vendian, a link between NW passive margin of Baltica and its active southern sector where the Scythian Platform and the Istanbul Zone are located up till now.

CONCLUSIONS

The palaeopole calculated for the most stable component isolated from the Vendian tuffs and basalts from Volhynia is far away from the Vendian–Cambrian APWP constructed on the basis of Scandinavian poles, but is very close to the pole isolated recently from the Vendian sediments of the White Sea Region.

According to the new palaeomagnetic data, two palaeogeographic models for Baltica in the Late Vendian–Early Cambrian are proposed. In our prefered model, the Baltic plate occupied the moderate southern latitudes in the Late Vendian and moved to the equator, meanwhile rotating anticlockwise by *ca*. 120°.

The new reconstruction of Baltica explains better the geological framework of its marginal zones than the stationary model previously proposed. The Late Neoproterozoic tectonic structures of the Brunovistulian Terrane and the Małopolska Block were developed near the present day SW corner of Baltica, which was then tectonically active.

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