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Paleomagnetism of Ordovician carbonate rocks from Malopolska Massif, Holy Cross Mountains, SE Poland — Magnetostratigraphic and geotectonic implications

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Abstract

The structural and geodynamic history of the Malopolska Massif (Holy Cross Mountains — Poland), situated within the Trans-European Suture Zone (TESZ) is still a matter of debate. Recent provenance studies and biogeographical data indicate that the Malopolska is a Gondwana-derived terrane accreted to Baltica between late Mid-Cambrian and Tremadocian times. Existing paleomagnetic data, however, are equivocal. They indicate either close proximity and coherence with Baltica since Silurian times or a significant Variscan dextral strike-slip displacement of Malopolska with respect to the latter along the Teisseyre–Tornquist Line. In order to address this problem a detailed paleomagnetic study of a condensed sequence of Middle to Upper Ordovician carbonate rocks from the Malopolska Massif (Mójcza quarry) has been undertaken. Samples were taken every 10 to 15 cm through the 4.5 m sequence which covers the Upper Llanvirnian and Caradocian. After detailed stepwise thermal demagnetization, a high unblocking temperature direction of magnetization with mixed polarities is identified. The directions pass the reversal test and yield an overall mean direction of Dec.: 323°, Inc.:−63°, k: 16.6, α_{95}: 5.8 after bedding correction. This corresponds to a paleo-(south)pole of 11°N, 46.8°E (dp: 7.2°, dm: 9.1°), which plots directly on the Ordovician segment of the apparent polar wander path for Baltica, thus rendering major post-Ordovician rotations of the area relative to Baltica unlikely. The paleomagnetic results reveal three zones of each reversed (R1–R3) and normal polarity (N1–N3). The section starts with a reversed polarity interval in the mid-Llanvirnian stage (R1). The transitions from R1 to N1 and from N1 to R2 in Middle Llanvirnian and from R2 to N2 during Upper Llanvirnian correspond well with previous paleomagnetic results based on graptolite biostratigraphy. After a short normal polarity interval (N2) the lower Caradocian is dominated by inverse polarity (R3). The following transition from R3 to N3 falls in the upper part of the *Amorphognathus tvaerensis* conodont zone. For this polarity change, the misfit between the magnetostratigraphy of the Mójcza section and previously published paleomagnetic results most likely reflects uncertainties of correlating between conodont and graptolite stratigraphies.

Keywords: Baltica; Holy Cross Mountains; magnetostratigraphy; Malopolska Massif; Ordovician; paleomagnetism

1. Introduction

The Trans-European Suture Zone (TESZ) is a broad and complex NE/SW trending zone which extends from

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the North Sea through to the Black Sea across Europe and is the most prominent geological domain separating the ancient Precambrian lithosphere of the East European Platform (EEP) from the Variscan and Alpine mobile belts of Western Europe [1,2]. Over the last few years, a number of geological and geophysical studies of the TESZ have been carried out. Seismic data show that the thickness of the crust changes from ca. 45 km in the EEP to ca. 30 km in the Variscan realm [3,4]. In the tectonically complex zone at the SW margin of the EEP, which comprises various crustal blocks [2,5], a number of different Paleozoic terranes have been identified. These terranes are defined by their contrasting lithological, stratigraphic and tectonic characteristics [2,6,7]. However, the Paleozoic geodynamic development of these terranes, and the process of accretion to the present-day southwestern margin of Baltica remains ambiguous, and a number of different models for the evolution of the TESZ have been proposed [8].

In southern Poland, three tectonostratigraphic fault-bounded crustal units are juxtaposed: the Lysogory Unit, the Malopolska Massif and the Upper Silesian Massif (Fig. 1). These three units display contrasting tectonic characteristics with individual sedimentary development during the Early Paleozoic [9]. Different models have been proposed addressing the tectonic evolution and affinities of these terranes [7,10].

Traditional paleogeographical interpretations have regarded these units as having developed along the Tornquist margin of Baltica from the Cambrian period onwards [11,12]. This was based on records of Early Cambrian trilobites in Malopolska and Upper Silesia which are diagnostic of the Baltic zoogeographical province [13,14]. The Lysogory and Malopolska units were also interpreted as crustal fragments, which were separated from Baltica in the Early Paleozoic [15,16]. Some authors have overlooked the bipartite subdivision of the Holy Cross Mountains and considered Lysogory and Malopolska to represent a single plate [17,18]. Recent provenance studies [9,10,19] and biogeographical data [20–23] provide strong arguments that the Lysogory, Malopolska and Upper Silesia blocks, although yielding faunal linkages to Baltica, are exotic terranes derived from the Gondwana margin. Moreover, they have individual and disparate drift-histories. Malopolska was the first terrane that joined the Baltica paleocontinent between late Mid-Cambrian and Tremadocian times [10].

Previously published paleomagnetic data allow two basic models. Lewandowski [24,25] suggests large-scale displacement of the Malopolska Massif along the Teisseyre–Tornquist Line during the entire Paleozoic accompanied by rotations with respect to the EEP until Variscan times as the paleopole positions for Malopolska, as reported by Lewandowski [24,25], are significantly different from the Baltic apparent polar wander path (APWP).

Alternatively, it has been proposed that the Malopolska Massif was fixed in its relative present position

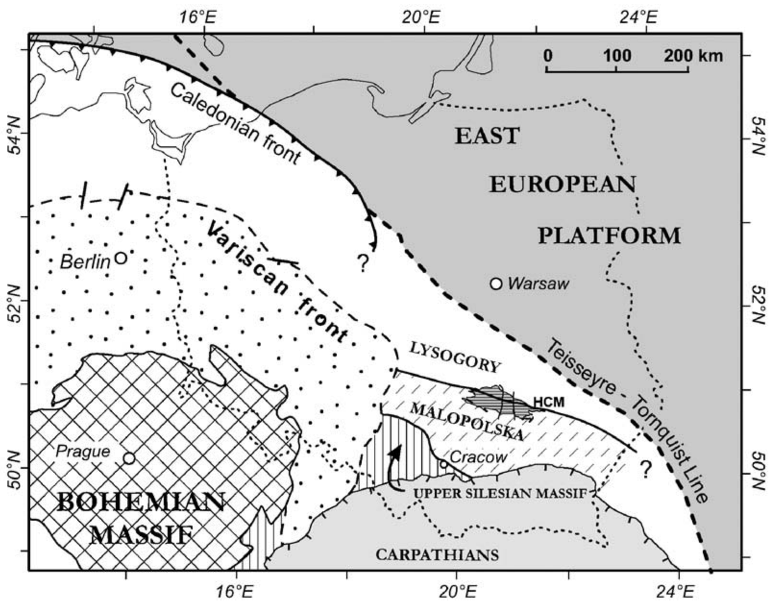

Fig. 1. Simplified structural map of central Europe showing the crustal units in the Variscan foreland of southern Poland and in the eastern part of the Variscan Belt. Dotted line indicates the Polish border. HCM, Holy Cross Mountains.

since Silurian times. Nawrocki [26] published a Late Silurian paleomagnetic pole which is in accord with the Baltic APWP, ruling out any significant post Silurian tectonic displacements of the Malopolska Massif relative to Baltica. In order to shed more light onto the timing and the mode of accretion and consolidation at the SW margin of the EEP in Paleozoic times, a paleomagnetic study was undertaken on a condensed Middle–Late Ordovician sequence of carbonate rocks in the Malopolska Massif.

2. Geological setting

Paleozoic rocks exposed in the Holy Cross Mountains (HCM) belong to the marginal parts of Lysogory and Malopolska which are separated by the NW–SE trending Holy Cross Fault (HCF). The Paleozoic of these two crustal units differs in facies, thickness of stratigraphic successions and continuity of their stratigraphic records. Both sequences comprise thick clastic and carbonate sediments ranging in age from the Vendian to Permian in Malopolska and from the Upper Cambrian to Permian in Lysogory (for review see [10] and [15]). Outside of the HCM, the Paleozoic sequences of Lysogory and Malopolska are covered by thick Mesozoic and Cenozoic sedimentary rocks and thus the lateral extension of these terranes and their tectonic affinities to other block of the TESZ are difficult to establish.

The most significant and distinctive feature of the sedimentary succession of Malopolska is the pre-Ordovician deformation of Cambrian and Precambrian rocks. Consequently, the base of the Ordovician forms a distinct angular unconformity. The Ordovician sediments represent a transgressive sequence, changing from offshore facies sandstones at the base to open-marine carbonate rocks with marls and shales at the top. Locally, the sequence is extremely condensed and fossiliferous. In places where argillaceous facies dominates, it is up to 150 m thick. The Silurian is developed in a monotonous facies of graptolite shales followed by up to 1200 m thick greywackes. Unlike in the Lysogory Unit, an angular unconformity separates the Upper Silurian and the Lower Devonian in Malopolska [27]. Facies patterns recognized along the HCF in the Silurian and Lower Devonian suggest that the amalgamation of Malopolska with Lysogory took place during late Silurian times [10].

3. Sampling and lithology

Ordovician rocks are poorly exposed in the HCM and only a few localities with surface outcrops exist. Although several sections were sampled, only the Middle Ordovician Mójcza Limestone proved to be suitable for paleomagnetic studies. This unit is well exposed at its type locality in an old quarry at Mójcza near the city Kielce (Fig. 2). The succession consists of fossiliferous sandstones (Bukowka Sandstone) of Tremadocian to lower Arenigian age, overlain by organodetrital limestones (Mójcza Limestone), which are latest Arenigian

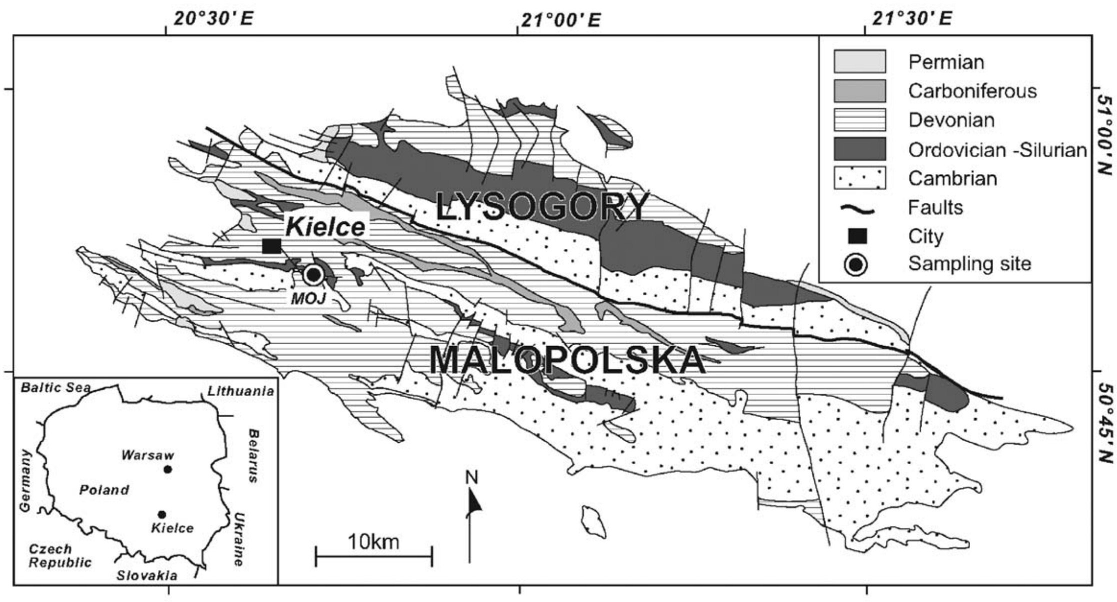

Fig. 2. Geological sketch map of the Holy Cross Mountains, Poland, with location of the sampled section at Mojcza, ca. 6 km southeast of Kielce.

to latest Caradocian in age, and marly limestones and shales (Zalesie Formation) of Ashgillian age on top. The section dips towards NE (053°) with an angle of about 38° and the exposed profile has a thickness of approximately 7 m (Fig. 3). In general, the succession is extremely condensed and includes transgressive and shallow marine deposits [27–29]. At the base of the succession, arenaceous limestones are cut by a basal discontinuity, above which a layer of organodetrital limestones with phosphatic nodules and ferruginous ooids occurs. The main part of the present-day exposure is occupied by organodetrital limestones with a thin bentonite layer in the central part of the section (Fig. 3). At the top, about 3.5 m above the bentonite layer, the sequence consists of argillaceous limestones interbedded with marls [29]. The most characteristic inorganic components of the Mójcza Limestone are ferruginous ooids. The occurrence of ooids seems to be controlled by delivery of iron into the sedimentary basin, possibly in connection with volcanism as documented by the bentonite layer, or transported from a local source area [29]. Although the succession is condensed, there is no reworking suggesting erosional events during the deposition of the Mójcza Limestone.

Samples for paleomagnetic analysis were collected from the condensed continuous sequence of organodetric limestone beds which span the Llanvirn and Caradoc with a stratigrahic thickness of some 4.5 m (Fig. 3). The stratigraphic range of this part of the formation is precisely determined based on conodonts [28,30]. Numerous analysis of the conodont color alteration indices (CAI, [31]) from Paleozoic rocks of the Malopolska Massif show CAI values of 1–2 [32], indicating maximum paleotemperatures below 150 °C [31]. Samples were collected at ca. 10–15 cm intervals in the central part of the section (Fig. 3), covering the time interval from the Upper Llanvirn *Eoplacognathus robustus* subzone to the Cardocian *Amorphognathus superbus* zone. All samples were taken with a portable, gasoline-powered drill and oriented in the field using a standard magnetic compass.

4. Biozonation

A characteristic feature of the Mójcza Limestone is the absence of complete macrofossils [29]. Biostratigraphically most important is a pelagic conodont fauna [29], which is dominated by platform-conodonts including the lineages of *Eoplacognatus, Pygodus* and *Amorphognatus* [29]. Dzik [28,30] described conodont apparatuses of sixty-seven species from thirty-six genera. For a precise biostratigraphical zonation of the sampled section, the evolutionary lineages and relationships of Ordovician platform conodonts given by Bergström [33] were applied here (Fig. 3). The arrows in the biozonation section of Fig. 3 mark the first and last appearances of conodont species, which are indicative of the zonal bounderies. The record shows stratigraphic completeness, with only one significant hiatus associated with the discontinuity at the lower part of the section, corresponding to the subzones *E. pseudoplanus* to *E. reclinatus*.

Samples for paleomagnetic analysis were collected above this discontinuity and cover the conodont zones from the *Pygodus serra* zone of the Llanvirnian to the *A. superbus* zone of the Caradocian. The almost continuous replacement of one lineage by another allows a detailed documentation of conodont zones and subzones in this part of the section [30]. No significant faunal changes are observed across a bentonite layer (Fig. 3), located in the Upper *Pygodus anserinus* zone. The volcanic activity which is documented by this bentonite layer had no direct influence on the fauna at Mójcza [29].

The conodont fauna is typical for shallow and warm water conditions, but cold water genera like *Sagittodontina, Scaccardella* and *Hamarodus*, as well as some genera of Welsh affinity such as *Complexodus, Phragmodus* and *Rhodesognathus* occur and are dominant in places [30]. The diversity of the Ordovician conodont assemblages seems to depend more on local ecologic factors and bathymetry than on climate [34].

Correlation of the Mójcza section with the global stratigraphy [35] was done using the biozonation for platform conodonts of Bergström [33]. The sampled section spans the time slices 4c to 5c as defined by Webby et al. [35] and represents about 9 myr from the *Eoplacognathus lindstroemi* subzone within the *P. serra* zone to the lowermost *Amorphognathus superbus* zone [28,30,33], indicating very low sedimentation rates (ca. 0.5 mm/1000 a).

5. Laboratory procedures

The field-drilled cores were cut into standard 2.2 × 2.5 cm specimens and their magnetization was measured using a DC-SQUID magnetometer (2G-Enterprises) in a magnetically shielded room at the Niederlippach paleomagnetic laboratory of the Ludwig-Maximilians-University, Munich. Samples were demagnetized using both stepwise thermal and alternating field techniques. The latter method failed to reveal the full character of the remanent magnetizations due to the presence of high coercivity minerals, such as goethite and hematite. Magnetic susceptibility was measured

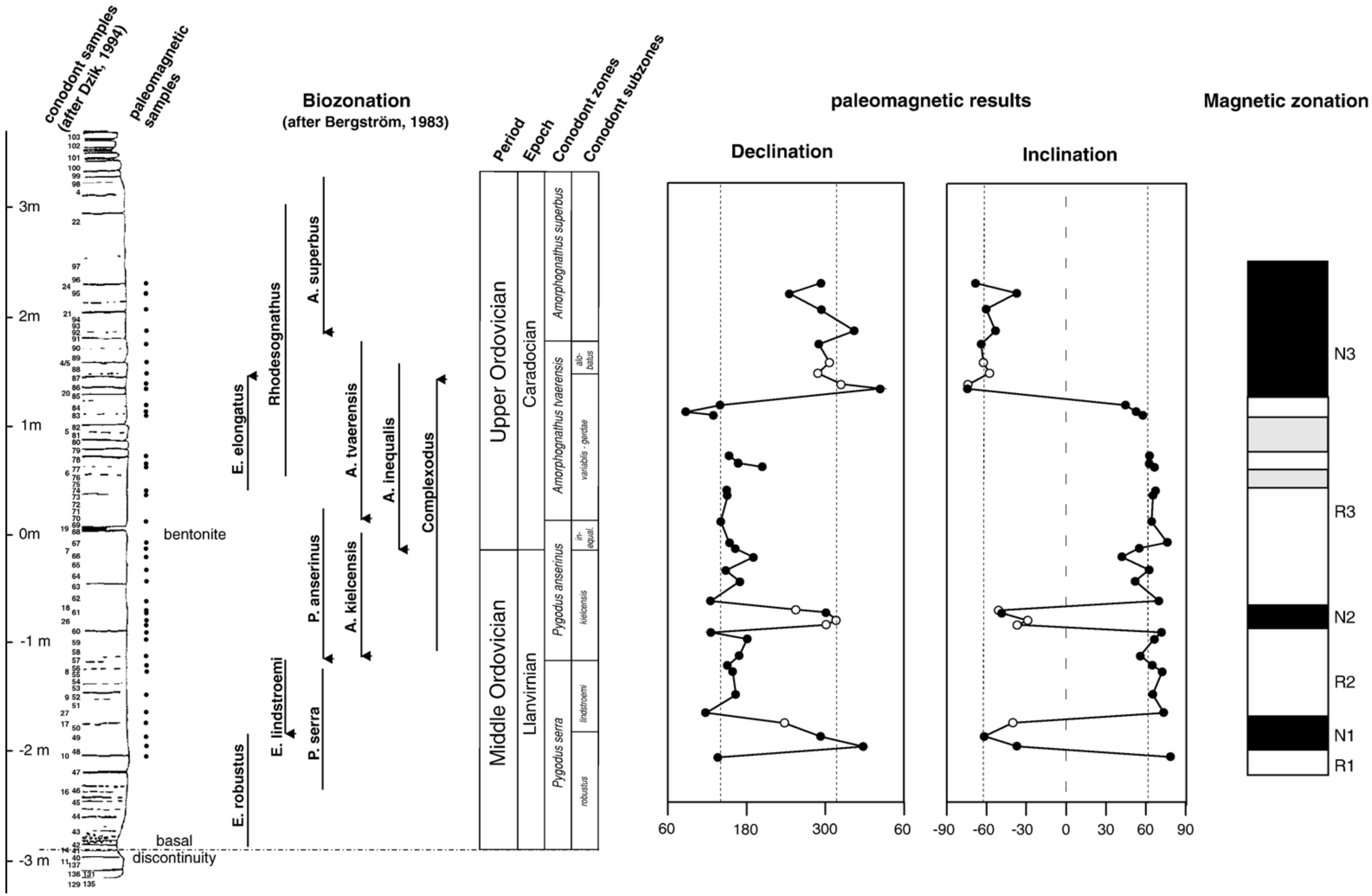

Fig. 3. Stratigraphic column of the sampled section of the Mójcza limestone with sample locations of faunal [30] and paleomagnetic studies. The correlation with the global stratigraphy [35] was done using the biozonation for platform conodonts of Bergström [33]. Arrows mark important first and last appearance dates of conodont species, which were used for correlation. The paleomagnetic results indicate at least five polarity changes. Filled circles mark results, where the direction of magnetization was identified by linear segments and stable endpoints, open circles indicate results from great circle analysis. Black (white) intervals represent normal (reversed) polarity of the Earth magnetic field. The grey parts indicate intervals of about 15 to 30 cm length where no samples were taken.

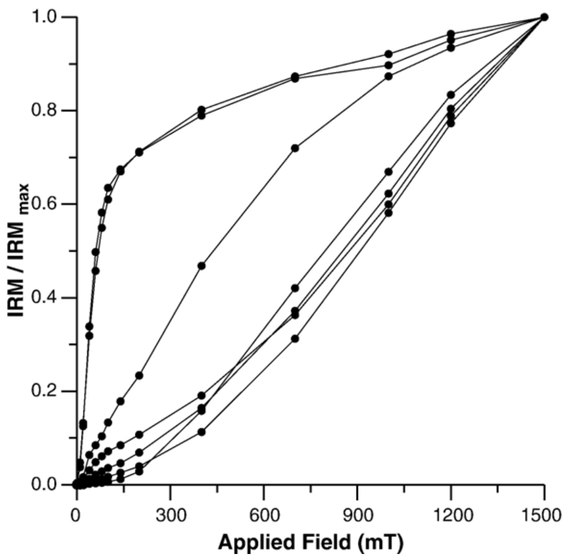

Fig. 4. Acquisition of a monodirectional isothermal remanent magnetization (IRM), normalized to the maximum IRM intensities.

after each heating step to monitor thermochemical alterations. Demagnetization results were analysed using orthogonal vector plots [36] and stereographic projections. Directions of linear demagnetization trajectories were identified by eye and calculated using principal component analysis [37]. Where overlapping coercivity or unblocking temperature (T_{UB}) spectra prevent complete separation of the magnetizations, great circle analysis was performed using the method of McFadden and McElhinny [38] on the planar demagnetization trajectories to identify the underlying direction. This method uses an iterative procedure whereby the maximum likelihood estimate of the endpoint direction within the acceptable sector for each great circle can be determined. This is then combined with the stable endpoint directions, resulting in determination of mean directions, which are calculated using Fisher statistics [39] in all cases.

Various rock magnetic experiments were carried out to characterize the carriers of magnetizations. These experiments include the acquisition of an isothermal remanent magnetization (IRM), thermal demagnetization of saturation IRM (SIRM) and the determination of hysteresis properties.

6. Rock magnetism

During IRM experiments two types of behavior can be observed (Fig. 4). One group (I) of specimens shows a steep increase in IRM intensity up to 150 mT and a slight but continuous increase in intensity at higher fields without reaching saturation up to the maximum applied field of 1.5 T, indicating a mixture of both low and high coercivity minerals. The other group (II) of samples (Fig. 4) is characterized by the continuous and gradual increase of IRM intensity up to the maximum applied field, diagnostic for the predominance of high coercivity minerals.

Thermal demagnetization of a triaxial IRM [40] acquired at 1.5, 0.5 and 0.2 T reveals magnetite (low coercivities; T_{UB} of ca. 580 °C) together with minor

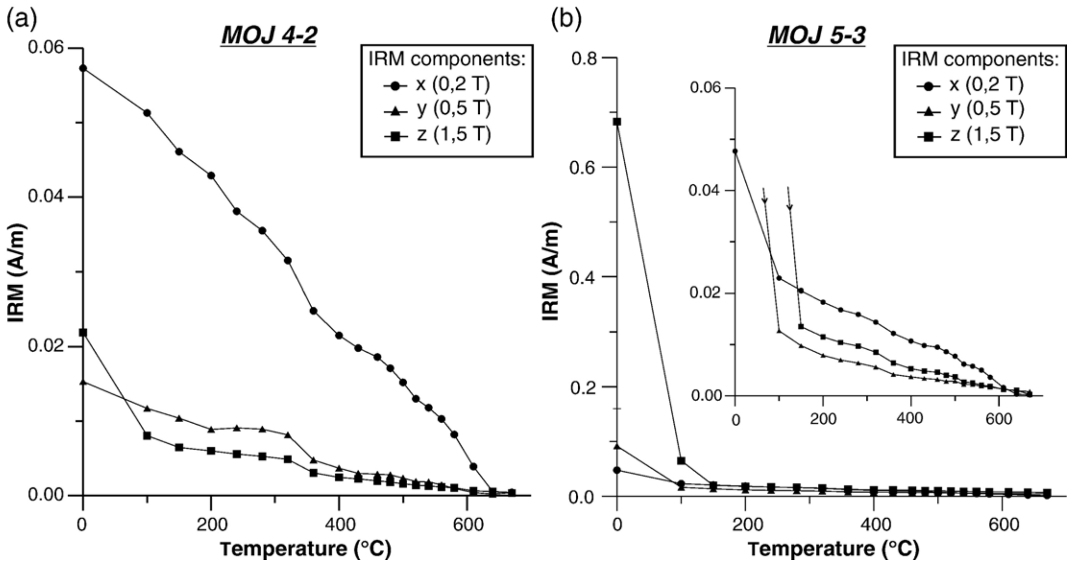

Fig. 5. Thermal demagnetization of triaxial IRM [40] for specimens MOJ4-2 (a) and MOJ5-3 (b). The inset in (b) shows the details of the demagnetization curves at higher temperatures.

amounts of goethite (high coercivities, low T_{UB}), iron sulphides (intermediate coercivity fraction, T_{UB} of 300–350 °C) and possibly hematite (high coercivity and T_{UB} above 600 °C) in specimens of group I.

The IRM of group II type specimens (Fig. 5b) is dominantly carried by goethite (high coercivity fraction, $T_{UB} < 150$ °C) and small amounts of iron sulphides, magnetite and haematite. The magnetic

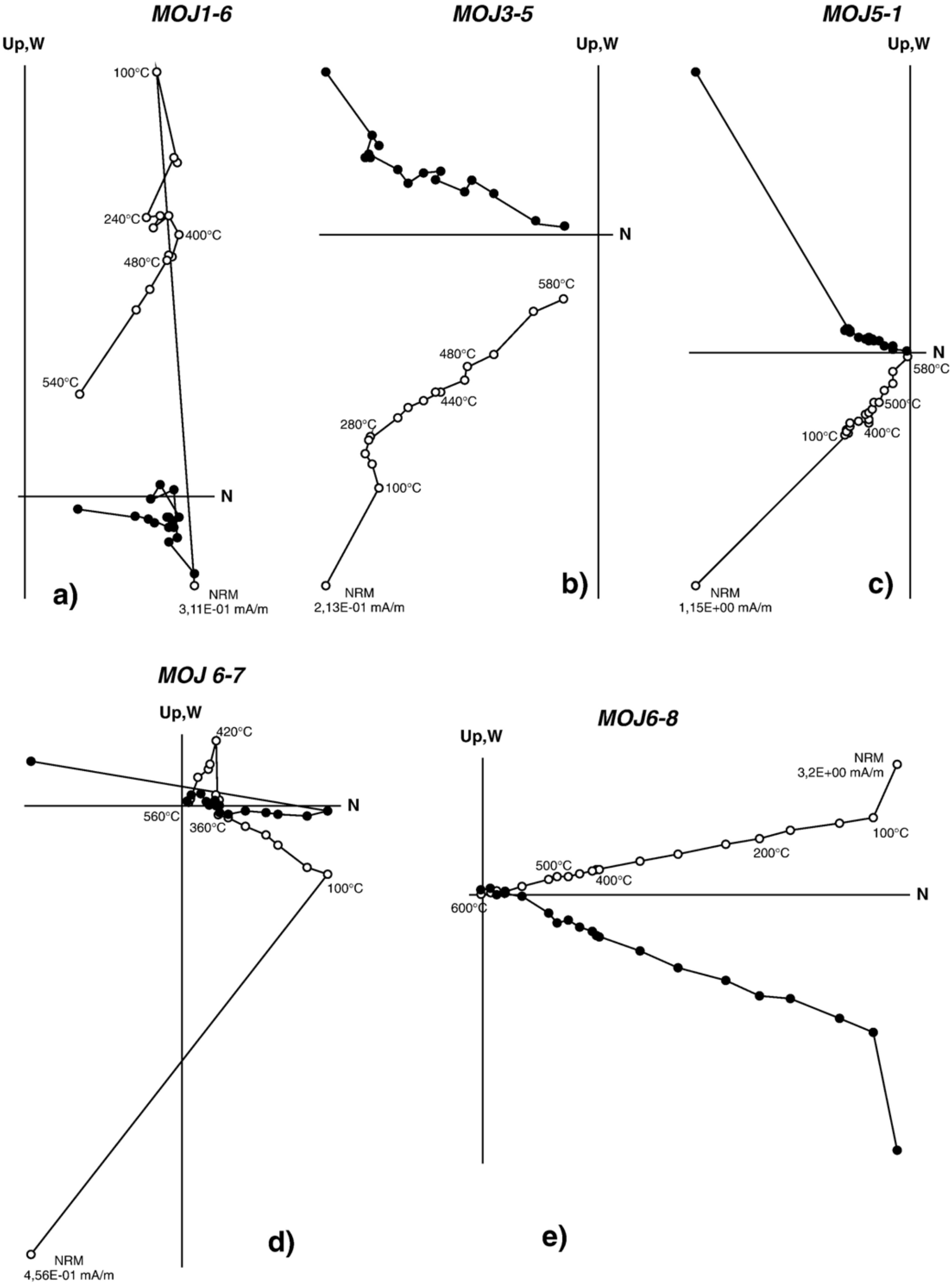

Fig. 6. Orthogonal projection of thermal demagnetization behavior of samples of the Mójcza limestone. All directions are plotted in geographic coordinates and solid (open) symbols represent the projection on the horizontal (vertical) plane.

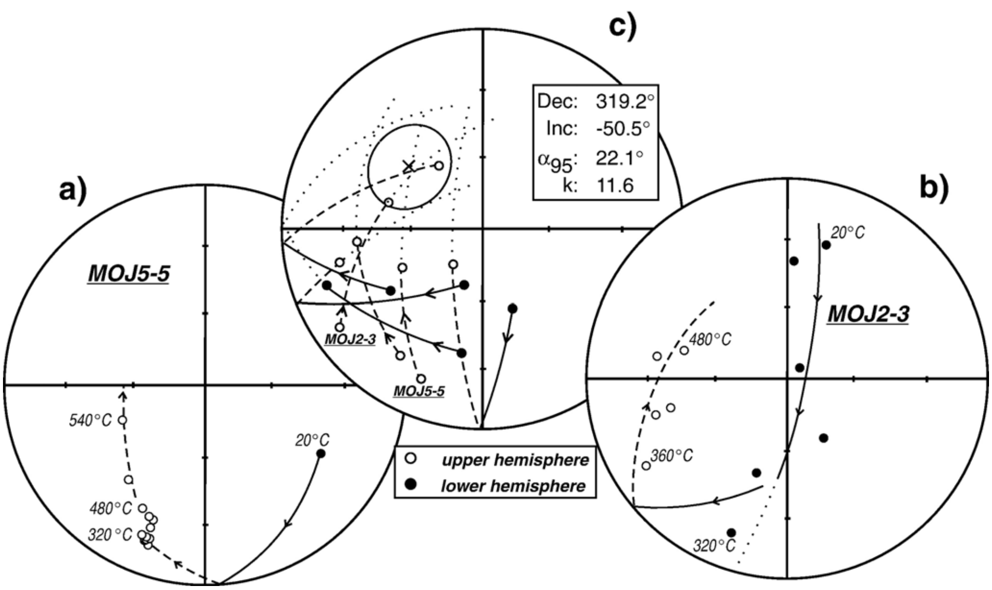

Fig. 7. Demagnetization behavior of specimens, where no stable endpoint direction could be identified (stereographic projection, stratigraphic coordinates). a) and b) In individual specimens: two great circle paths can be identified from room temperature to ca. 320 °C and from ca. 360 up to 540 °C. At temperatures higher than 480 and 540 °C the magnetization directions become random due to mineralogical alteration and no further reliable measurements could be made. c) Great circle trajectories with start and end points of 7 specimens with mean direction obtained by great circle analysis after McFadden and McElhinny [38]. Only the high temperature segments of the great circle trajectories and their extrapolations are shown in c).

susceptibility of most specimens increases significantly at demagnetization temperatures above 400 °C. This indicates alteration of magnetic minerals, possibly the oxidation of iron sulphides and the formation of magnetite.

7. Thermal demagnetization

The intensity of the initial natural remanent magnetization (NRM) is generally low and ranges from 0.2–4 mA/m. During thermal treatment, in most specimens

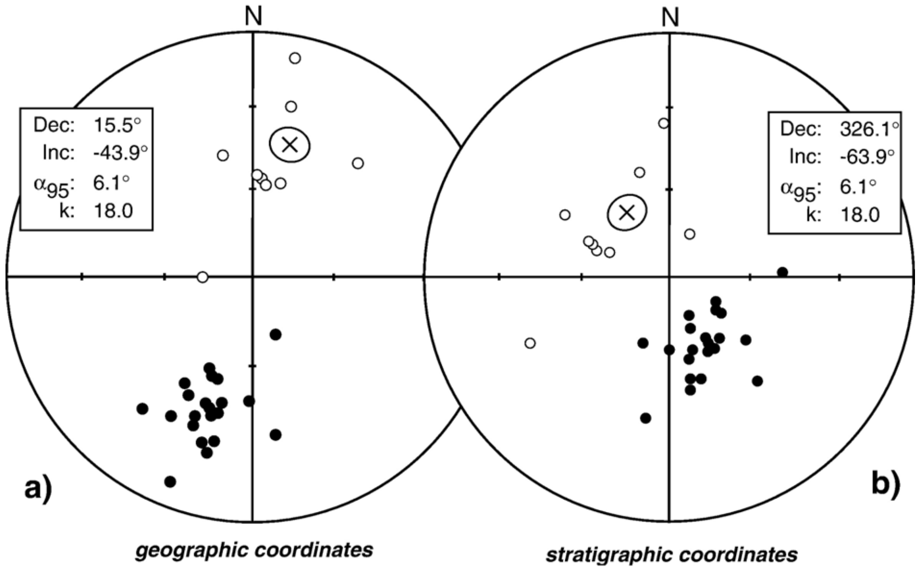

Fig. 8. Equal area stereographic projection of single sample directions (data from linear segments and stable endpoints only) in geographic (a) and stratigraphic (b) coordinates of the bipolar component observed in the Mójcza limestone. The reversal test [41] is positive (classification *C*), indicating the primary nature of the magnetization. Also shown are the cone of 95% confidence and the overall sample mean direction.

Table 1
Paleomagnetic results from the Mójcza quarry

Polarity interval	Age	N	In situ		Bedding		k	α_{95}	Paleopole position		
			D (°)	I (°)	D (°)	I (°)		(°)	Lat (°N)	Lon (°E)	dp/dm (°)
N3	Car	9	13.5	−55.7	298	−66.7	13.5	14.8	23.2	59.4	20.1/24.4
R3	Car/Llanv	15	196.3	41.1	152	62.9	24.2	7.9	8.2	40.5	9.8/12.5
N2	Llanv	4	337.5	−46.6	297.9	−42.7	12.9	36	3.2	74.2	27.5/44.5
R2	Llanv	7	203.4	43.1	155.5	68.3	62.7	7.7	14.5	36.1	10.9/12.9
N1	Llanv	3	355.3	−35	322.4	−46.2	5.9	65.6	−4.9	53.6	53.8/84.0
R1	Llanv	1	214.3	53.5	133	78.6	–	–	–	–	–
∑ N		16	1.6	−50.3	305.2	−58.4	10.4	12.1	11.9	61.1	13.2/17.9
∑ R		23	198.6	41.8	153	64.7	30.1	5.7	10.2	39.2	7.4/9.2
N+R	Car/U. Llanv	39	13.6	−44.9	322.5	−63.3	16.6	5.8	11	46.8	7.2/9.1
								Paleopole position in situ	−11.7	8.3	4.6/7.3

N, number of samples; D and I, declination and inclination; k, precision parameter [37]; α_{95}, half angle of the cone of 95% confidence; Car, Caradocian; Llanv, Llanvirnian; U, Upper; Lat and Lon, Latitude and Longitude of the paleo-(south)pole; dp and dm, semi-axis of the oval of the 95% confidence; site location: N 50.84°, E 20.69°.

demagnetization of two or more magnetic components is observed. In some specimens, the T_{UB} spectra of different components overlap. In such cases, great circle analysis was performed using the method of McFadden and McElhinny [38]. However, in most samples a high T_{UB} stable endpoint direction can be identified.

Different kinds of behavior during demagnetization can be observed in orthogonal projection (Fig. 6a–e). Many specimens show a relatively simple behavior: after removal of a low temperature component A of random orientation, which is carried by goethite, a second component B can be identified at intermediate demagnetization temperatures in some specimens (Fig. 6d). A third component C is observed at high demagnetization temperatures in almost all specimens. C is characterized by normal (C_N, Fig. 6a,d,e) and reversed (C_R, Fig. 6b,c) polarities.

In specimens, where T_{UB} spectra overlap, the demagnetization trajectories in stereographic projection are reasonably well defined (Fig. 7a,b) and show two distinct great circle paths. During demagnetization up to 320 °C, the magnetization vectors move along a great circle from a direction close to the direction of the present-day geomagnetic field in the sampling area (northerly declination, positive inclination) towards a southerly shallow (in situ) direction. At higher demagnetization temperatures (360–540 °C), the magnetic vectors move towards a north/northwesterly negative direction in stratigraphic coordinates (Fig. 7a,b).

8. Paleomagnetic results

Component B with a shallow southerly direction can be identified in a total of 12 specimens in the temperature range between 320 and up to 480 °C. The demagnetization vectors show large scatter between samples and no mean direction was calculated. However, most of the low temperature great circle paths move towards shallow southerly directions (Fig. 7) and are thought to

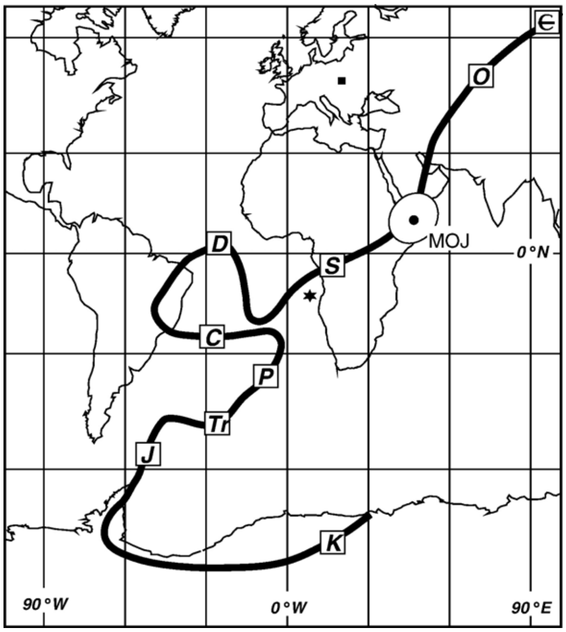

Fig. 9. Apparent polar wander path (south poles) of Baltica after Smethurst et al. [42]. The new Middle Ordovician paleo-(south)pole (circle with 95% error oval) for the Holy Cross Mountains falls on the Middle Ordovician segment of the APWP. The star indicates the paleo-(south) pole position, which corresponds to the directions of components C_N and C_R in geographic coordinates. The square marks the sampling area. Ages in the path are as follows: Є=Cambrian, O=Ordovician, S=Silurian, D=Devonian, C=Carboniferous, P=Permian, Tr=Triassic, J=Jurassic, K=Cretaceous.

indicate a weak Permo-Carboniferous overprint. Components C_R/C_N are identified as stable endpoint directions in 32 samples during demagnetization up to 580 °C and are thought to be carried by magnetite. Components C_R and C_N are almost antiparallel (Fig. 8) and their stable endpoints yield mean directions of Dec.: 153.0°, Inc.: 64.7°, k: 30.1, α95: 5.7° (C_R) and Dec.: 307.1, Inc.: −62.5, *k*: 10.4, α_{95}: 16.7 (C_N). The mean directions and corresponding paleopole positions of C_R and C_N for each polarity interval are listed in Table 1. Seven samples show evidence for overlapping T_{UB} spectra and no stable endpoint direction could be determined. However, their high temperature great circle paths all move towards the direction of component C_N (Fig. 7c) and the combined mean direction of stable endpoints and great circles after McFadden and McElhinny [38] for C_N is Dec.: 305.2°, Inc.:−58.4°, *k*: 10.4, α_{95}: 12.1° (Table 1). The angular difference between the stable endpoint directions of components C_R and C_N is 11.4°, thus yielding a positive reversal test [41] at the 95% confidence level with a critical angle of 13.1° (classification C).

For specimens where overlapping T_{UB} spectra prevents the identification of linear segments with stable endpoints, the endpoint directions of great circle trajectories were used for the magnetostratigraphical record (open circles in Fig. 3). Although those directions are less reliable, the data is considered to be of sufficient quality to determine the polarity of the Earth's magnetic field (Fig. 3). Given the expected position of Baltica in the Middle Ordovician at southern latitudes [42], the positive (negative) inclinations of C_R (C_N) correspond to a reversed (normal) polarity of the Earth's magnetic field during the time of sedimentation and magnetization. The overall mean direction of C_R and C_N after bedding correction (Dec.: 322.5°, Inc.:−63.3°, *k*: 16.6, α_{95}: 5.8°) corresponds to a paleo-(south)pole position of 11.0°N, 46.8°E (Table 1), which falls directly on the Caradocian–Llanvirnian segment of the apparent polar wander path (APWP) for Baltica [42] (circle in Fig. 9). The mean directions of C_R and C_N in geographic coordinates (Dec.: 13.6°, Inc.:−44.9°, *k*: 16.6, α_{95}: 5.8°) yields a paleo-(south)pole position of −11.7°N, 8.3°E, which lies adjacent to the Early Silurian segment of the APWP by Smethurst et al. [42] (star in Fig. 9). Given the positive reversal test and the fact that the reversal pattern of C_R and C_N is stratigraphically controlled, components C_R and C_N are considered to be primary in origin. Their age is constrained by the well established conodont

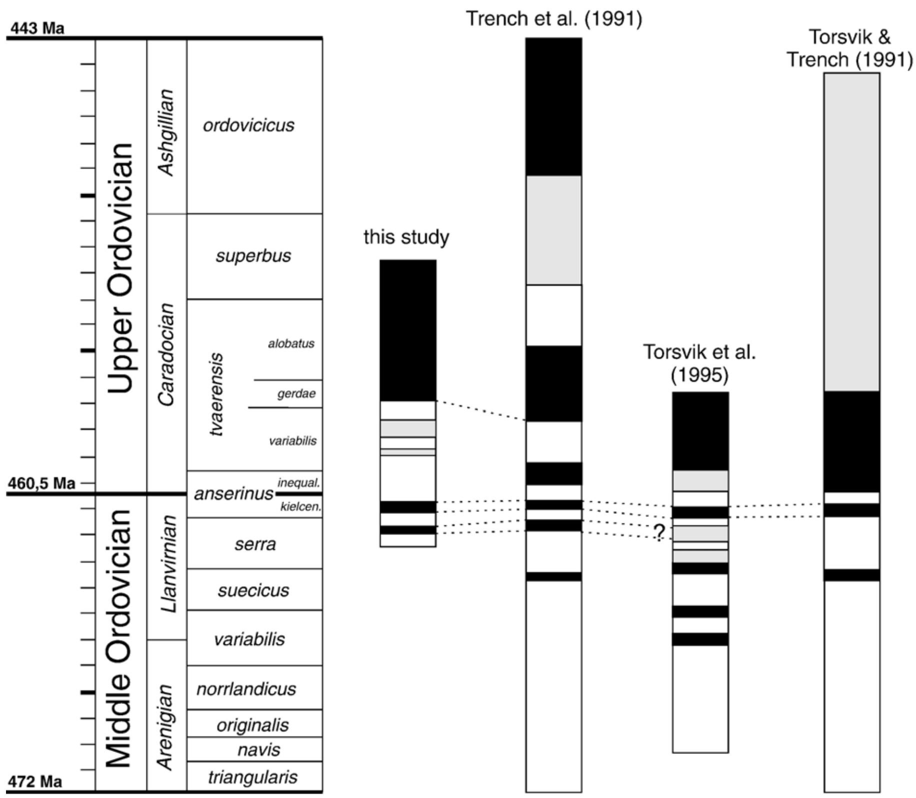

Fig. 10. Comparison of the results from the Mójcza limestone with published magnetostratigraphies. Black (white) intervals represent normal (inverse) polarities. Grey colors indicate incomplete sampling.

biostratigraphy of the Mójcza Limestone and the bedding corrected paleo-(south)pole position of 11.0°N, 46.8°E is considered representative for the Malopolska Massif of the Holy Cross Mountains in Llanvirnian and Caradocian times.

9. Conclusions

The paleomagnetic results indicate at least five polarity changes between Middle Llanvirnian (*P. serra* zone) and Late Caradocian times (*A. superbus* zone) and a long interval of inverse polarity from Upper Llanvirnian to Middle Caradocian (Figs. 3 and 10). However, this interval includes two sampling gaps and the presence of associated transitional directions (Fig. 3) may point towards the existence of another, unidentified reversal. The results from the Mójcza limestone can be compared with published Ordovician magnetostratigraphies [43–45], which are based primarily on graptolite biostratigraphy (Fig. 10). The conodont and graptolite biozones were compared using the Ordovician stratigraphic charts, compiled by Webby et al. [35]. The Upper Llanvirnian reversal record in the Mójcza Limestone is in very good agreement with the data of Trench et al. [44] and Torsvik et al. [45] (Fig. 10). In the Lower Caradocian, a normal polarity interval which is given by Trench et al. [44] might have been missed during sampling, due to the strongly condensed nature of the Mójcza section. The obvious differences in the Caradocian between the Polish magnetostratigraphy and the compilations of Trench et al. [44], Torsvik and Trench [43] and Torsvik et al. [45] is thought to reflect possible uncertainties in the biostratigraphic age control and the correlation between graptolite and conodont biozones.

The paleo-(south)pole obtained in this study (11.0°N, 46.8°E; Table 1) falls directly on the Caradocian–Llanvirnian segment of the apparent polar wander path for Baltica [42] (Fig. 9), clearly indicating that the Malopolska Massif had accreted to southern Baltica before mid-Ordovician times. The new paleomagnetic data from the Malopolska Massif in Holy Cross Mountains do not support the hypothesis of large-scale tectonic movements along the Teisseyre–Tornquist Line after the Middle Ordovician and also contradict the hypothesis, that any major local tectonic rotations of the investigated area have occurred since that time.

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References

[1] T.C. Pharaoh, R.W. England, J. Verniers, A. Zelazniewicz, Introduction: geological and geophysical studies in the Trans-European Suture Zone, Geological Magazine 134 (5) (1997) 585–590.
[2] A. Berthelsen, Mobile Europe, in: D. Blundell, R. Freeman, S. Mueller (Eds.), A Continent Revealed — The European Geotraverse, Cambridge Univ. Press, Cambridge, 1992, pp. 11–32.
[3] A. Zielhuis, G. Nolet, Deep seismic expression of an ancient plate boundary in Europe, Science 265 (1994) 79–81.
[4] A. Guterch, M. Grad, H. Thybo, G.R. Keller, POLONAISE'97 — an international seismic experiment between Precambrian and Variscan Europe in Poland, Tectonophysics 314 (1999) 101–121.
[5] A. Guterch, M. Grad, R. Materzok, E. Perchuc, Deep structure of the Earth's crust in the contact zone of the Paleozoic and Precambrian platforms in Poland (Tornquist–Teisseyre Zone), Tectonophysics 128 (1986) 251–279.
[6] W. Pozaryski, The middle Europian Caledonides-wrenching orogen composed of terranes, Przeglad Geologiczny 38 (1990) 1–9 (in Polish with English summery).
[7] W. Pozaryski, A. Grocholski, H. Tomczyk, P. Karnkowski, W. Moryc, The tectonic map of Poland in the Variscan epoch, Przeglad Geologiczny 40 (1992) 643–651.
[8] T.C. Pharaoh, Palaeozoic terranes and their lithospheric boundaries within the Trans-European Suture Zone (TESZ): a review, Tectonophysics 314 (1999) 17–41.
[9] Z. Belka, H. Ahrendt, W. Franke, K. Wemmer, The Baltica–Gondwana suture in central Europe: evidence from K–Ar ages of detrital muscovites and biogeographical data, in: W. Franke, R. Altherr, V. Haak, O. Oncken (Eds.), Orogenic Processes — Quantification and Modelling of the Variscan Belt, Special Publication, vol. 179, Geological Society of London, London, 2000, pp. 87–102.
[10] Z. Belka, P. Valverde-Vaquero, W. Dörr, H. Ahrendt, K. Wemmer, W. Franke, Accretion of first Gondwana-derived terranes at the margin of Baltica, in: J.A. Winchester, T.C. Pharaoh, J. Verniers (Eds.), Palaeozoic amalgamation of Central Europe, Special Publication, vol. 201, Geological Society of London, London, 2002, pp. 19–36.
[11] J. Bergström, Strike-slip faulting and Cambrian biogeography around the Tornquist Zone, Geologiska Föreningens I Stockholm Föhandlingar 106 (1984) 382–383.
[12] G. Vidal, M. Moczydlowska, The Neoproterozoic of Baltica—stratigraphy, palaeobiology and general geological evolution, Precambrian Research 73 (1995) 197–216.
[13] S. Orlowski, Lower Cambrian trilobites from Upper Silesia (Goczalkowice borehole), Acta Geologica Polonica 25 (1975) 377–383.
[14] S. Orlowski, Lower Cambrian and its trilobites in the Holy Cross Mts. Acta Geologica Polonica 35 (1985) 231–250.
[15] R. Dadlez, Debates about the pre-Variscan tectonics of Poland, Studia Geophysica Et Geodaetica 39 (1995) 227–234.
[16] T. Pharaoh, et al., Trans-European Suture Zone. Phanerozoic accretion and the evolution of contrasting continental lithospheres, in: D.G. Gee, H.J. Zeyen (Eds.), Europrobe 1996—

Lithosphere Dynamics: Origin and Evolution of Continents, Uppsala University, 1996, pp. 41–54.
[17] L.R.M. Cocks, W.S. McKerrow, C.R. van Staal, The margins of Avalonia, Geological Magazine 134 (1997) 627–636.
[18] L.M. Cocks, R.A. Fortey, Lower Paleozoic margins of Baltica, Geologiska Föreningens I Stockholm Föhandlingar 120 (1998) 173–179.
[19] P. Valverde-Vaquero, W. Dörr, Z. Belka, W. Franke, J. Wiszniewska, J. Schastok, U–Pb, single-grain, dating of detrital zircons in the Cambrian of Central Poland: implications for Gondwana versus Baltica provenance studies, Earth and Planetary Science Letters 184 (2000) 225–240.
[20] A. Seilacher, Upper Paleozoic trace fossils from the Gilf Kebir–Abu Ras area in southwestern Egypt, Journal of African Earth Sciences 1 (1983) 21–34.
[21] B. Jendryka-Fuglewicz, Analiza porownawcza raienionogow z utworow kambru Gor Swietokrzyskich i platformy prekambryjskiel w Polsce, Przeglad Geologiczny 467 (1992) 150–155.
[22] B. Jendryka-Fuglewicz, Kambryjska eksplozja zycia. Najstarsze zespoly brachiopodow w profilach geologicznych Polski, Abstracts of the XVI Palaeontological Meeting, Wiktorowo, 1998, pp. 18–19.
[23] A. Zylinska, Stratigraphic and biogeographic significance of Late Cambrian trilobites from Lysogory (Holy Cross Mountains, central Poland), Acta Geologica Polonica 52 (2002) 217–238.
[24] M. Lewandowski, Palaeomagnetic constraints for Variscan mobilism of the Upper Silesian and Malopolska Massifs southern Poland—reply, Geological Quarterly 39 (1995) 283–292.
[25] M. Lewandowski, A palaeomagnetic study of fracture fills in the Holy Cross Mountains of central Poland and its application in dating tectonic processes, Geophysical Journal International 137 (1999) 783–792.
[26] J. Nawrocki, Late Silurian paleomagnetic pole from the Holy Cross Mountains: constraints for the post-Caledonian tectonic activity of the Trans-European Suture Zone, Earth and Planetary Science Letters 179 (2000) 325–334.
[27] M. Szulczewski, Depositional evolution of the Holy Cross Mts. (Poland) in the Devonian and Carboniferous — a review, Geological Quarterly 39 (1995) 471–488.
[28] J. Dzik, Conodont biostratigraphy and palaeogeographical relations of the Ordovician Mójcza Limestone (Holy Cross Mts., Poland), Acta Palaeontologica Polonica 23 (1978) 51–72.
[29] J. Dzik, A. Pisera, Sedimentation and fossils of the Mójcza Limestone, Palaeontologia Polonica 53 (1994) 5–41.
[30] J. Dzik, Conodonts of the Mójcza limestone, Palaeontologica Polonica 53 (1994) 43–128.
[31] A.G. Epstein, J.B. Epstein, L.D. Harris, Conodont Color Alteration — An Index to Organic Metamorphism, Geol. Surv. Prof. Pap. 995 (1977) (27 pp.).
[32] Z. Belka, Thermal maturation and burial history from conodont colour alteration data, Holy Cross Mountains, Poland, Courier Forschungsinstitut Senckenberg 118 (1990) 241–251.
[33] S.M. Bergström, Biogeography, evolutionary relationships, and biostratigraphic significance of platform conodonts, Fossil and Strata 15 (1983) 35–58.
[34] J. Dzik, Relationships between Ordivician Baltic and North American Midcontinent conodont faunas, Fossils and Strata 15 (1983) 59–85.
[35] B.D. Webby, R.A. Cooper, S.M. Bergström, F. Paris, Stratigraphic framework and time slices, in: B.D. Webby, F. Paris, M.L. Droser, I.G. Percival (Eds.), The Great Ordovician Diversification Event, Columbia University Press, New York, 2004.
[36] J.D.A. Zijderveld, AC demagnetization of rocks: analysis of results, in: D.W. Collinson, K.M. Creer, S.K. Runcorn (Eds.), Methods in Paleomagnetism, Elsevier, New York, 1967, pp. 254–287.
[37] J.L. Kirschvink, The least-squares line and plane and the analysis of paleomagnetic data, Geophysical Journal of the Royal Astronomical Society 62 (1980) 699–718.
[38] P.L. McFadden, M.W. McElhinny, The combined analysis of remagnetization circles and direct observations in palaeomagnetism, Earth and Planetary Science Letters 87 (1988) 161–172.
[39] R.A. Fisher, Dispersion on a sphere, Proceedings of the Royal Society of London. Series A 217 (1953) 295–305.
[40] W. Lowrie, Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties, Geophysical Research Letters 17 (2) (1990) 159–162.
[41] P.L. McFadden, M.W. McElhinny, Classification of the reversal test in palaeomagnetism, Geophysical Journal International 103 (1990) 725–729.
[42] M.A. Smethurst, A.N. Khramov, S. Pisarevsky, Palaeomagnetism of Lower Ordovician Orthoceras Limestone, St. Petersburg, and a revised drift history for Baltica in the early Palaeozoic, Geophysical Journal International 133 (1998) 44–56.
[43] T.H. Torsvik, A. Trench, Ordovician magnetostratigraphy: Llanvirn–Caradoc limestones of the Baltic platform, Geophysical Journal International 107 (1991) 171–184.
[44] A. Trench, W.S. McKerrow, T.H. Torsvik, Ordovician magnetostratigraphy: a correlation of global data, Journal of Geological Society, London 148 (1991) 949–957.
[45] T.H. Torsvik, A. Trench, K.C. Lohmann, S. Dunn, Lower Ordovician reversal asymmetry: an artifact of remagnetization or nondipole field disturbance? Journal of Geophysical Research 100 (B9) (1995) 17885–17898.