

Late Neoproterozoic to Early Palaeozoic palaeogeography of the Holy Cross Mountains (Central Europe): an integrated approach

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Abstract: Study of geochemistry, examination of isotope ages of detrital minerals, palaeomagnetic analysis, and a study of the trilobites were performed to provide constraints on the palaeogeographical position of the Holy Cross Mountains in Late Ediacaran–Early Palaeozoic time. The geochemical results indicate an active continental margin or continental island arc provenance of the Ediacaran sediments. Sediments from a passive continental margin were deposited here during the Cambrian and Ordovician. The palaeomagnetic pole isolated from Cambrian rocks of the Małopolska region of the Holy Cross Mountains corresponds to the Cambrian segment of the Baltic apparent polar wander path. Isotope age estimations indicate that Cambrian sediments of the Małopolska region contain detritus not only from a latest Neoproterozoic source but also from sources with ages of *c.* 0.8–0.9 Ga, 1.5 Ga and 1.8 Ga. The Małopolska, Brunosilesia, Dobrugea and Moesia terranes, which originally developed near the present southern edge of Baltica and were partly involved in the Cadomian orogen, were dextrally relocated along its Trans-European Suture Zone margin. The first stage of this movement took place as early as latest Ediacaran time, while Baltica rotated anticlockwise. Anticlockwise rotation of Baltica at the Cambrian–Ordovician boundary implies further dextral movement of the Małopolska block.

The Trans-European Suture Zone separates the pre-Cambrian East European Craton from several minor tectonic blocks regarded as a set of Phanerozoic terranes (Pożaryski 1991; Berthelsen 1993; Franke 1995). It extends from the North Sea in the NW to the Black Sea in the SE through central Europe (Fig. 1). The Holy Cross Mountains are the best exposed Palaeozoic massif in the central part of the Trans-European Suture Zone. The Palaeozoic core of the Holy Cross Mountains, including sedimentary rocks ranging in age from Cambrian to Early Carboniferous, emerged from below the Permian and Mesozoic cover during the Late Cretaceous movements (Kutek & Głazek 1972). It consists of two distinct tectonostratigraphic regions separated by the Holy Cross Dislocation (Fig. 2). The southern part of the Holy Cross Mountains, named the Kielce region, belongs structurally to the Małopolska Massif (Pożaryski & Tomczyk 1968). The crystalline basement of the Małopolska Massif is unknown. In the southern part of the Małopolska Massif several deep boreholes have reached a succession of weakly metamorphosed clastic rocks. Compston *et al.* (1995) dated a volcanic tuff from the uppermost part of the succession at 549 ± 3 Ma. The Late Ediacaran succession is not exposed or drilled in the Kielce region of the Holy Cross Mountains.

From Cambrian to Devonian time, the two regions of the Holy Cross Mountains underwent somewhat different tectonic and facies development. Two pre-Variscan tectonic events are recognized in the Kielce region: the first between the Middle Cambrian and the Early Ordovician (the so-called Sandomierian tectonic movements), and the second between the Late Silurian

and Early Devonian. In the Łysogóry region, the folded rocks (Late Cambrian to Earliest Carboniferous) comprise a complete sedimentary sequence without any distinct breaks (Stupnicka 1992). Palaeomagnetic data from Ordovician (Schätz *et al.* 2002) and Silurian rocks (Nawrocki 2000) indicate that at least after the Sandomierian deformations, the Kielce region was near its present position with respect to Baltica.

The two units of the Holy Cross Mountains are regarded by some workers (e.g. Belka *et al.* 2002) as the first Gondwana-derived terranes rifted in the Cambrian and accreted to the margin of Baltica during the Cambrian–Early Ordovician (Belka *et al.* 2002) or in the Late Silurian (Pożaryski 1991). The peri-Gondwanan origin of the Małopolska Massif is inferred mainly from the isotope ages of detrital micas and zircons (*c.* 540–560 Ma) derived from the Cambrian sediments, and biogeographical affinity of the Early Cambrian brachiopods (Belka *et al.* 2002). However, Żelaźniewicz (1998) suggested that the Neoproterozoic (Ediacaran) foreland flysch basin of the Małopolska Massif and neighbouring Brunovistulian terrane was developed next to the East European Craton. The Baltic affiliation of the Holy Cross Mountains was also postulated by Cocks (2002) and Cocks & Torsvik (2005), who emphasized the Baltic links of the Cambrian trilobites and the Ordovician brachiopods from the Kielce unit of the Holy Cross Mountains.

According to Winchester & PACE TMR Network Team (2002), the presence of Cadomian-type basement, with evidence of end-Proterozoic deformation, cannot be taken as evidence of a Gondwanan origin of any terrane. The occurrence of late Proterozoic basement in the Uralides (Glasmacher *et al.* 1999)

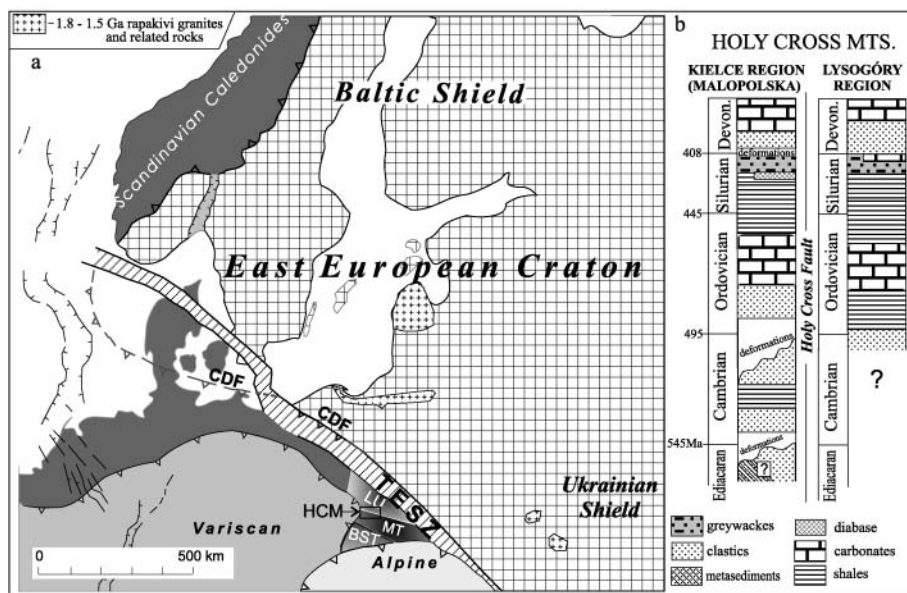


Fig. 1. (a) The location of the Holy Cross Mountains (HCM) within a tectonic sketch map of Central Europe (TESZ, Trans-European Suture Zone; CDF, Caledonian Deformation Front; LU, Łysogóry Unit; MT, Małopolska terrane; BST, Brunosilesian terrane). (b) Stratigraphic columns with stratigraphic succession for the Holy Cross Mountains. The Ediacaran rocks are not exposed in the Kielce region of the Holy Cross Mountains. They were drilled in several places of the Małopolska Block, south of the Holy Cross Mountains. Ages are adopted from the time scale proposed by Gradstein *et al.* (2004).

indicates that it is not conclusive proof of a Gondwanan origin. The Cadomian belt was several thousand kilometres long and did not involve only peri-Gondwana (Nance & Murphy 1994; Torsvik *et al.* 1996).

The difficulties of determining the Neoproterozoic palaeogeography of the Holy Cross Mountains are partly connected with the lack of an unequivocal palaeogeography for the Baltic plate at that time. Based on the palaeomagnetic poles from the Fen complex (Piper 1988; Meert *et al.* 1998) only a minor mobility of the Baltic plate between 555 and 500 Ma has been proposed (e.g. Hartz & Torsvik 2002; Cocks & Torsvik 2005). In this reconstruction Baltica is located between 30° and 60°S with its present SW edge facing north. However, this model does not explain some tectonic problems such as the presence of the Neoproterozoic orogen in the basement of the Brunovistulian block, and partly metamorphosed Ediacaran flysch in the basement of the Małopolska block. These blocks are situated near the present SW edge of Baltica. A modification of Baltica palaeogeography has been recently proposed by Nawrocki *et al.* (2004a) and Llanos *et al.* (2005), who have suggested a significant mobility of the Baltic plate in the late Ediacaran, based on palaeomagnetic data from the Volhynian basalts (Nawrocki *et al.* 2004a) and sediments of NW Russia (Popov *et al.* 2002; Llanos *et al.* 2005). In the model of Nawrocki *et al.* (2004a) the Baltic plate moved at that time from moderate southern latitudes to the equator, rotating anticlockwise about 120°. Before this movement the Trans-European Suture Zone margin of Baltica faced the western part of peri-Gondwana 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 Cocks & Torsvik 2005).

The discrepancies between the models of Holy Cross Mountains palaeogeography are caused not only by the problems with Baltica palaeogeography but also because of the lack of credible provenance constraints. Among these, the isotope ages of detrital minerals, whole-rock geochemistry and palaeomagnetic information need to be updated. Also, the Cambrian trilobite faunas of the Holy Cross Mountains need further verification. The aim of the present paper is to address these deficiencies.

The isotope ages of detrital micas and zircons

Previous studies

K–Ar cooling ages of detrital mica in the Cambrian and Ordovician rocks of the Holy Cross Mountains were studied by Bełka *et al.* (2000, 2002). In the Małopolska Massif those workers found detrital mica grains with K–Ar cooling ages of about 535–545 Ma. This suggests a single source region with a Cadomian imprint (Bełka *et al.* 2000, 2002). U–Pb studies of detrital zircons from the Lower Cambrian rocks of Małopolska (Kędziorka outcrop) have provided ages of about 540 Ma and 2.0 Ga, and suggest ages of *c.* 1.2–1.37, 1.5, >2.5 and >3.0 Ga (Bełka *et al.* 2002). According to Bełka *et al.* (2002), this wide age spectrum correlates well with detrital zircon ages known from Neoproterozoic rocks of West Avalonia and with basement isotopic signatures of the Amazonian Craton. Cambrian rocks of the Łysogóry Unit contain detrital muscovites with K–Ar cooling ages of about 1.7, 1.3, 0.7–0.9 and 540 Ma (Fig. 2). Bełka *et al.* (2000) suggested a contribution of Late Cambrian detritus of the Łysogóry Unit from both Baltic and Cadomian sources. Valverde-Vaquero *et al.* (2000) investigated detrital zircons from the Upper Cambrian rocks of Łysogóry and obtained ages of about 600 Ma, 1.8–2.1 Ma and >2.5 Ga known from both Gondwanan and Baltic sources. Abundant detrital muscovites in the Lower Cambrian sandstones of the neighbouring Brunovistulian terrane show K–Ar cooling ages from 542 to 566 Ma (Bełka *et al.* 2000).

New K–Ar and U–Pb data

Samples for new K–Ar dating of detrital mica were taken from 12 localities in the Małopolska part of the Holy Cross Mountains and four localities in the Łysogóry region. The sampled rocks represent different formations of Cambrian and Silurian rocks (Table 1, Fig. 2). Only one sample was taken from the Lower Silurian mudstone. The remaining Silurian samples were collected from Ludlow and Pridoli greywackes. To obtain the age spectrum of detrital zircons in the Lower Ordovician rocks of the Małopolska Massif one sample was collected from Upper

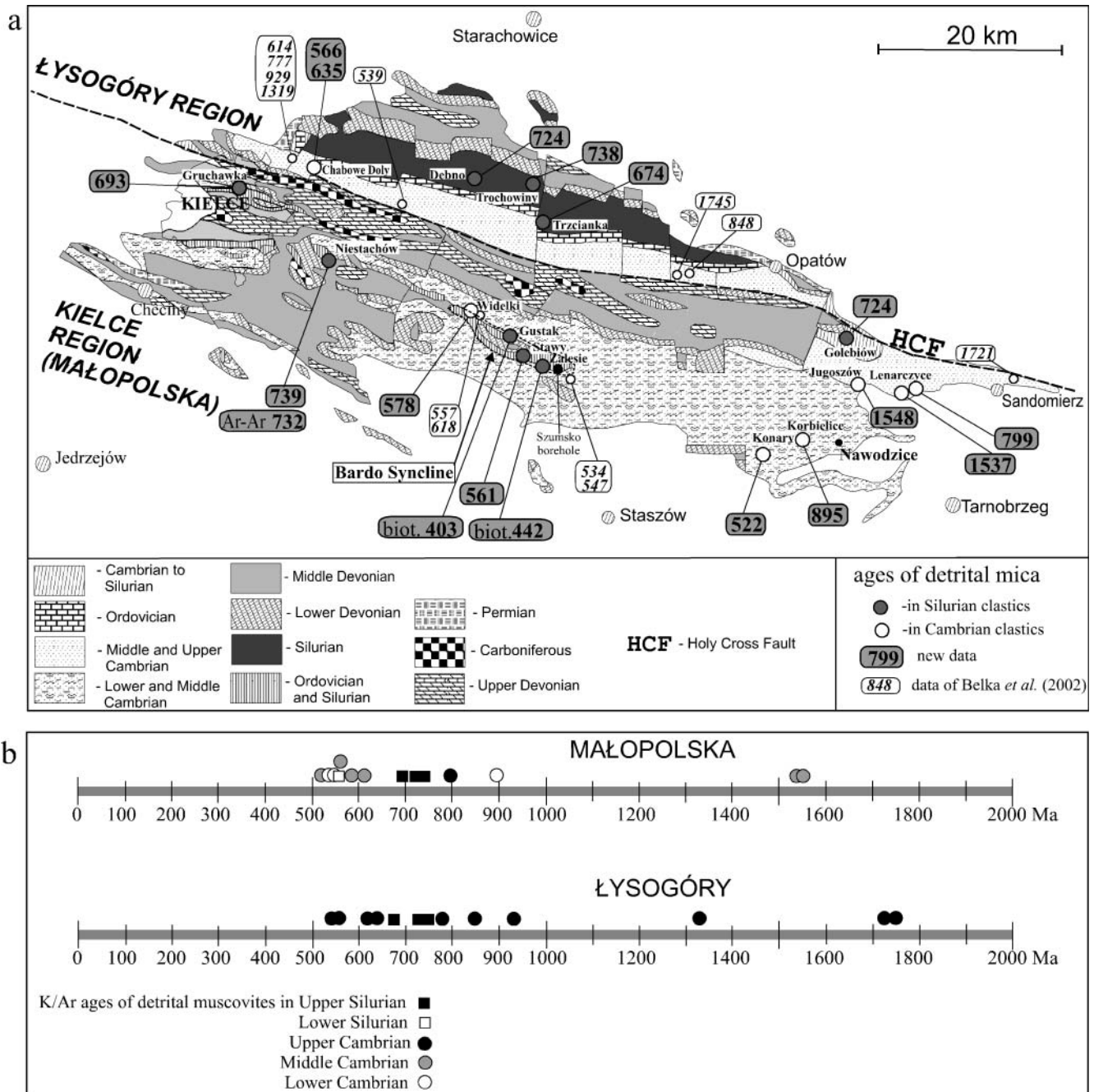


Fig. 2. K–Ar ages of detrital muscovite in the Cambrian and Silurian rocks of the Holy Cross Mts. presented on the background of a simplified geological map of the region (a) and linear age diagrams (b). The Ar–Ar age of the muscovite from the Silurian greywackes (Niestachów locality) and K–Ar ages of biotite from the same sediments (Gustak and Zalesie localities) are also presented. (For further details see Table 1 and Fig. 3.)

Tremadoc sandstones from between 65 and 67 m depth in the Szumsko IG-1 borehole (Fig. 2). The zircon grains were separated from these sandstones and studied by sensitive high-resolution ion microprobe (SHRIMP) in the laboratory of the Research School of Earth Sciences, Australian National University.

Mica samples containing only the fresh cores of the grains were processed and analysed at the Institute of Nuclear Research of the Hungarian Academy of Sciences. The potassium content was determined by flame photometry with a Na buffer and Li internal standard. Argon was extracted from the samples by RF fusion in Mo crucibles, in a previously heated stainless steel vacuum system. The Ar isotope ratio

was measured in the static mode, using a 15 cm radius magnetic sector type mass spectrometer. Atomic constants suggested by Steiger & Jäger (1976) were used for calculation of the ages.

A summary of new K–Ar data is presented in Table 1 and Figure 2. The cooling ages of mica from the Upper Silurian sediments are consistent and similar in both regions of the Holy Cross Mountains, and are in the range 674–739 Ma. The input from a late Neoproterozoic source documented by a cooling age of 560 Ma was recognized in the sample from Lower Silurian mudstones only. The K–Ar ages of two biotite samples from the Silurian greywackes are close to the stratigraphic age of these rocks. The Cambrian sediments from the Małopolska

Table 1. Summary of K–Ar data for detrital muscovites and biotites from Cambrian and Silurian clastic rocks of the Holy Cross Mountains

Sample locality and stratigraphy	Dated fraction	K (%)	⁴⁰ Ar rad (%)	⁴⁰ Ar rad (cm ³ STP g ^{−1}) × 10 ^{−4}	K–Ar age (Ma)
<i>Lysogóry</i>					
Chabowe Doły 1 (Upper Cambrian)	Muscovite	6.71	97.7	1.9858	635.3 ± 23.8
Chabowe Doły 2 (Upper Cambrian)	Muscovite	6.70	97.5	1.7328	566.3 ± 21.2
Debno (Upper Silurian)	Muscovite	2.66	97.1	0.9118	723.7 ± 21.8
Trochowiny (Upper Silurian)	Muscovite	6.87	92.2	2.4349	737.6 ± 27.7
Trzcianka (Upper Silurian)	Muscovite	4.36	90.5	1.3840	674.2 ± 25.4
<i>Małopolska</i>					
Korbielice (Lower Cambrian)	Muscovite	3.17	97.3	1.4269	895.2 ± 26.9
Wielki (Middle Cambrian)	Muscovite	7.49	95.9	1.9844	577.7 ± 21.6
Lenarczyce (Middle Cambrian)	Muscovite	7.15	97.5	7.416	1537.0 ± 61.0
Jugosów (Middle Cambrian)	Muscovite	7.97	98.6	7.596	1548.0 ± 58.0
Konary (Middle Cambrian)	Muscovite	4.89	90.5	1.1525	522.0 ± 19.6
Lenarczyce 1 (Upper Cambrian)	Muscovite	5.56	87.6	2.1704	798.7 ± 30.2
Stawy (Lower Silurian)	Muscovite	7.46	96.7	1.9081	560.9 ± 21.0
Niestachów (Upper Silurian)	Muscovite	7.01	96.8	2.4865	738.7 ± 27.7
Golebiów (Upper Silurian)	Muscovite	6.72	95.2	2.3281	724.4 ± 27.2
Gruchawka (Upper Silurian)	Muscovite	7.41	90.5	2.4349	693.3 ± 26.1
Gustak (Upper Silurian)	Biotite	4.45	91.1	0.7808	402.5 ± 15.2
Zalesie (Upper Silurian)	Biotite	2.71	77.4	0.5288	442.1 ± 16.9

part of the Holy Cross Mountains contain muscovites not only from a late Neoproterozoic source defined by Belka *et al.* (2002) but also from sources with an igneous–metamorphic overprint associated with the *c.* 0.8–0.9 Ga and 1.5 Ga ages. Two samples taken from the Upper Cambrian sediments of the Lysogóry region revealed the presence of late Neoproterozoic ages only.

The dataset obtained from zircon grains separated from the Upper Tremadoc sandstones of the Szumsko IG-1 borehole suggests the presence of zircons with ages of *c.* 500 Ma, 550 Ma, 650 Ma, 1.85 Ga, 2.0 Ga and 2.7 Ga (Fig. 3a).

Results of ⁴⁰Ar–³⁹Ar analysis of detrital muscovite from Silurian greywacke

The cooling age of detrital muscovite from Silurian greywacke sampled at Niestachów was also investigated using the ⁴⁰Ar–³⁹Ar method. The sample was analysed at the Research School of Earth Sciences, Australian National University, Canberra. The biotite standard GA1550 was used. The sample was heated in a series of steps, with a duration of 14 min for each step. Correction factors to account for K-, Cl- and Ca-derived Ar isotopes are (³⁶Ar/³⁷Ar)_{Ca} = 3.5 × 10^{−4}, (³⁹Ar/³⁷Ar)_{Ca} = 7.86 × 10^{−4}, (⁴⁰Ar/³⁹Ar)_K = 2.2 × 10^{−2}, (³⁸Ar/³⁹Ar)_K = 0.136 and (³⁸Ar)_{Cl}/^{(39)Ar}_K = 8.0.

The studied sample revealed the presence of two recognizable plateaux for the low- and high-temperature steps, at 811 ± 3 Ma and 716 ± 4 Ma, respectively (Fig. 3b). The integrated age (732 ± 3 Ma) agrees well with the age estimated by the K–Ar method (738 ± 28 Ma, Table 1). Our ⁴⁰Ar–³⁹Ar experiment indicates that the studied muscovites were cooled through a temperature range of about 300–400 °C at about 720–750 Ma and the original crystallization age of the mica is probably between 800 and 900 Ma.

The ⁴⁰Ar–³⁹Ar age of the Bardo diabase

The age of mafic intrusions cutting the Palaeozoic strata of the Holy Cross Mountains in some places is still a matter of controversy. Their age of emplacement is very important in reconstructing the Late Caledonian tectonic regime in the Holy Cross Mountains. The most extensive magmatic intrusion of this region occurs in the Bardo syncline in the central part of the Kielce region (Figs 1 and 4a). The diabase intrusion penetrates the Silurian rocks of this syncline, close to the stratigraphic boundary between Lower Ludlow graptolite shales and Upper Ludlow greywackes. The overall thickness of the intrusion varies between 20 and 30 m. Tectonic and stratigraphic observations

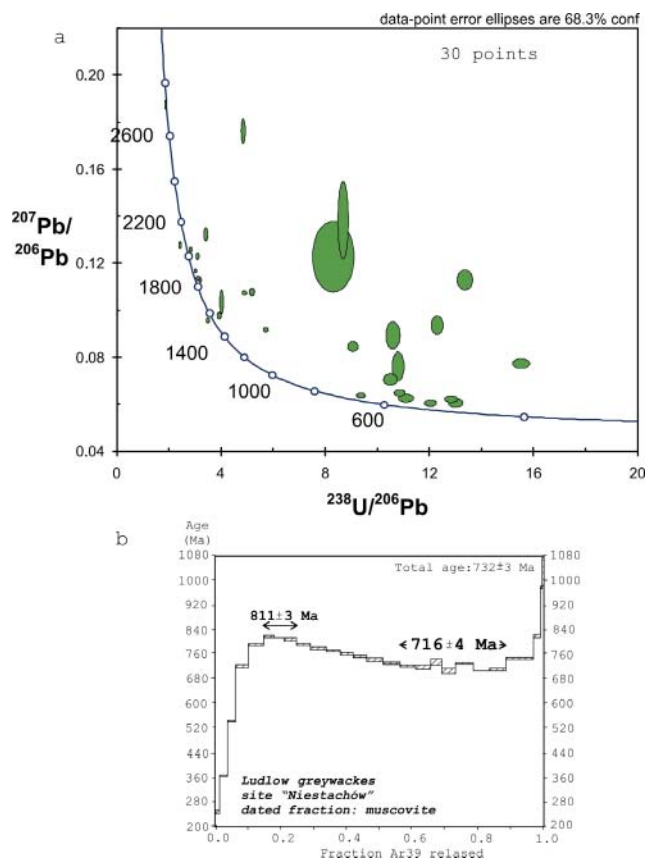


Fig. 3. (a) U–Pb concordia diagram for detrital zircons from the Tremadoc sandstones of the Kielce region (Szumsko IG-1 borehole, 65–67 m of depth). (b) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for the muscovite separated from the Ludlow greywackes of the Kielce region (Niestachów locality; see Fig. 2).

point to a Late Ludlow–Siegenian age interval for the Bardo diabase (Kowalczewski & Lisik 1974). However, preliminary isotope studies do not exclude a Variscan age (Migaszewski 2002). A palaeomagnetic study of the Bardo diabases provides a

prefolding palaeomagnetic pole concordant with the Ludlow segment of the apparent polar wander path (APWP) for Baltica (Nawrocki 2000).

A sample for ^{40}Ar – ^{39}Ar studies was taken from a fresh core of the intrusion taken at an outcrop in the southern limb of the syncline near Zalesie village (Fig. 4a). A set of plagioclase grains was analysed in the laboratory at the Research School of Earth Sciences, Australian National University. The studied sample revealed the presence of two plateaux for the low- and high-temperature steps, at 432 ± 2 Ma and 425 ± 11 Ma, respectively (Fig. 4b). On the other hand, the step size weighting indicates that the section of the age spectrum from the step-heating run, from 0.4 to 0.97, is 424 ± 6 Ma. The integrated age (433 ± 3 Ma) is slightly too old because the middle Ludlow strata containing the intrusion cannot be older than 422 Ma (Gradstein *et al.* 2004). Nevertheless, our data point clearly to a Silurian age for the Bardo intrusion.

Geochemical signatures

For the whole-rock geochemistry and chemical discrimination of provenance a sample set from the Late Ediacaran, Cambrian, Ordovician and Upper Silurian sequences of the Małopolska and Łysogóry regions was used. The geochemical study of the Upper Silurian greywackes from the Holy Cross Mountains indicates a continental island arc provenance of the detritus (Kozłowski *et al.* 2004). The Late Ediacaran non-mature sandstones of the Małopolska unit display relatively low SiO_2 content (59.1–76.0%), a moderate to high content of Al_2O_3 (11.38–16.94%), a uniform ratio of Al_2O_3 to SiO_2 , and variable contents of Na_2O (Table 2, Fig. 5a). They are rich in sodium (3.08–4.31% Na_2O). The mature quartz sandstones of Cambrian and Ordovician age from the Małopolska unit and of Late Cambrian age from the Łysogóry unit have a completely different composition. They have a high content of SiO_2 (80.72–92.72%), low Al_2O_3 contents (from 2.27% in quartz arenites to 13.39% in quartz wackes), a low ratio of Al_2O_3 to SiO_2 , and a low content of Na_2O (0.04–0.41%). The late Ediacaran sandstones also have higher contents of Ni and Co (25–64 ppm) than the early Palaeozoic sandstones (2–15 ppm). They also show a constant content of Zr (c. 200 ppm). The Zr content of the early Palaeozoic sandstones varies from 139 to 1122 ppm, probably

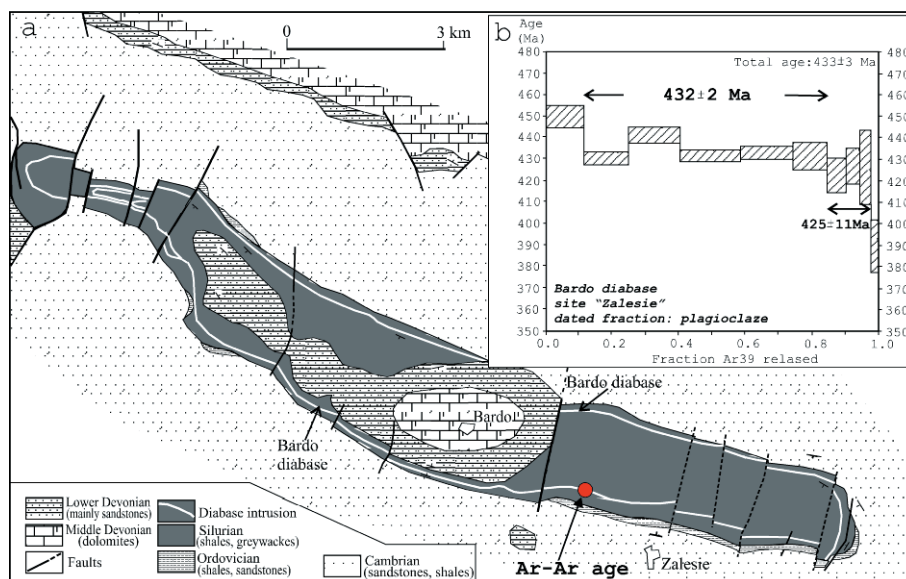


Fig. 4. (a) Geological sketch map of the Bardo Syncline (Kielce region of the Holy Cross Mountains) (after Czarnocki 1958). (b) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for the plagioclase separated from the Bardo diabase.

Table 2. *Results of geochemical analyses*

Sample no.:	3-Kw-116	3-Jr-428	3-Pm-113	3-BW-223	KZB	KOC	KUS	KCD	WDNE	WDE2	MGO	3-Jr-387
Age:	pCm	pCm	pCm	pCm	LCm	LCm	MCm	Ucm	Ucm	Ucm	O	O
Region:	MB	MB	MB	MB	MB	MB	MB	LU	LU	LU	MB	MB
Lithology:	fw	aw	lw	m	m	qa	qw	qw	qw	m	qa	qa
SiO ₂	71.77	71.25	71.25	65.44	71.92	88.53	84.41	82.52	83.48	73.42	92.72	85.47
TiO ₂	0.75	0.75	1.00	0.86	0.87	0.80	0.69	0.62	0.62	1.11	0.52	0.44
Al ₂ O ₃	13.87	12.91	15.39	16.68	15.33	6.18	9.29	8.61	10.46	19.00	2.27	6.25
Fe ₂ O ₃	5.54	6.72	6.42	9.59	6.13	2.02	2.30	4.70	2.40	1.18	1.69	2.47
MnO	0.12	0.13	0.11	0.04	0.01	<0.01	0.01	0.01	<0.01	<0.01	0.01	0.06
MgO	1.37	2.39	1.39	1.59	1.15	0.42	0.55	0.88	0.42	0.55	0.22	1.09
CaO	1.11	0.71	1.24	0.47	0.25	0.09	0.34	0.64	0.14	0.15	1.01	2.21
Na ₂ O	3.43	3.55	1.05	2.80	0.81	0.29	0.25	0.41	0.10	0.16	0.04	0.20
K ₂ O	1.69	1.47	2.02	2.42	3.45	1.64	2.14	1.35	2.32	4.40	0.72	1.42
P ₂ O ₅	0.37	0.12	0.12	0.13	0.08	0.03	0.02	0.26	0.05	0.04	0.79	0.39
Cr ₂ O ₃	0.012	0.011	0.009	0.011	0.006	0.009	0.005	0.007	0.012	0.019	0.021	<0.001
LOI	4.9	3.4	5.8	4.0	5.5	2.2	3.9	3.1	3.2	4.9	1.5	5.2
Total	99.85	99.84	99.86	99.81	99.82	99.77	99.85	99.79	99.98	99.93	99.69	99.86
Pb	3.5	29.1	7.6	24.7	13.4	6.1	3.4	13.2	6.3	3.2	5.9	5.1
Zn	50	86	46	69	59	49	28	44	10	1	163	15
Co	9.4	18.0	11.5	15.5	12.8	3.3	4.1	17.3	2.0	0.9	1.8	4.3
Ni	54.3	30.8	21.0	35.7	22.7	9.0	6.7	28.9	4.8	1.5	4.6	8.1
V	100	83	109	113	85	41	48	62	62	107	31	39
Cs	1.8	1.3	4.3	6.7	5.1	1.3	3.3	3.9	8.9	7.3	1.8	2.0
Rb	56.9	40.8	65.3	84.1	134.1	56.4	87.8	72.4	90.7	113.9	32.6	39.5
Ba	299	150	256	264	337	258	218	185	284	335	57	413
Sr	129.5	109.8	76.3	109.3	73.6	36.7	52.2	90.3	64.5	96.5	206.0	148.4
Nb	13.9	14.8	13.9	17.8	16.2	13.1	12.8	11.1	11.3	20.1	8.2	8.9
Ta	0.9	1.3	1.0	0.9	1.1	1.0	1.0	0.8	0.8	1.3	0.6	1.8
Th	7.4	6.0	7.3	10.7	12.8	13.1	10.3	16.1	10.6	15.1	13.8	7.0
U	1.3	1.7	2.3	3.3	2.5	3.7	2.4	3.7	2.2	4.0	3.7	2.3
Hf	5.0	5.7	7.2	5.4	8.9	25.2	11.0	17.7	7.0	12.4	30.2	6.2
Zr	169.0	205.0	285.5	210.7	306.9	890.2	398.1	689.7	235.6	465.2	1122.2	229.0
Sc	13	11	15	15	15	12	11	15	13	21	13	4
Y	28.0	19.4	31.5	31.7	33.1	32.9	22.0	56.4	29.0	36.3	75.9	27.4
La	28.3	32.4	24.7	32.8	40.9	46.3	27.6	45.0	35.2	48.1	39.2	26.0
Ce	56.6	68.3	52.3	68.0	87.7	90.6	59.9	100.0	72.9	93.4	93.5	55.7
Pr	6.56	7.01	6.30	7.86	9.58	10.95	6.23	11.91	8.80	10.75	10.87	6.19
Nd	27.2	29.1	26.3	30.6	37.3	44.1	23.9	48.6	34.5	40.7	46.7	25.9
Sm	5.9	5.6	6.3	6.8	6.3	8.0	3.8	10.4	6.8	7.5	12.1	5.2
Eu	1.34	1.26	1.43	1.36	1.36	1.42	0.85	2.17	1.29	1.72	2.73	1.35
Gd	5.16	4.74	5.15	5.51	5.55	6.15	3.45	9.61	6.02	7.19	13.47	5.18
Tb	0.85	0.54	0.93	0.95	1.15	1.05	0.66	1.59	0.97	1.07	2.12	0.78
Dy	4.70	3.55	5.28	5.09	5.68	4.85	3.81	9.11	5.45	6.33	11.70	4.50
Ho	0.93	0.80	1.12	1.08	1.24	1.27	0.83	1.87	0.98	1.29	2.47	0.90
Er	2.76	1.83	3.08	3.15	2.68	2.61	1.96	4.89	2.70	3.24	6.39	2.24
Tm	0.39	0.28	0.49	0.56	0.51	0.57	0.39	0.77	0.50	0.68	1.02	0.35
Yb	2.56	2.04	3.12	3.79	3.37	3.67	2.44	4.61	2.75	3.64	6.74	2.05
Lu	0.41	0.37	0.50	0.52	0.51	0.62	0.43	0.65	0.46	0.55	1.05	0.35
Total REE	143.7	157.8	137.0	168.1	203.8	222.2	136.2	251.2	179.3	226.2	250.1	136.7
(La/Yb) _N	7.47	10.73	5.35	5.85	8.20	8.53	7.64	6.60	8.65	8.93	3.93	8.57
(La/Gd) _N	4.57	5.70	4.00	4.96	6.14	6.28	6.67	3.90	4.88	5.58	2.43	4.19
(Gd/Yb) _N	1.63	1.88	1.34	1.18	1.33	1.36	1.15	1.69	1.77	1.60	1.62	2.05
Eu/Eu*	0.74	0.75	0.77	0.68	0.70	0.62	0.72	0.66	0.62	0.72	0.65	0.79
Th/Sc	0.57	0.55	0.49	0.71	0.85	1.09	0.94	1.07	0.82	0.72	1.06	1.75
La/Sc	2.18	2.95	1.65	2.19	2.73	3.86	2.51	3.00	2.71	2.29	3.02	6.50

The analyses were performed at the Acme Analytical Laboratories, Vancouver. The major oxides, Ba and Sc were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES) after LiBO₂ fusion; trace elements were determined by inductively coupled plasma mass spectrometry (ICP-MS) from a LiBO₂ fusion or aqua regia digestion. Major oxides in wt%, trace elements in ppm. Total Fe as Fe₂O₃. Oxide contents are normalized to 100% volatile free. aw, arkosic wacke; fw, feldspathic wacke; lw, lithic wacke; qw, quartz wacke; qa, quartz arenite; m, mudstone. Eu/Eu* = Eu_N/(Sm_N × Gd_N)^{1/2}; N, chondrite normalized (normalizing values from Taylor & McLennan 1985). pCm, Precambrian; LCm, Lower Cambrian; MCm, Middle Cambrian; Ucm, Upper Cambrian; O, Ordovician; MB, Małopolska Block; LU, Lysogory Unit.

because of the sorting of heavy minerals during transportation of the material.

The geochemical signatures of particular samples are presented in a multi-element plot (Fig. 5b) normalized against an average upper continental crust composition (UCC, Taylor & McLennan 1985). Homogeneity of the less mobile elements in the late Ediacaran sandstones is evident. These rocks display a

low content of potassium, relatively high content of phosphorus, very low caesium content, and a negative Ta–Nb anomaly. The geochemical record noted in the Lower Cambrian mudstones of the Małopolska unit is also homogeneous. Different geochemical behaviour is observed in the mature Lower Cambrian quartz arenites (low contents of Sr, P, V and Ni, and enrichment in Zr and Hf), Middle–Upper Cambrian quartz wackes, and Ordovi-

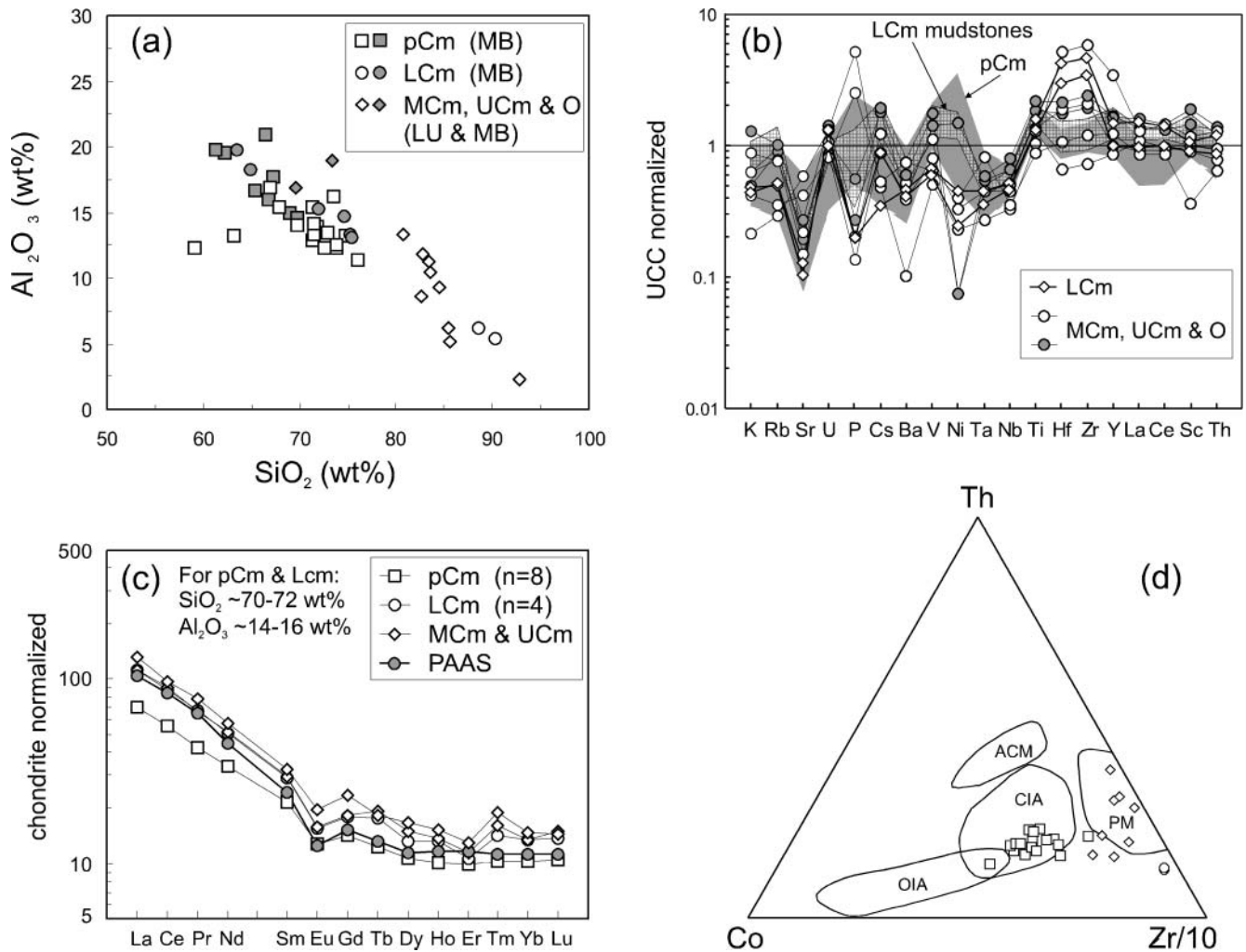


Fig. 5. (a) Variation diagram for the Late Proterozoic and Early Palaeozoic clastic rocks from the Małopolska Block (MB) and Lysogory Unit (LU). Open symbols, sandstones; filled symbols, mudstones. (b) Multi-element plot normalized against an average upper continental crust composition (UCC, Taylor & McLennan 1985). Open symbols, sandstones; filled symbols, mudstones. (c) Chondrite-normalized REE patterns of the Late Proterozoic and Cambrian average greywackes and mudstones. Post-Archaeon Australian average shale plotted for reference (PAAS, Taylor & McLennan 1985). n, number of samples. (See text for details.) (d) Th–Co–(Zr/10) discriminant plot of the tectonic setting for studied sandstones. Fields (after Bhatia & Crook 1986): OIA, oceanic island arc; CIA, continental island arc; ACM, active continental margin; PM, passive margin. Symbols as in (a). pCm, Precambrian; LCm, Lower Cambrian; MCm, Middle Cambrian; UCm, Upper Cambrian; O, Ordovician.

cian quartz arenites. The variation in their chemical composition is very distinct, not only in the range of mobile elements K–Ni, but also in the group of relatively non-mobile Ta–Th.

The concentration of REE is regarded as a generally accepted marker of provenance of clastic sedimentary rocks (Taylor & McLennan 1985). Chondrite-normalized REE patterns of the late Ediacaran and Cambrian greywackes and mudstones are presented in Figure 5c. For comparison the REE pattern of a Precambrian clay shale from Australia (PAAS) considered as a typical passive continental margin sediment (Bhatia 1985; McLennan 1989) is also shown. Preliminary geochemical comparison of the Ediacaran sediments and the Lower Cambrian mudstones shows their apparent similarity. However, a better conclusion is possible if we compare samples with similar mean contents of SiO_2 and Al_2O_3 . In comparison with the Ediacaran samples, the Lower Cambrian samples have larger sum of REE (198 ppm) and higher degree of fractionation of the light REE (LREE), demonstrated by a higher ratio of $(\text{La}/\text{Yb})_N = 8.36$ and $(\text{La}/\text{Gd})_N = 6.65$. On the other hand, these variables for the

Lower Cambrian mudstones are very close to those observed in the Middle and Upper Cambrian mudstones, where only a slightly higher sum of REE is observed. The mean values of the same variable obtained from the Ediacaran samples are as follows: sum of REE = 131 ppm, $(\text{La}/\text{Yb})_N = 7.03$ and $(\text{La}/\text{Gd})_N = 4.95$. These values are lower than in the PAAS, whereas the Cambrian samples are slightly enriched compared with the PAAS. These data may point to a significant change of geochemical behaviour in the Małopolska sediments at the Ediacaran–Cambrian boundary. It is not easy to determine whether the REE geochemistry in the mature Cambrian sediments was controlled by the geochemistry of the source areas or by sedimentary processes (e.g. sorting of heavy minerals). It seems that in the early Cambrian both components were important and the provenance changed gradually. A greater differentiation of crustal rocks forming the source for the Lower Cambrian sediments than for the Ediacaran ones probably gave differences in provenance. In both periods the differentiation processes occurred in the old continental crust (*sensu* McLennan

et al. 1993). The source area of the Ediacaran sediments was the old continental basement in an active tectonic setting, whereas that of the Lower Cambrian sediments may be connected with a passive margin of the stable old craton.

The tectonic setting of the source areas was also identified by means of the Th–Co–(Zr/10) discriminant plot of Bhatia & Crook (1986), which shows a continental island arc as a source area for the Ediacaran sediments (Fig. 5d). The Cambrian and Ordovician sandstones are located near or in the field of a passive continental margin.

Palaeomagnetic data

A palaeomagnetic study of the Early Palaeozoic rocks of the Holy Cross Mountains was carried out by Lewandowski (1993), Nawrocki (2000) and Schätz *et al.* (2002). The Ordovician and Early Devonian palaeomagnetic poles isolated from the Małopolska part of the Holy Cross Mountains were interpreted by Lewandowski (1993) in terms of large-scale dextral tectonic transport of this unit along the margin of the East European Craton during the Variscan orogeny. On the other hand, however, the Silurian and Ordovician palaeopoles obtained later from the Małopolska rocks (Nawrocki 2000; Schätz *et al.* 2002) do not support this model because they are concordant with the Baltic APWP (Fig. 6). Moreover, the palaeomagnetic pole 'Z' of secondary origin isolated from the Late Silurian diabase of the Bardo syncline (Fig. 6, Nawrocki 2000) is concordant with the Early Carboniferous segment of the Baltic APWP if it is calculated in ancient coordinates (i.e. after restoration of Silurian beds). This supports a very limited amplitude of the Early Devonian (Lochkovian–Pragian?; see Malec 1993) movements in the Holy Cross Mountains.

A new palaeomagnetic study of calcareous mudstones with carbonate concretions correlated with the Early–Middle Cambrian Kamieniec Shales formation. A total of 22 palaeomagnetic samples were taken from the road section near the village of Nawodzice (Fig. 2). This *c.* 150 m long section comprises shales and mudstones with carbonate and siderite concretions. The studied beds dip south at varying angles. Pilot samples were subjected to both alternating field (AF) and thermal demagnetization experiments. The second method was more effective and most samples were demagnetized using this technique. Demag-

netization results were analysed using orthogonal vector plots (Zijderveld 1967), and directions of the linear segments were calculated using principal component analysis (Kirschvink 1980). Magnetic mineralogy was determined using isothermal remanent magnetization (IRM) techniques and thermomagnetic analyses (Lowrie 1990).

The studied samples were weakly magnetized. The maximum value of natural remanent magnetization (NRM) intensity ranged to $2.5 \times 10^{-4} \text{ A m}^{-1}$. Most of the samples revealed a low-stability NRM component removed by temperatures of about 200 °C (Fig. 7a). This component was strongly dispersed and therefore was not evaluated statistically. After removal of the low-stability overprint a medium-stability component with unblocking temperatures higher than 370 °C was identified. The exact value of the unblocking temperature could not be defined because of a substantial increase of magnetic susceptibility at temperatures of about 300 °C in the samples with siderite and of about 400 °C in the samples that probably contained ferric sulphides. The IRM experiments (Fig. 7d) show that, even in the sample with siderite, magnetite with an unblocking temperature of *c.* 570 °C is the main carrier of the IRM. The characteristic directions of the medium-stability component group are better defined after the tectonic correction (Fig. 7b and c). The mean values of declination and inclination agree well with the Late Permian–Early Triassic directions characteristic for the Holy Cross Mountains (Nawrocki *et al.* 2003). However, this magnetization cannot be of this age because the studied rocks were deformed before the Permian, probably in the Middle Carboniferous (Stupnicka 1992). The direction was converted to the palaeomagnetic pole 'NW' that was compared to the APWP for Baltica (Fig. 6). This palaeopole corresponds to the Early Cambrian segment of the path constructed on the basis of Scandinavian poles (Torsvik & Rehnström 2001; Lewandowski & Abrachamsen 2003).

Palaeogeographical significance of Cambrian trilobites

The most numerous fossils in Cambrian strata of the Holy Cross Mountains are trilobites, known from this region for over 100 years and used as the basis of the applied biostratigraphic scheme (i.e. Orłowski 1988, 1992; Żylińska 2001). The distribution of trilobites in the succession is, however, uneven. Most of

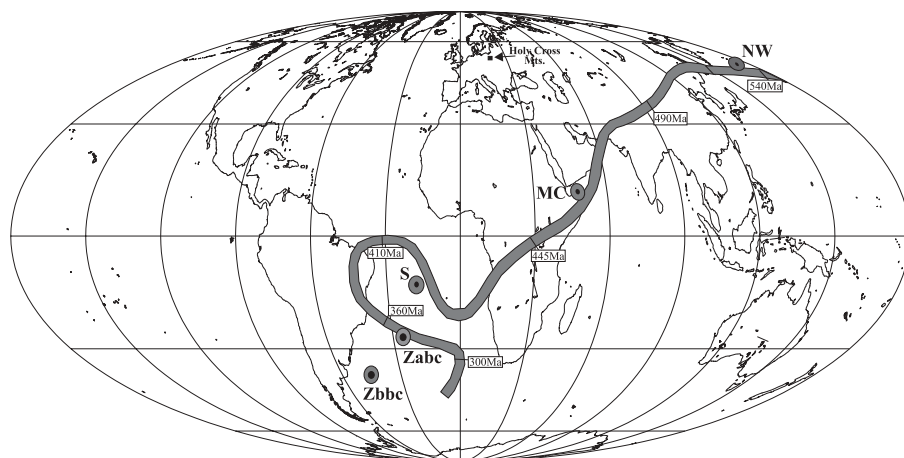


Fig. 6. Southern APWP for Baltica and selected palaeopoles obtained from Early Palaeozoic rocks of the Holy Cross Mountains (Kielce region). The Late Cambrian–Permian segment of the path is according to Torsvik *et al.* (1990, 1996), Torsvik & Rehnström (2001) and Lewandowski & Abrachamsen (2003). NW, palaeopole from the Lower–Middle Cambrian sediments of the Nawodzice section (this paper); MC, palaeopole from the Ordovician Mójca Limestones (Schätz *et al.* 2002); S, primary palaeopole from the Bardo diabase (Nawrocki 2000); Zabc, secondary palaeopole from the Bardo diabase (southern limb of the Bardo syncline) in ancient coordinates (Nawrocki 2000); Zbbc, the same palaeopole but without tectonic correction.

the recognized trilobite taxa include endemic species, although in some parts of the succession the taxa recognized also occur in other biogeographical areas and are significant enough to show the palaeogeographical links of the Holy Cross Mountains basin in selected intervals of the Cambrian. The most clear biogeographical affinities can be observed in the case of trilobite assemblages from the upper part of the Kamieniec formation, the lower part of the Słowiec formation, the Uszów formation and for the Furongian (upper Cambrian) Wiśniówka and Klonówka formations, and these are discussed below in detail. Trilobite assemblages from other parts of the Cambrian succession are also briefly described in terms of their biogeographical links.

Ocieseki Sandstones

This formation, comprising fine-grained sandstones with intercalations of siltstones, and silt and clay shales, is up to 1200 m

in thickness (Orłowski 1988). The trilobite assemblages point to the *Holmia*–*Schmidtellus* Zone, through the *Protolenus*–*Strenuaeva* Zone to the lowermost part of the *Paradoxides insularis* Zone. The *Holmia*–*Schmidtellus* assemblage (e.g. at Ocieseki; see Fig. 8a) is dominated by holmiids (i.e. *Holmia marginata* Orłowski, *Schmidtellus panowi* (Samsonowicz) or *Kjerulfia orcina* Orłowski) (Orłowski 1985a), which at the species level are endemic either to the Holy Cross Mountains only, or to the Holy Cross Mountains and Upper Silesian area (Żylińska 2002b; Nawrocki *et al.* 2004b), and at the genus level point to links with the palaeocontinent of Baltica (Żylińska 2002b). The *Protolenus*–*Strenuaeva* Zone (Łapigrosz, Zbelutka; Fig. 8a) contains mainly the endemic Ellipsocephaliidae (i.e. *Kingaspidoidea sanc-tacrucensis* (Czarnocki), *Berabichia kiaeri* (Samsonowicz) and *Isafeniella orłowinensis* (Czarnocki)) (Orłowski 1985a, Geyer 1990), which, however, are not particularly biogeographically indicative at the genus level (Geyer 1990; Żylińska 2002b).

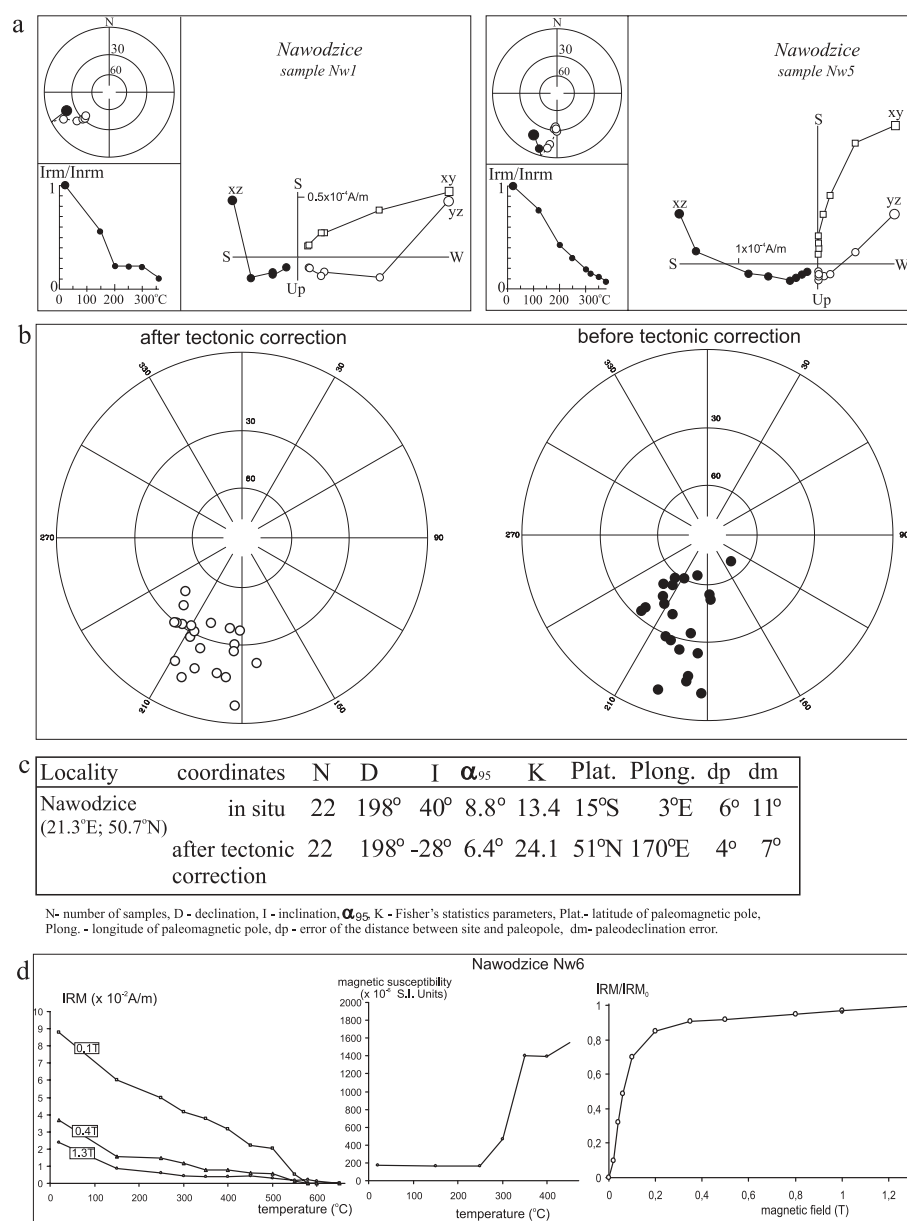


Fig. 7. (a) Typical demagnetization characteristics (demagnetization paths, intensity decay curves and orthogonal plots) of Lower–Middle Cambrian sediments from Nawodzice (Kielce region of the Holy Cross Mountains; see Fig. 2). Circles in the orthogonal plots represent vertical projections; squares represent horizontal projections. I_{rm} , intensity of remanent magnetization; I_{nrm} , initial intensity of natural remanent magnetization. (b) Stereographic projections of line-fit palaeomagnetic directions from the studied Cambrian rocks. Open (closed) symbols denote upward (downward) pointing inclinations. (c) Table of characteristic directions and palaeopoles. N, number of samples used in calculations; D and I, declination and inclination (in degrees); 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. (d) Thermal demagnetization of orthogonal-axis IRM curve, magnetic susceptibility v. temperature plot and IRM acquisition curve prepared for sample NW6 from the Nawodzice section.

Kamieniec Shales

This formation crops out in the eastern part of the Kielce region (Orłowski 1975a) (Kamieniec) and has also been recognized in the Zareby IG-1 borehole (Bednarczyk *et al.* 1965) (Fig. 8a). It comprises shales with intercalations of fine-grained sandstones (Orłowski 1988). The thickness of this formation is estimated at 200 m. Rare but diverse trilobites point to the *Holmia*–*Schmidtellus* and *Protolenus*–*Strenuaeva* zones. The older zone is represented by *Holmia marginata* Orłowski and *Kjerulfia orcina* Orłowski (Orłowski 1985a), and the younger by *Isafeniella trifida* (Orłowski), *Serrodiscus primarius* Orłowski, *Hamatolenus (H.) glabellus* (Orłowski), *Protolenus (P.) expectans* (Orłowski), *Strettonia cobboldi* Orłowski *et* Bednarczyk and *Protolenus (Hupeolenus) czarnockii* Orłowski *et* Bednarczyk (Fig. 8b) (Bednarczyk *et al.* 1965; Orłowski 1985a; Geyer 1990). The trilobite assemblage representing the *Protolenus*–*Strenuaeva* Zone, although typically encompassing endemic taxa, at the genus level resembles the late Early Cambrian–early Middle Cambrian trilobite assemblages from West Gondwana (Morocco, Spain) (e.g. Geyer & Landing 2004) and Avalonia (Westrop & Landing 2000). Moreover, recently it has been pointed out that the traditional placement of the Lower–Middle Cambrian boundary at the appearance of paradoxidids is diachronous (Geyer & Palmer 1995; Geyer & Landing 2004), and therefore attempts have been made to define this boundary instead on evolutionary events within the trilobite assemblages (Geyer & Landing 2004; Zhao *et al.* 2004). In this case, because the trilobite assemblages from the Holy Cross Mountains resemble those recognized in Moroccan and Spanish successions, the Lower–Middle Cambrian boundary *sensu* Geyer & Landing (2004) probably lies within the Kamieniec Shales (Fig. 9a).

Słowiec Sandstones

The formation is present in isolated outcrops in the central (Brzechów, Słowiec) and eastern part (Wygielzów) of the Kielce region (Fig. 8a). Exposures of the lower part of this formation at Brzechów are the most interesting in biogeographical terms. Besides the enigmatic echinoderms *Velumbrella czarnockii* Stasińska and *Rotadiscus* sp. (Stasińska 1960; Masiak & Żylińska 1994), which are unique in Europe, the coarse-grained sandstones at Brzechów contain a trilobite assemblage including *Myopsolenites kielcensis* (Bednarczyk), *Palaeolenus medius* (Bednarczyk), *Kingaspoides sanctacrucensis* (Czarnocki), *Acadoparadoxides oelandicus* (Sjögren), *Acadoparadoxides cf. murensis* (Sdzuy) and *Berabichia* sp. (Fig. 8b) (Bednarczyk 1970, and unpubl. data), pointing again to strong links with the West Gondwanan successions (Geyer & Landing 2004). The only link to Baltica is expressed in the presence of *Acadoparadoxides oelandicus*; the biostratigraphic correlation shows, however, that the Brzechów assemblage may represent a time interval not present at all in the successions of Baltica (Geyer & Shergold 2000; Geyer & Landing 2004).

Usarzów Sandstones

This formation occurs only in the easternmost part of the Kielce region (Usarzów, Jugoszów; Fig. 8a). The trilobite assemblage comprises numerous endemic species of *Ornamentaspis* (*O. hupei*, *O. guerichi*, *O. jugosovi*, *O. longa*, *O. opatovi*, *O. puschi*, *O. samsonowiczi*, *O. sandomiri* and *O. usarzovi*), *Protolenus (P.) polonicus* Orłowski and *Ellipsostrenua henningsmoeni* (Orłowski), which are accompanied by typically Baltic *Acadoparadox-*

ides oelandicus (Sjögren), *A. insularis* (Westergård), *A. pinus* (Holm) and *Ellipsocephalus hoffii* (Schlottheim) (Orłowski 1964; Geyer 1990). In this case the fauna shows a distinct mixed endemic–Baltic character. Based on the Baltic species, the formation can be correlated with the lower part of the Middle Cambrian (*sensu* Westergård 1946) in Scandinavia, in the *Paradoxides oelandicus* Zone (Orłowski 1964, 1988).

Pepper Mts. Shales

The trilobite assemblage from this formation includes *Paradoxides* sp., *Triplagnostus (T.) gibbus* (Linnarsson), *Peronopsis fallax* (Linnarsson), *Solenopleura munsteri* (Strand), *Solenopleurina linnarssoni* (Brøgger) and *S. cf. canaliculata* (Angelin) (Orłowski 1964, 1985b), pointing roughly to the middle part of the Middle Cambrian. However, the occurrence of these extremely rare trilobites is restricted to only two localities (the old quarry in the Pepper Mts. and Pęczek Hill near Sandomierz; Fig. 8a) and the exact age of this assemblage is not clear. Therefore, although the assemblage seems Baltic in character, the biogeographical affinities should not be extended to the entire formation (according to the acritarchs recognized by Szczepanik (1997), the range of this formation should be extended upwards into the Furongian–upper Cambrian).

Wiśniówka Sandstones

This formation, comprising fine-grained sandstones intercalated with siltstones and silty and clayey shales, occurs in a narrow southern belt extending along the entire Łysogóry region. The best exposed strata with trilobite and ichnofaunal assemblages can be observed in the Wiśniówka quarries (in the west) and in the abandoned quarry at Węworków (in the east) (Fig. 8b). The recognized low-diversity and low-abundance trilobite assemblage comprising *Aphelaspis rara* (Orłowski), *Protopeltura aciculata* (Angelin), *Olenus solitarius* (Westergård) and *Solenopleuridae* gen. et sp. indet., associated with the acritarchs *Cymatiogalea velifera* and *C. cristata*, as well as *Stelliferidium cf. cornitulum*, *Raphaesphaera turbata* and *Vulcanisphaera africana* (Żylińska 2001, 2002a; Żylińska & Szczepanik 2002), points to the lowermost part of the *Parabolina spinulosa* Zone. In terms of biogeographical affinities, the assemblage is dominated by the Avalonian species *Aphelaspis rara*, accompanied by much rarer Baltic (*Protopeltura aciculata*) and Avalonian–Baltic forms (*Olenus solitarius*) (Żylińska 2002a) (Fig. 9b).

Klonówka Formation

Strata assigned to this formation occur northwards from the sandstone belt representing the Wiśniówka Formation, and are exposed in small ravines and road-cuts (Orłowski 1968), as well as in boreholes (Tomczykowa 1968) (Fig. 8a). Within this formation four trilobite assemblages differing in age as well as biogeographical affinities have been distinguished (Żylińska 2002a; Żylińska & Szczepanik 2002) (Fig. 9b). Recently, the trilobites have been redescribed and illustrated (Żylińska 2001). The Lisie Jamy exposure contains the oldest, low-diversity and low-abundance assemblage, comprising *Leptoplastides irae* (Orłowski) and *Leptoplastinae* gen. et sp. indet. Although the trilobites point to a wide interval spanning the *Leptoplastus*–*Protopeltura praecursor* zones (Żylińska 2002a), the accompanying acritarchs narrow the age to the *Protopeltura praecursor* Zone (Żylińska & Szczepanik 2002). The biogeographical affinities of this assemblage remain unclear, as it is represented by a

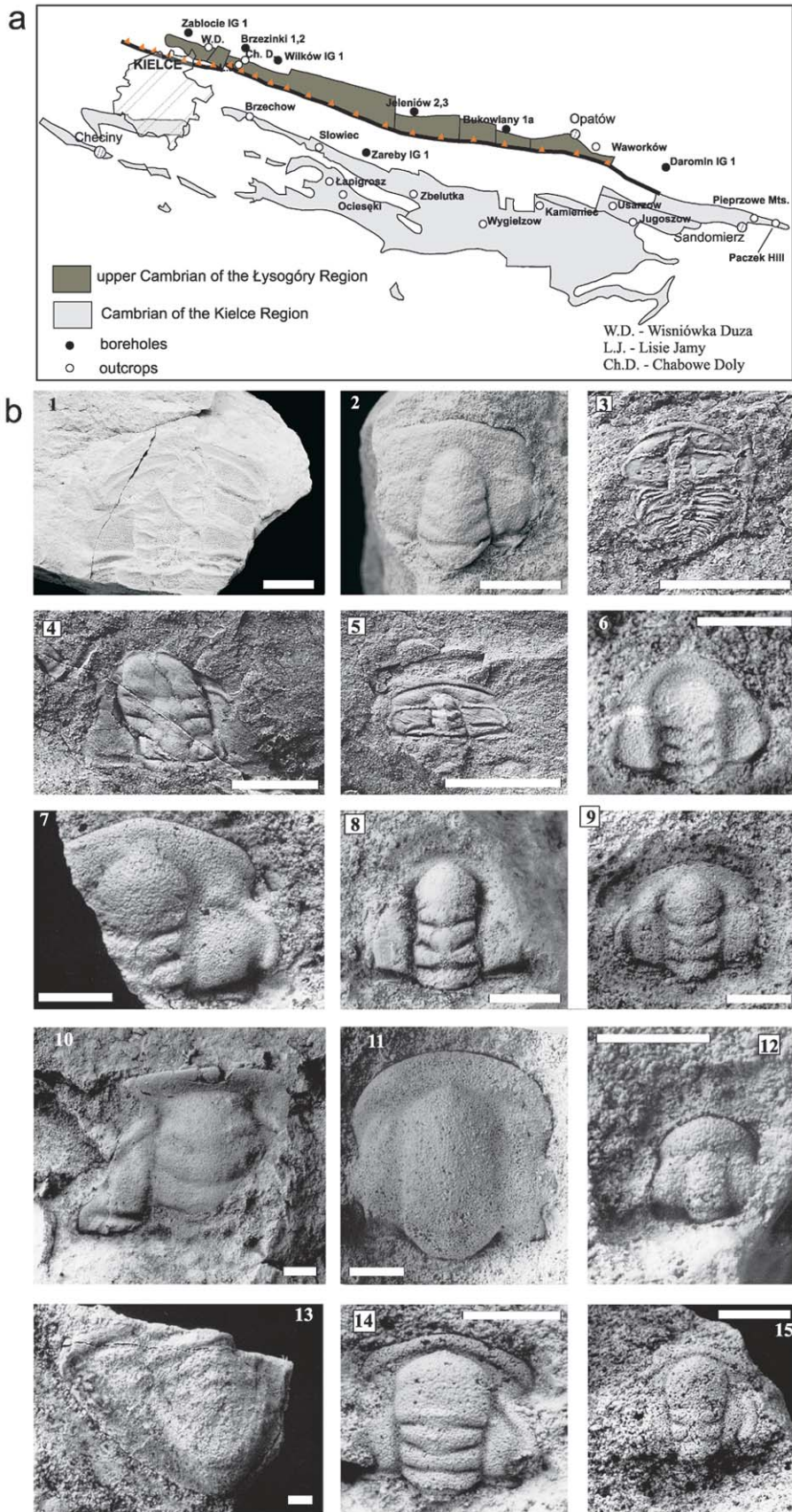


Fig. 8. (a) Map showing outcrops and boreholes in the Holy Cross Mountains where Cambrian trilobites described in the text were found. (b) Trilobites from the Lower–Middle Cambrian transition in the Holy Cross Mts. Scale-bar represents 0.5 cm. 1–5, from the upper part of the Kamieniec formation: 1, *Hamatolenus*(*Hamatolenus*) *glabellus* (Orłowski), Kc24/2, Kamieniec; 2, *Protolenus*(*Protolenus*) *expectans* Orłowski, 1.544, Nowa Łagowica; 3 and 5, *Protolenus*(*Hupeolenus*) *czarnockii* Orłowski & Bednarczyk, Zareby borehole near Łagów (3, OS69/7; 5, OS69/3); 4, *Strettonia cobboldi* Orłowski & Bednarczyk; OS69/3, Zareby borehole near Łagów. 6–15, from the lower part of the Słowic Fm in Brzechów: 6–9, *Palaeolenus medius* (Bednarczyk) (6, INGPAN WB13; 7, IGPW WK21; 8, MUZWG ZI/29/0944; 9, IGPW WK25); 10 and 13, *Myopsolenites kielcensis* (Bednarczyk) (10, INGPAN WB44 (holotype); 13, MUZWG ZI/29/0967); 11, *Kingaspidoidea sanctacrucensis* (Czarnocki), INGPAN WB49; 12, *Berabichia* sp., INGPAN WB26; 14, *Acadoparadoxides oelandicus* (Sjögren), IGPW WK40; 15, *Acadoparadoxides* cf. *mureoensis* (Sdzuy), MUZWG ZI/29/0959.

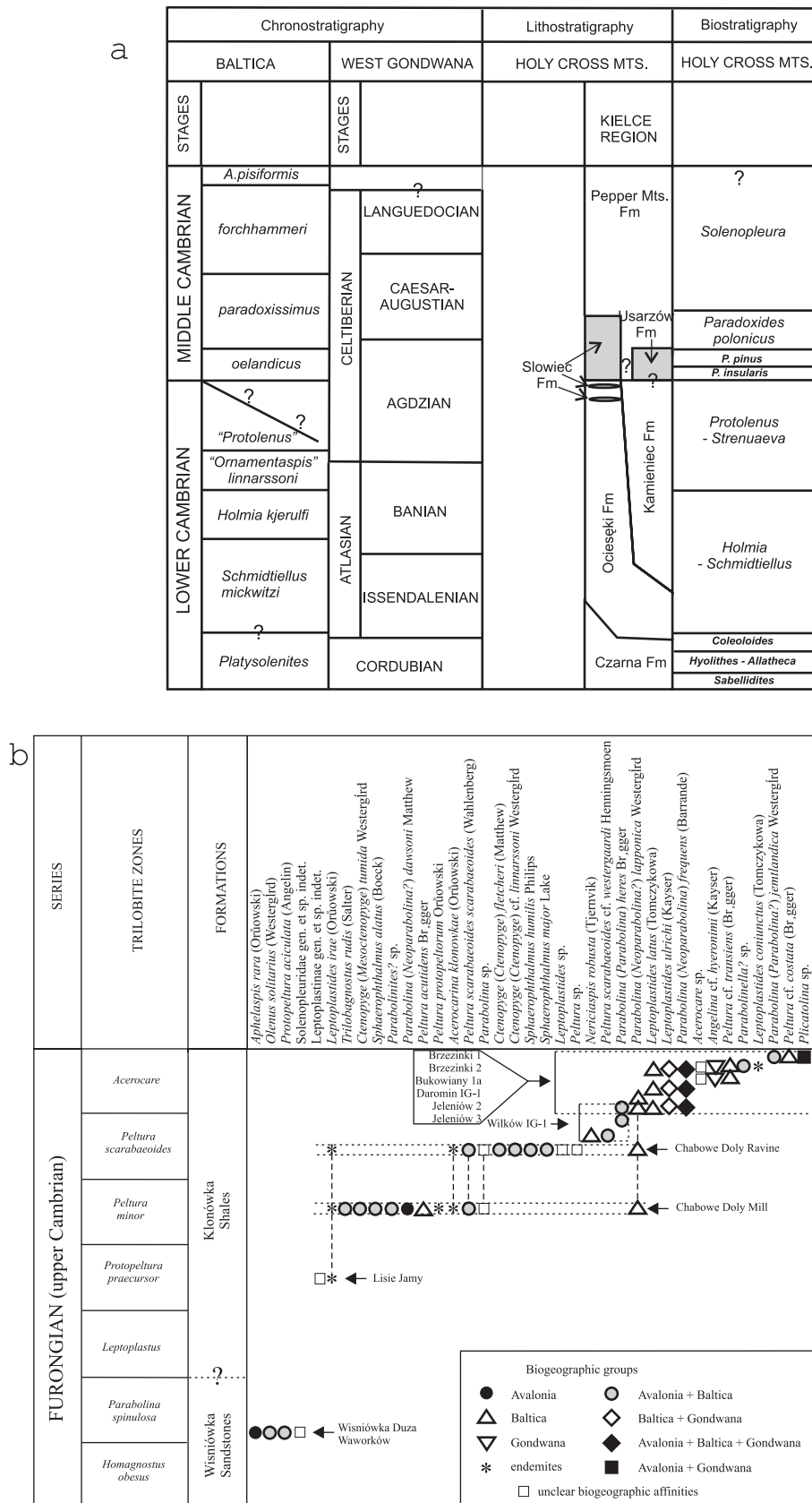


Fig. 9. (a) Lithostratigraphy of the Lower and Middle Cambrian succession in the Holy Cross Mts., modified from Orłowski (1975a), compared with the chronostratigraphic schemes for Baltica (after Geyer & Shergold 2000) and West Gondwana (after Geyer & Landing 2004) and the local biostratigraphic scheme (after Orłowski 1975, 1992; Kowalski 1983, with modifications). **(b)** Stratigraphic distribution and biogeographical affinities of Furongian (upper Cambrian) taxa in the Holy Cross Mts., modified from Żylińska (2002a).

very small number of specimens including a widely distributed endemic species and a form assigned only at family level. Younger, high-diversity trilobite assemblages have been noted from a series of exposures referred to as Chabowe Doły. The first assemblage, comprising 12 taxa typical of the upper part of the *Peltura minor* Zone, occurs in a 60 cm coarse sandstone (Chabowe Doły Mill). The next assemblage contains 11 taxa indicative of the lower part of the *Peltura scarabaeoides* Zone (Chabowe Doły Ravine). The upper part of the *P. scarabaeoides* Zone has been documented in the lower part of the Wilków IG-1 borehole and contains only two taxa. The last interval has been recognized only in boreholes on the northern slopes of the Main Range (Brzezinki 1 and 2, Wilków IG-1-upper part, Jeleniów 2 and 3, Bukowiany 1a and Daromin IG-1) (Tomczykowa 1968; Tomczykowa & Tomczyk 2000; Żylińska 2002a, and unpubl. data). The trilobites from this interval form a high-diversity assemblage (12 taxa), and are characterized by the presence of very numerous representatives of the genus *Leptoplastides* Raw (*L. coniunctus* (Tomczykowa), *L. latus* (Tomczykowa) and *L. ulrichi* (Kayser)) and the species *Parabolina* (*Neoparabolina*) *frequens* (Barrande).

Species-level biogeographical analysis of the trilobites from the Wiśniówka and Klonówka formations points to a distinct change taking place in the Furongian (upper Cambrian) (Żylińska 2002a) (Fig. 9b). Baltic fauna, including fauna appearing in other biogeographical areas, is present in all intervals of the Holy Cross Mountains Furongian (i.e. *Protopeltura aciculata* (Angelin), *Sphaerophthalmus alatus* (Boeck), *Parabolina* (*Neoparabolina*?) *lapponica* Westergård, *Peltura scarabaeoides* (Wahlenberg) and *Leptoplastides latus* (Tomczykowa)). Its diversity and abundance increases towards the top of the Furongian. Avalonian fauna is almost restricted to the lower part of the Furongian (*Parabolina spinulosa* Zone; see above); whereas in the *Peltura minor* Zone it is represented by only one taxon (virtually one specimen of *Parabolina* (*Neoparabolina*?) *dawsoni* Matthew), to disappear completely above. In turn, Gondwanan fauna is present only in the uppermost part of the Cambrian (i.e. *Angelina* cf. *hyeronimi* (Kayser), *Leptoplastides ulrichi* (Kayser) and *Parabolina* (*Neoparabolina*) *frequens* (Barrande)). The continuous decrease in the abundance and diversity of the endemic fauna (*Acerocarina klonowkae* (Orłowski), *Leptoplastides coniunctus* (Tomczykowa), *L. irae* (Orłowski) and *Peltura protopeltorum* Orłowski) can be observed towards the top of the Cambrian. Avalonian–Baltic fauna is present in all intervals, although in the uppermost part of the Furongian (*Acerocare* Zone) its diversity and abundance become distinctly smaller. In this interval it is replaced by the Avalonian–Baltic–Gondwanan fauna (*Parabolina* (*Neoparabolina*) *frequens* (Barrande)) and Baltic–Gondwanan fauna (*Leptoplastides ulrichi* (Kayser)). Summarizing, the Furongian trilobite assemblages from the Holy Cross Mountains change from low-diversity assemblages dominated by Avalonian fauna, to more diverse assemblages with a constant increase of Baltic fauna and a parallel decrease of endemic fauna.

Discussion

The Małopolska Massif

Studies of geochemistry of selected clastic rocks from the Małopolska unit indicate that Ediacaran sediments are of first cycle and provenance connected with an active continental margin or continental island arc. Polycyclic sediments linked with a passive continental margin were deposited there during

the Cambrian and Ordovician. The Upper Silurian greywackes from the Holy Cross Mountains also indicate a continental island arc provenance of the detritus. The return to a continental island arc signature in the Silurian does not necessarily record the development of a new island arc, especially as this period immediately postdates the docking of Avalonia at the end of the Ordovician (Samuelsson *et al.* 2002). On the other hand, however, the Silurian ages of biotite derived from the Upper Silurian greywackes of the Holy Cross Mountains (Table 1) may point to the development of an island arc in the Silurian as well. The presence of a Silurian island arc in the vicinity of the Trans-European Suture Zone may also be supported by K-bentonite beds in late Wenlock to Pridoli strata of western Ukraine, which mark several episodes of explosive silicic volcanism associated with an active subduction margin (Huff *et al.* 2000).

The palaeomagnetic pole isolated from the Early–Middle Cambrian Kamieniec Shale formation (Małopolska part of the Holy Cross Mountains) corresponds to the Cambrian segment of the Baltic APWP constructed on the basis of Scandinavian poles (Torsvik & Rehnström 2001; Lewandowski & Abrachamsen 2003). Most of the recognized trilobite taxa of the Holy Cross Mountains include endemic species, although in some parts of the succession taxa recognized also in other biogeographical areas are significant enough to show the palaeogeographical links of the Holy Cross Mountains basin in selected intervals of the Cambrian. The clearest biogeographical affinities of trilobite assemblages can be observed in the upper part of the Kamieniec formation, the lower part of the Słowiec formation, the Usarzów formation and for the Furongian (upper Cambrian) Wiśniówka and Klonówka formations. A significant contribution of Baltic trilobites can be observed in the lowest and uppermost part of the early–middle Cambrian succession of the Kielce region and in the uppermost part of the late Cambrian sequence of the Łysogóry region. The peri-Gondwanian trilobites dominate in the Kamieniec and Słowiec formations of the Kielce region, and the Wiśniówka formation of the Łysogóry region. The affinities of trilobite fauna could imply cyclic changes in palaeogeography of the Holy Cross Mountains not supported by other provenance data. Therefore trilobites do not allow construction of any unequivocal palaeogeographical solution for the Holy Cross Mountains. The occurrence of particular trilobite species may instead be controlled by the lithofacies and oceanic currents.

New isotope age estimations indicate that Cambrian sediments of the Małopolska part of the Holy Cross Mountains contain muscovites not only from a late Neoproterozoic source defined by Bełka *et al.* (2002) but also from sources with an igneous–metamorphic overprint of *c.* 0.8–0.9 Ga and 1.5 Ga. The late Neoproterozoic ages of detrital minerals from the Cambrian sediments of the Holy Cross Mountains point to its proximity to the area involved in the Cadomian orogenic belt. A part of these minerals may be derived from the foreland metamorphosed flysch of the southern Małopolska unit. On the other hand, the detrital muscovites with an age of 1.5 Ga were probably derived from the contact zones of rapakivi-type granites of the East European Craton. Also, the detrital zircons with isotope age *c.* 1.8 Ga recognized in the Tremadoc sandstones of the Szumsko borehole point clearly to a Fennoscandian source.

The possible Cambrian proximity of the Małopolska region and the Trans-European Suture Zone margin of the Baltic plate can be also inferred from the similarity of the palaeomagnetic pole isolated from the Kamieniec Shale formation and the Baltic coeval poles. Also, the geochemical record does not point to middle Cambrian convergence and subsequent collision of the Małopolska region with Baltica as postulated by Bełka *et al.*

(2002). The occurrence of the foreland metamorphosed flysch and contrast in geochemical signature between Ediacaran and Cambrian sediments indicate that the Małopolska region was located in the area of intense tectonic activity at the end of the Neoproterozoic. This unit could be the foreland of the Cadomian orogen. According to Żelaźniewicz (1998), this orogen was developed near the Trans-European Suture Zone margin of Baltica. It should be stressed, however, that an '*in situ*' evolution of the Małopolska region in the Ediacaran is not possible, as the Polish segment of Baltica was then tectonically passive (see Poprawa *et al.* 1999).

Palaeomagnetic data obtained from the Cambrian (this paper), Ordovician (Schätz *et al.* 2002) and Silurian (Nawrocki 2000) rocks indicate that no large-scale rotation or palaeolatitudinal drift of the Małopolska Block with respect to Baltica has occurred since the Middle Cambrian. The tectonic mobility of this unit at the Cambrian–Ordovician boundary may be due to a large (60°) anticlockwise rotation of the whole of Baltica (Torsvik *et al.* 1996). It is very likely that this movement was responsible for tectonic deformations of the Cambrian strata in the Holy Cross Mountains, producing several thrust and fold structures attributed to the so-called Sandomierian orogeny (see, e.g. Gęgała 2005).

The geochemical study of the Upper Silurian greywackes from both units of the Holy Cross Mountains indicates a continental island arc provenance of the detritus (Kozłowski *et al.* 2004). The Middle Neoproterozoic detrital muscovites found in these sediments suggest that the island arc was connected with a crustal unit metamorphosed at *c.* 730 Ma. This unit was located west of the Holy Cross Mountains, as can be inferred from the directions of transport of clastic material (see Kozłowski *et al.* 2004). Shortly after development of the island arc at the western foreland of the Holy Cross Mountains, but still in the Silurian (late Ludlow–Pridoli), an extensional tectonic regime was established in the Kielce region, where diabases of this age were intruded. Subsequently, Early Devonian (Lochkovian–Pragian?; see Malec 1993) tectonic deformation of the Palaeozoic strata of the Kielce region occurred. The amplitude and range of this deformation was, however, very limited, as can be inferred from the secondary palaeomagnetic pole isolated from the diabase of the southern limb of the Bardo syncline. This pole indicates that Silurian strata from the southern part of the Bardo syncline were not deformed before the Carboniferous (Nawrocki 2000).

The Łysogóry Unit

Detrital zircon and muscovite data obtained from the Upper Cambrian sediments revealed a complex provenance pattern of clastic material that was probably originally derived from the Cadomian orogen and the Baltic basement. Apart from the late Neoproterozoic and early Proterozoic micas the Cambrian and Silurian rocks of the Łysogóry Unit contain detrital muscovites of Middle Neoproterozoic age. It should be stressed that the age spectrum of muscovite separated from the Upper Silurian greywackes of the Łysogóry Unit is exactly the same as in the Małopolska part of the Holy Cross Mountains. As stated above, the geochemistry of these rocks is also the same, indicating a continental island arc provenance of the detritus (Kozłowski *et al.* 2004). Belka *et al.* (2002) recognized the Łysogóry Unit as an exotic terrane that was derived from the Gondwana margin and brought closer to Baltica during the Late Cambrian. Lack of collision evidence, the partly Baltic source of detrital minerals in the Cambrian sediments, and the deep structure of lithosphere similar to that of the East European Craton detected by seismic

studies (Malinowski *et al.* 2005) point instead to a stationary model for the Łysogóry Unit and its close link with the mobile edge of the East European Craton, as postulated by some workers (e.g. Dadlez 1995).

Other tectonic units of the Trans-European Suture Zone in Poland

One of the first tectonic units of Central Europe defined as a 'terrane' is the Brunosilesia terrane. It still remains the best documented terrane of the central part of the Trans-European Suture Zone (Brochwiec-Lewiński *et al.* 1986; Pożaryski 1991; Pharaoh 1999). The basement of the Brunosilesia terrane is composed of metamorphic and igneous rocks, mostly late Neoproterozoic in age (Dudek 1980; Van Breemen *et al.* 1982; Finger *et al.* 2000a, b; Żelaźniewicz *et al.* 2001). This indicates directly that the Brunosilesia terrane formed part of the Cadomian belt. It is not easy to establish in which part of this belt the basement of the Brunosilesia terrane was developed, or when the terrane was derived from this belt. The orogenic structures of the Brunovistulian terrane could have developed either in the peri-Gondwana area or in the active southern margin of Baltica as proposed by Nawrocki *et al.* (2004b). The palaeomagnetic pole obtained from the Early Cambrian red beds of the Brunosilesia terrane (Nawrocki *et al.* 2004b) gives a palaeolatitude that fits the Early Cambrian location of the Trans-European Suture Zone margin of Baltica or the Arabian part of peri-Gondwana. This second location of the Brunosilesia terrane is less possible in the Early Cambrian because of differences in trilobite fauna. Cambrian trilobite fauna from the Brunosilesia terrane, if diagnostic, tend to indicate Baltic links. The endemic taxon *Schmidtellus panowi* (Samsonowicz) has been recognized in the Małopolska and the Brunosilesia terrane only (see Nawrocki *et al.* 2004b), and therefore may point to the Early Cambrian proximity of the two units and consequently their closeness to the Trans-European Suture Zone margin of Baltica, as the Małopolska block has been there at least since the Cambrian. Other evidence indicates that the Brunosilesia terrane had to be separated from the peri-Gondwanan area and transported to the SW edge of the East European Craton at least before the Middle Ordovician. It is rather unlikely that the Middle–Late Ordovician carbonates of the Brunovistulian terrane containing Baltican conodont fauna (Belka *et al.* 2002) were deposited in the NW part of Gondwana, which was then situated in the polar regions. The final stage of the tectonic transport of the Brunovistulian terrane towards the Małopolska block took place after the Ludlow, but before the sedimentation of the Lower Devonian sandstones of the 'old red' type. The Ludlow sediments of the Małopolska block were not derived from the Brunosilesia terrane but from an island arc located west of the Małopolska area, in the place occupied now by the Brunosilesia terrane (Kozłowski *et al.* 2004). The Early Devonian proximity of the Brunovistulian terrane and the Małopolska block can be inferred from the distribution of boundaries of particular 'old red' facies (Pajchlowa & Miłaczewski 1974). These boundaries cut the Cracow–Lubliniec fault zone that separates the two units.

The list of tectonic units involved in the Polish part of the Trans-European Suture Zone should be supplemented by a terrane that supplied the early Palaeozoic basins of the Holy Cross Mountains with detrital muscovites of Middle Neoproterozoic cooling ages, probably connected with the breakup of Rodinia and development of mature oceanic arcs that formed, for example, the basement of Avalonia (Nance *et al.* 2002). The Middle Neoproterozoic ages of detrital muscovites derived from

the Cambrian and Silurian sediments of both units of the Holy Cross Mountains are not known from the basement of the SW slope of Baltica. The provenance data indicate that at least until the Ludlow a crustal unit with a middle Neoproterozoic basement was close to the Holy Cross Mountains. It was moved to the west when the Brunosilesian terrane approached the Małopolska block. This unit was probably incorporated into the Variscan orogen of western Poland. The westerly source of detritus with an island arc signature in the Silurian rocks of the Holy Cross Mountains could be connected with the basement of 'Far Eastern Avalonia', which, according to Winchester & PACE TMR Network Team (2002), underlies present-day west-central Poland west of the Moravian Line. It should be stressed, however, that this explanation is not in agreement with some geological and geophysical evidence. In contrast to their occurrence in the Holy Cross Mountains, muscovites of Middle Neoproterozoic cooling ages do not occur in the Silurian rocks of the Pomeranian segment of the Trans-European Suture Zone (Nawrocki & Poprawa 2006). In the Holy Cross Mountains muscovites of that age are present not only in the Silurian but also in the Cambrian rocks. Avalonia, as part of peri-Gondwana, was not close to the Holy Cross Mountains at least in the Cambrian–Early Ordovician, yet muscovites of Middle Neoproterozoic age are present in the Cambrian sequences of the Holy Cross Mountains. Additionally, the presence of 'Far Eastern Avalonia' in NW Poland is not supported by large-scale seismic refraction and wide-angle reflection experiments (Dadlez *et al.* 2005). Therefore, the terrane that supplied the early Palaeozoic basins of the Holy Cross Mountains with detrital muscovites of Middle Neoproterozoic cooling ages cannot be 'Far Eastern Avalonia'. We have named it the Wielkopolska terrane.

Global model

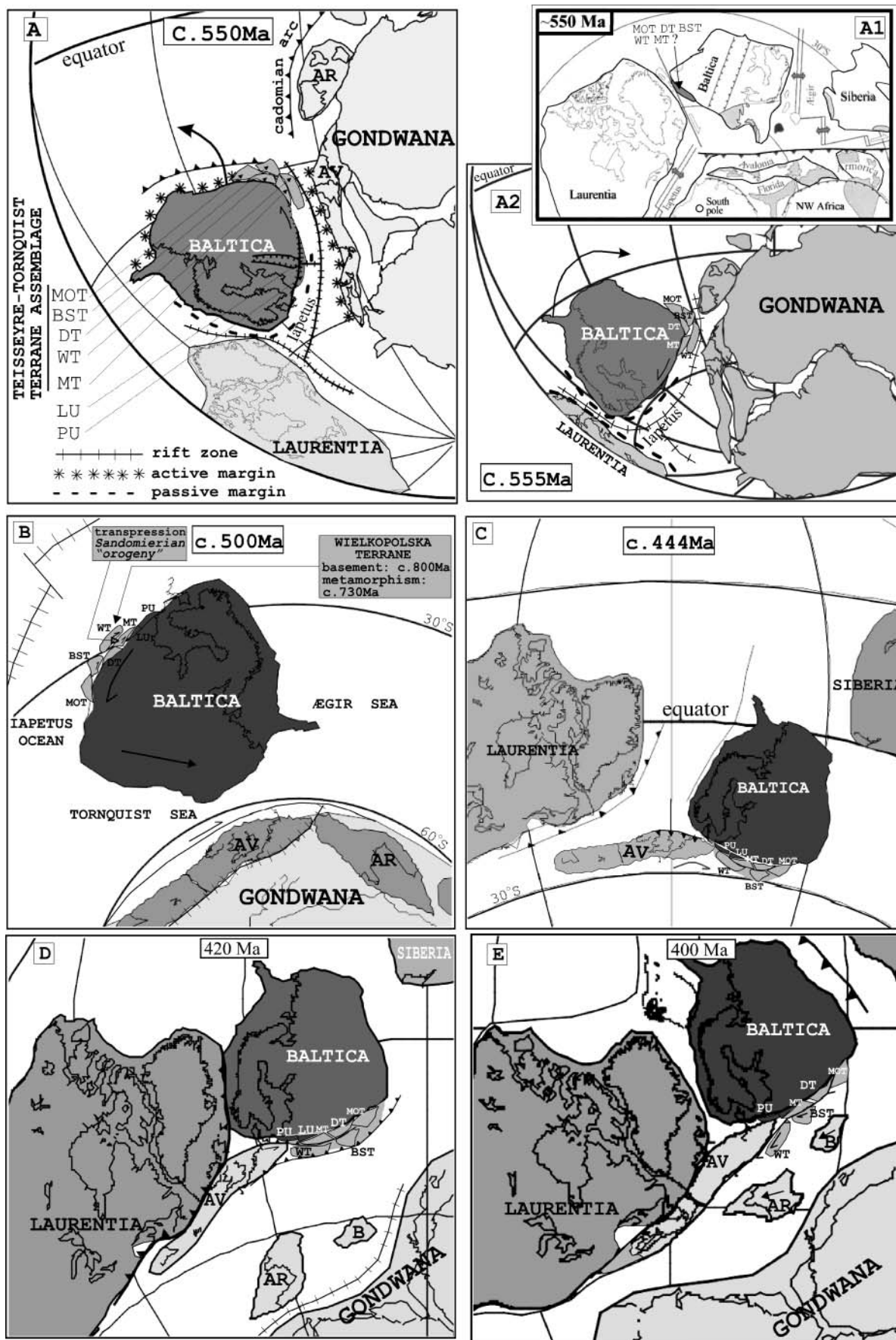
Three models of palaeogeography of late Ediacaran Baltica are presented in Figure 10a and a2. We prefer the model of Late Ediacaran Baltica that corresponds to the modified Late Vendian–Early Cambrian APWP for Baltica (Nawrocki *et al.* 2004a). It shows the Baltic plate moving at that time from moderate southern latitudes to the equator and rotating anticlockwise by about 120° (Fig. 10a). This reconstruction explains the occurrence near the present SW edge of Baltica of tectonic blocks with late Neoproterozoic deformations and magmatism. These blocks, named here the Teisseyre–Tornquist Terrane Assemblage (Fig. 10a), originally developed near the present southern edge of the East European Craton and, involved in the Cadomian orogen, were dextrally relocated along the Trans-European Suture Zone margin of Baltica. The first stage of this movement took place as early as the latest Ediacaran while Baltica rotated anticlockwise. The Małopolska and Dobrugea blocks can probably be regarded as proximal terranes detached from the SW corner of Baltica and moved dextrally along its edge at the Ediacaran–Cambrian boundary. The Brunosilesia and Moesia terranes have an exotic origin, and were probably derived from the Cadomian part of peri-Gondwana during the Late Ediacaran rifting that separated the Avalonian part of peri-Gondwana from SW Baltica. The presence of the Brunosilesia terrane with a late Neoproterozoic basement, overlapped by Early Cambrian sediments containing a trilobite fauna of Baltic affinity possibly related to the Małopolska Massif (Orłowski 1975b; Żelaźniewicz 1998; Finger *et al.* 2000a; Nawrocki *et al.* 2004b) supports the model presented in Figure 10a. Moreover, this reconstruction can also explain why some detrital zircon grains from the Cambrian sediments of the present SW Baltica have

late Neoproterozoic ages (Valverde-Vaquero *et al.* 2000) and why the detrital mica from the Middle Cambrian units of the Małopolska terrane has a cooling age of *c.* 1.5 Ga. The Pomerania and Łysogóry Units (Fig. 10a) were created by Late Ediacaran rifting processes and have never moved significantly from the region of detachment.

The reconstruction with the Trans-European Suture Zone margin of Baltica facing north (Torsvik & Rehnström 2001; Cocks & Torsvik 2005; Fig. 10a1) does not explain sufficiently the occurrence in the Trans-European Suture Zone edge of Baltica of the Teisseyre–Tornquist Terrane Assemblage as early as the Cambrian. This assemblage could have developed near the Uralian margin of Baltica (Fig. 10a1) and moved along its southern margin during the Late Cambrian–Early Ordovician while Baltica rotated anticlockwise. However, the palaeomagnetic data and some cooling ages of detrital mica indicate that the Małopolska terrane and the Brunosilesia terrane were in the Trans-European Suture Zone area at least since the Middle Cambrian. 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. New Late Ediacaran palaeomagnetic data (Nawrocki *et al.* 2004a; Llanos *et al.* 2005) cannot exclude a clockwise direction of Baltica rotation at the Ediacaran–Cambrian boundary as presented in Figure 10a2. However, this tectonic regime would not allow relocation of the Teisseyre–Tornquist Terrane Assemblage from the Cadomian belt to the central part of the Trans-European Suture Zone. It would be possible only in the Late Cambrian while Baltica rotated anticlockwise.

Baltica rotated anticlockwise again at the Cambrian–Ordovician boundary (see e.g. Torsvik *et al.* 1996). This implies further dextral movement of exotic terranes of the Teisseyre–Tornquist Terrane Assemblage. Tectonic transpression between the Wielkopolska and Małopolska terranes created deformations attributed to the Sandomierian orogenic phase (Fig. 10b), which has been recognized in the Kielce region of the Holy Cross Mountains (Gagała 2005). The Trans-European Suture Zone area was relatively stable during the early part of the Ordovician. This 'quiet' time ended in the middle to latest Ordovician, depending on the zone of the Trans-European Suture Zone, when island arcs started to grow west of Baltica as a result of closure of the Tornquist Sea (Torsvik & Rehnström 2003) and the first stages of narrowing of the Rheic Ocean (Franke 2000; Tait *et al.* 2000). Between the late Llanvirn and middle Caradoc the sedimentary and ecological conditions during deposition of carbonates from the Kielce region were controlled by a western palaeocurrent that flowed along the northern margins of the Małopolska Block (Trela 2005). Termination of this palaeocurrent and nutrient delivery and subsequent phosphatization of the Ordovician limestones was coeval with closure of the Tornquist Sea as a result of the collision of Avalonia and Baltica as well as migration of the Małopolska Block together with Baltica towards a lower latitude position (Trela 2005).

The tectonic processes associated with the final closure of the Rheic Ocean and narrowing of the Saxo-Thuringian Ocean (Franke 2000) rearranged the Trans-European Suture Zone in the Early Devonian. The Brunosilesian terrane was moved to its present position near the Małopolska terrane and the Wielkopolska terrane was relocated to the west (Fig. 10e). The Małopolska terrane was then uplifted and locally deformed. The emplacement of the Bardo diabase in the Late Silurian indicates that the Early Devonian deformations in the Kielce region of the Holy Cross Mountains were preceded by an extensional regime.



Conclusions

(1) Geochemical studies indicate that the Ediacaran sediments of the Małopolska terrane (which includes the Kielce region of the Holy Cross Mountains) are of first cycle and provenance connected with an active continental margin or continental island arc. Sediments linked with a passive continental margin were deposited there during the Cambrian and Ordovician. The Upper Silurian greywackes of the Holy Cross Mountains again have a detrital continental island arc provenance.

(2) The palaeomagnetic pole isolated from the Early–Middle Cambrian rocks of the Małopolska part of the Holy Cross Mountains corresponds to the Cambrian segment of the Baltic APWP constructed on the basis of Scandinavian poles.

(3) The affinities of the Cambrian trilobite fauna from the Holy Cross Mountains could imply cyclic and rapid changes in the geographical setting of this area, unsupported by the other provenance data. Therefore, it is concluded that the occurrence of particular trilobite species may be controlled not by palaeogeography but by the lithofacies and oceanic currents.

(4) New isotope age estimations indicate that the Cambrian sediments of the Małopolska part of the Holy Cross Mountains contain muscovites not only with late Neoproterozoic cooling ages but also with an igneous–metamorphic overprint of *c.* 0.8–0.9 Ga and 1.5 Ga. The 1.5 Ga age and the isotope age of detrital zircons from the Tremadoc sandstones (*c.* 1.8 Ga) point to a Fennoscandian source of some detritus of the Holy Cross Mountains.

(5) The Małopolska, Brunosilesia, Dobrugea and Moesia terranes, originally developed near the present southern edge of the East European Craton and partly involved in the Cadomian orogen, were dextrally relocated along the Trans-European Suture Zone margin of Baltica. The first stage of this movement took place as early as the latest Ediacaran while Baltica rotated anticlockwise. Anticlockwise rotation of Baltica at the Cambrian–Ordovician boundary implies further dextral movement of the Małopolska and other terranes. The list of units included in the Teisseyre–Tornquist Terrane Assemblage should be supplemented by a terrane that supplied the early Palaeozoic basins of the Holy Cross Mountains with detrital muscovites with Middle Neoproterozoic ages. This unit, named here the Wielkopolska terrane, was probably incorporated in the Variscan orogen of western Poland.

(6) Tectonic processes associated with the final closure of the Rheic Ocean and narrowing of the Saxo-Thuringian Ocean rearranged the Trans-European Suture Zone in the Early Devonian. The Brunosilesian terrane was moved to its present position near the Małopolska terrane then uplifted and locally deformed.

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Fig. 10. Simplified palaeogeographical reconstructions showing selected continents (adopted from Torsvik *et al.* (1996) and Torsvik & Rehnström (2001)), and Baltica with adjacent tectonic units in the Late Ediacaran (**a**, **a1**, **a2**), Late Cambrian (**b**), latest Ordovician (**c**), Late Silurian (**d**) and Early Devonian (**e**) (**a**, Baltica according to Nawrocki *et al.* 2004a; **a1**, Baltica according to Cocks & Torsvik 2005; **a2**, Baltica with the opposite sense of Late Ediacaran rotation to that in (**a**)). AV, Avalonia; AR, Armorica; B, Bohemia; LU, Łysogóry Unit; PU, Pomerania Unit. Teisseyre–Tornquist Terrane Assemblage: MOT, Moesia terrane, BST, Brunosilesia terrane, DT, Dobrugea terrane, WT, Wielkopolska terrane, MT, Małopolska terrane.

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