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Palaeomagnetism of some Devonian carbonates from the Holy Cross Mts. (Central Poland): large pre-Permian rotations or strain modified palaeomagnetic directions?

Jacek GRABOWSKI and Jerzy NAWROCKI

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Palaeomagnetic studies of Middle and Upper Devonian carbonate rocks in the Holy Cross Mts. (Central Poland, SW foreland of the East European Craton — EEC) involved samples from the southern (Kielce) and northern (Łysogóry) unit. Haematite-bearing carbonates showed syn-folding remagnetisation of Early Permian age. The pole of this component is situated on the apparent polar wander path (APWP) of the EEC. The syn-folding age implies deformation of the Variscan syncline during Alpine uplift of the Holy Cross Mts. In dark limestones and dolomites magnetite was a dominant magnetic mineral. The age of magnetisation is interpreted as pre-Late Carboniferous: syn-folding in one locality and either pre- or syn-folding in four others. Four poles calculated from these components are shifted to the NW from the reference southern APWP for the EEC and one pole is concordant with its Early Carboniferous segment. The occurrence of rotated and unrotated palaeomagnetic poles could indicate that some fragments of both Kielce and Łysogóry units were subjected to local clockwise rotations during Variscan compression. An alternative explanation might be that Variscan pre- and/or syn-folding components could be strain modified or resultant magnetisations and they should not be used in palaeotectonic reconstruction.

Jacek Grabowski and Jerzy Nawrocki, Polish Geological Institute, Rakowiecka 4, PL-00-975 Warszawa, Poland; e-mail: jgra@pgi.waw.pl, jnaw@pgi.waw.pl (received: November 21, 2000; accepted: February 15, 2001).

Key words: Poland, Holy Cross Mts., Devonian palaeomagnetism, remagnetisation.

INTRODUCTION

Palaeomagnetic data from the Palaeozoic rocks of the Holy Cross Mts. (HCM) have been gathered for 20 years. Their interpretation is, however, still controversial. The main point of debate is the age of final accretion of the HCM area to the East European Craton (EEC, Baltica continent). The HCM are situated in the vicinity of the Trans-European Suture Zone — TESZ (Fig. 1), which is one of the most prominent geological boundaries in Europe, separating the Palaeozoic mobile belts of Western Europe from the pre-Cambrian EEC (e.g. Guterch *et al.*, 1986; Berthelsen, 1993; Pharaoh, 1999). Some geological models, interpret the TESZ line as a strike-slip zone of Caledonian (e.g. Brochwicz-Lewiński *et al.*, 1981) or Variscan age (e.g. Badham, 1982; Matte *et al.*, 1990). Models based on palaeomagnetic data suggest either a significant (~1000 km) Variscan strike-slip displacement of the southern part of the HCM along the SW border of the EEC (Lewandowski, 1993) or the relative stability of the area at least since the latest Silurian (Nawrocki, 2000).

New palaeomagnetic and rock magnetic data obtained from Middle and Upper Devonian carbonates of the HCM area are presented here. The age and origin of characteristic magnetisations and their bearing on geodynamic models is discussed.

GEOLOGICAL SETTING

The Holy Cross Mts. is an area of Palaeozoic rocks that was uplifted and exposed mainly due to vertical movements at the end of the Cretaceous and in the Miocene (Kutek and Głazek, 1972). The Palaeozoic core of the HCM consists of two distinct tectono-stratigraphic units: the northern — Łysogóry Unit and the southern — Kielce Unit (Fig. 2). The latter constitutes part of the Małopolska Block (Pożaryski and Tomczyk, 1968). These two units are separated by the Holy Cross Dislocation.

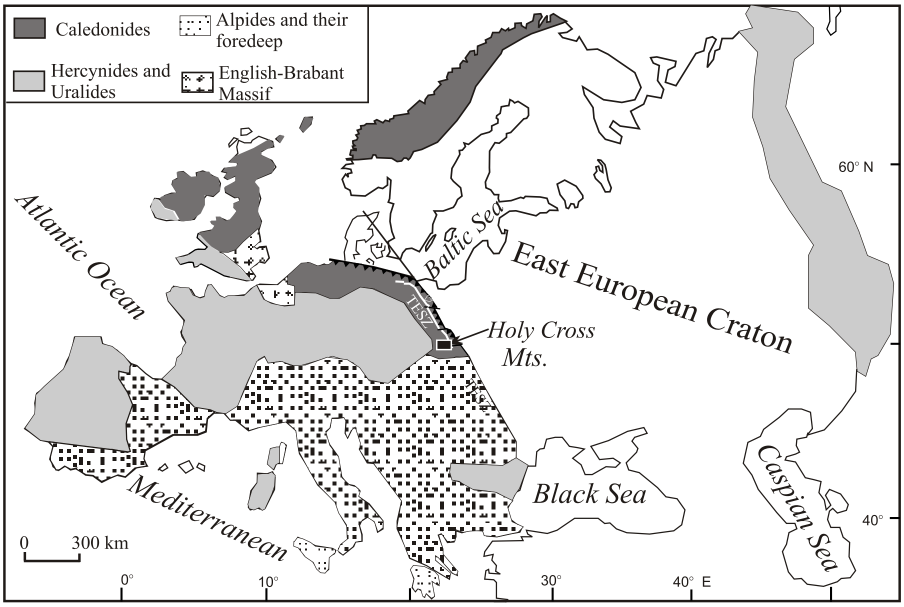

Fig. 1. The location of the Holy Cross Mts. within a tectonic sketch map of Europe; TESZ — Trans-European Suture Zone

They show a different tectonic and facies development, especially in the Early Palaeozoic and Early Devonian (Stupnicka, 1992; Lewandowski, 1993; Szulczewski, 1995). The Kielce Unit reveals polyphase tectonics with major angular unconformities between the Middle Cambrian and Lower Ordovician (Early Caledonian) and between the Silurian and Lower Devonian (Late Caledonian) (e.g. Stupnicka, 1992). In the Łysogóry Unit the Caledonian tectonic phases are not evident. According to Znosko (1996) and Kowalczewski and Dadlez (1996) the style of tectonic features in the Lower Palaeozoic of the Łysogóry region accounts for Caledonian deformation. Stupnicka (1992) and Mizerski (1995), however, point to the Sudetian phase (Visean/Namurian) of the Variscan orogeny, as the most important tectonic event in the Łysogóry Unit. Middle and Upper Devonian carbonate rocks, the subject of the present palaeomagnetic study, are the part of a syn-Variscan structural unit in both regions. A carbonate platform with variable littoral, reef and basinal facies developed after cessation of clastic sedimentation by the end of the Emsian (Szulczewski, 1995). Dolomites form the major part of the Middle Devonian. In the Eifelian early diagenetic dolomites prevail, while in the Givetian and Frasnian dolomites are mostly epigenetic in origin (Narkiewicz, 1991). Differences in the facies development of the Middle-Upper Devonian are observed between the Kielce and Łysogóry units (Szulczewski, 1995), however, similarities in the general patterns of subsidence across the Holy Cross Dislocation might suggest palaeogeographic proximity of both regions in the Devonian (Narkiewicz, 1996). After the Visean

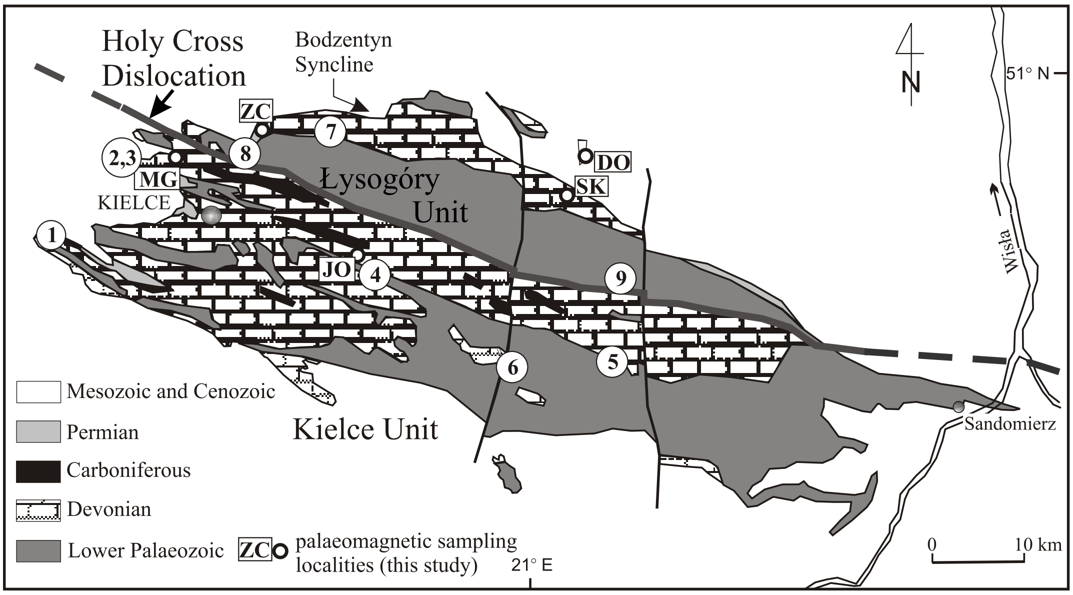

Fig. 2. Geological sketch map of the Holy Cross Mts. with sampled localities, numbers indicate the position of previously palaeomagnetically studied localities listed in the Table 3

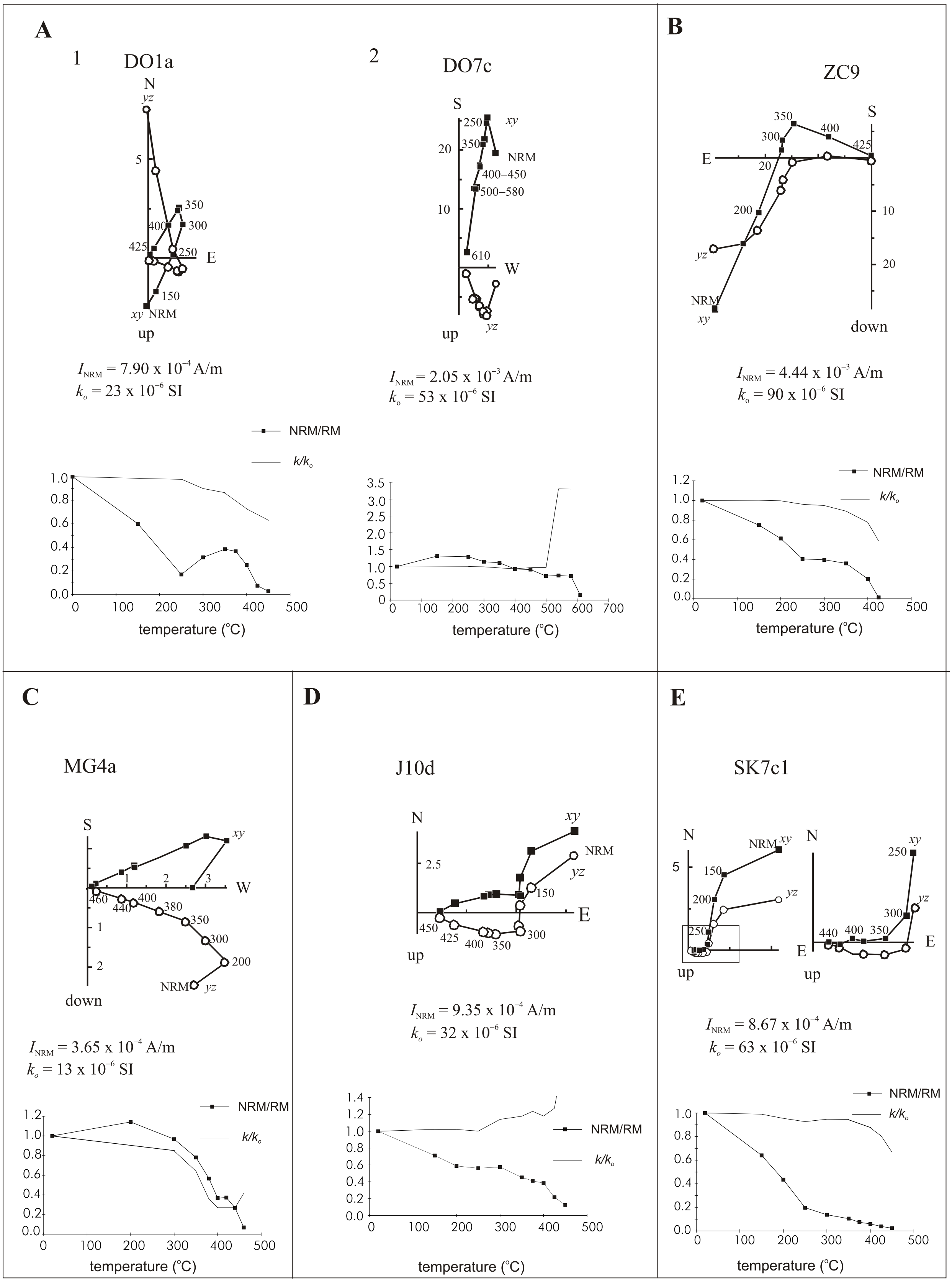

Fig. 3. Orthogonal plots of thermal demagnetisation of typical specimens (upper diagrams) and intensity decay curves (NRM/RM) + magnetic susceptibility changes during thermal treatment (k/k_o) (lower diagrams)

A — locality DO, dolomite; **B** — locality ZC, dolomite; **C** — locality MG, dark limestone; **D** — locality JO, dolomite; **E** — locality SK, dark limestone; *xy*, *yz* — the planes of projection, intensity units in 10^{-4} A/m; all projections, except a2, after tectonic correction, I_{NRM} — intensity of the natural remanent magnetisation; k_o — initial magnetic susceptibility

Table 1

Description of sampled localities

Locality	Code	Lithology	Age	Strike/Dip	*N*
Mogiłki	MG	dark limestones	Upper Frasnian	6/76, 0/37, 10/54, 188/44	15
Józefka	JO	dark limestones, dark dolomites	Givetian/Frasnian	56/36	10 (6 limestones, 4 dolomites)
Zachełmie	ZC	dolomites	Eifelian/Givetian	12/40	16 (1 hand sample, 15 cores)
Skały	SK	dark limestones, dark dolomites	Eifelian/Givetian	25/40	11 (4 limestones, 7 dolomites)
Doły Opacie	DO	dolomites	Eifelian/Givetian	192/40	7

N — number of hand samples (cores) collected from the outcrops

both regions were folded due to N–S to NNE–SSW directed compression (e.g. Lamarche *et al*., 1999) and uplifted. During the Permian the area was extensively eroded and then overlain by conglomerates. Since the Late Permian through the Mesozoic the HCM area was covered with marine and terrestrial sediments. They constituted the infill of the Mid-Polish Trough that developed along the former TESZ and subsided from the Permian to the Cretaceous (e.g. Dadlez *et al*., 1995 and references therein). During the Maastrichtian-Paleocene a tectonic inversion of the basin took place (Kutek and Głazek, 1972; Dadlez *et al*., 1995) under NE–SW directed compression (Lamarche *et al*., 1999). This tectonic event caused mostly brittle deformation of the Palaeozoic strata in the HCM and generally did not affect the geometry of the Variscan folds (Lewandowski, 1981; Lamarche *et al*., 1999). However, as the Permo-Mesozoic cover is locally strongly folded at the margins of the Palaeozoic core of the HCM, it has been postulated that Alpine folding involved the Palaeozoic rocks at the SW part of the HCM (Lamarche *et al.*, 2000).

SAMPLING LOCALITIES

The localities sampled are situated in the Kielce (Mogiłki — MG, Józefka — JO) and Łysogóry (Zachełmie — ZC, Skały — SK and Doły Opacie — DO) units of the HCM (Fig. 2). A total of 44 hand samples and 15 drill cores was collected and analysed. The localities were active or abandoned quarries. A fold test was possible between ZC, SK and DO localities which are located on the opposite limbs of the Bodzentyn Syncline (Fig. 2, Tab. 1) — ZC and SK at its southern and DO on its northern limb. At all these three localities the strata dip monoclinally and any fold test within the locality could not be applied. At locality MG the samples were collected from the thick bedded limestones dipping monoclinally to the N (samples MG1-10) and from the narrow folds occurring in thin-bedded limestones intercalated with marls (samples MG11–15). These folds are upright folds, locally slightly inclined towards N or S, with horizontal axes trending WNW–ESE. They originated as second rank, slightly disharmonic folds developed during folding of the thick-bedded limestones during the Variscan orogeny (Jarosiński, pers. comm.). It was possible to perform a local fold test within this locality.

Mid to Late Devonian carbonates from the HCM have never been heated to temperatures higher than 120–150°C (Belka, 1990). The conodont alteration index (CAI) varies from 1 to 3.5 and the highest values were observed along the Holy Cross Dislocation. CAI values in the localities sampled ranged from 1.5 in JO through 2.5 in SK to 3.5 in MG. The thermal event was undoubtedly Variscan (Belka, *op. cit.*).

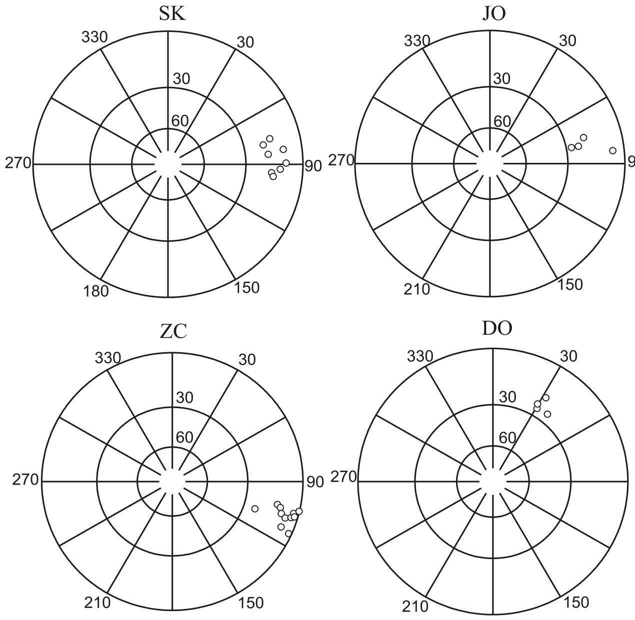

Fig. 4. Stereographic plots of characteristic sample mean components for localities SK, JO, ZC and DO (after tectonic correction); black dots — lower hemisphere projection, white dots — upper hemisphere projection (refers also to Figs. 5, 6 and 10)

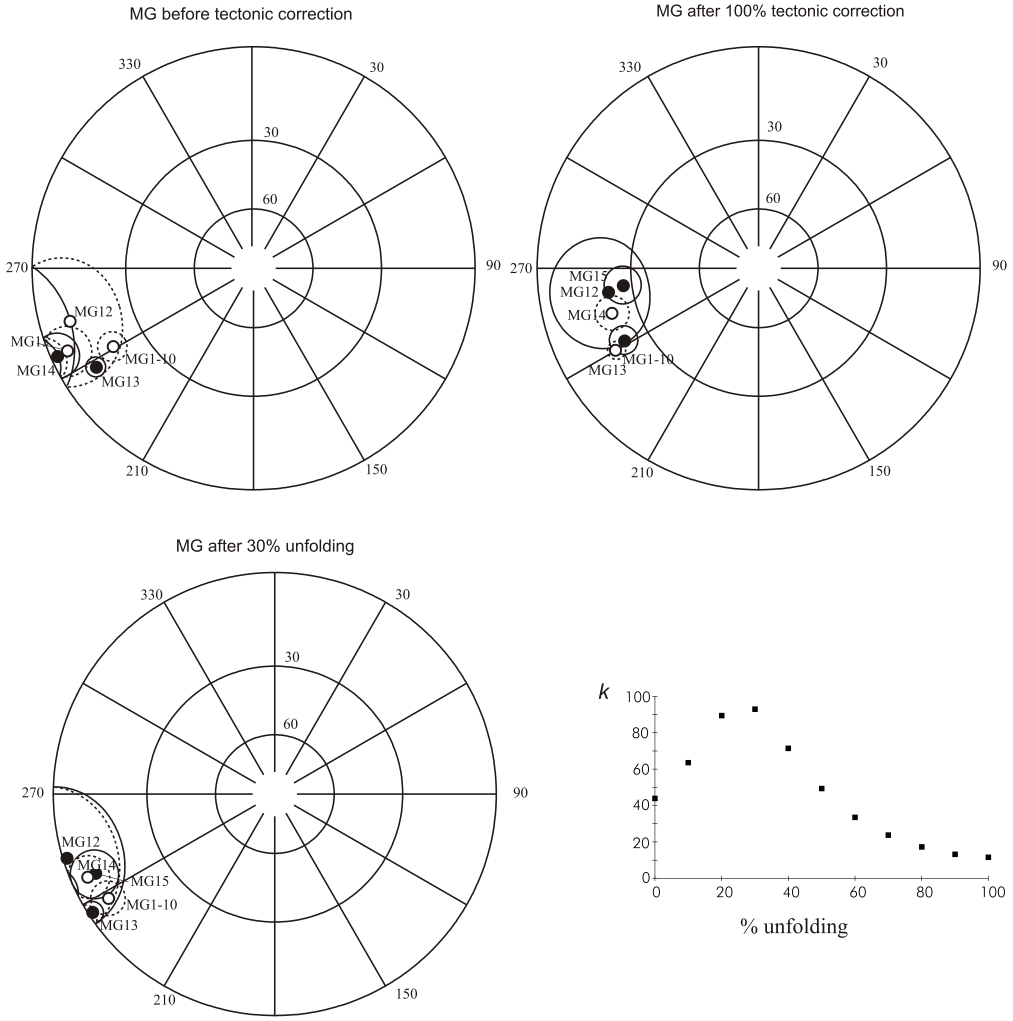

Fig. 5. Stereographic projection of characteristic site mean components at the locality MG before, after 100% tectonic correction, after 30% unfolding and incremental fold test

Other explanations as in Fig. 4

LABORATORY AND INTERPRETATIVE METHODS

Standard palaeomagnetic specimens 2.5 cm in diameter and 2.2 cm in height were drilled from the hand samples. 3–6 specimens were normally obtained from each hand sample. Natural remanent magnetisation (NRM) was measured by means of a *JR-5* spinner magnetometer (noise level: 10^{-5} A/m), while magnetic susceptibility during thermal demagnetisation was monitored with a *KLY-2* bridge (sensitivity: 10^{-8} SI units). Anisotropy of magnetic susceptibility (AMS) was computed using the *Aniso* program (Jelinek, 1977) (details given below). The rock specimens were thermally demagnetised with a MMTD non-magnetic oven. Demagnetisation experiments and the NRM measurements were performed inside Helmholz coils that reduced the geomagnetic field by about 95%. Characteristic directions were calculated using principal component analysis (Kirschvink, 1980). Palaeomagnetic poles were plotted using the GMAP for *Windows* package (Torsvik and Smethurst, 1994). Apparent polar wander paths (APWP), calibration and dating of palaeomagnetic components was performed using Palmer's (1983) time scale.

Stepwise acquisition of the isothermal remanence magnetisation (IRM) up to 1.3 T and thermal demagnetisation of the 3 axes IRM acquired in fields of 0.1, 0.4 and 1.3 T (Lowrie, 1990) were applied for identification of the magnetic minerals. IRM was applied using a MMPM pulse magnetiser. Both methods are routinely applied in rock magnetic investigations (e.g. Opdyke and Channell, 1996). IRM is an artificial magnetisation produced in laboratory, by subjecting a rock specimen to a magnetic field. Stepwise acquisition of the IRM depends on subjecting the rock specimen to a progressively increased magnetic field. The IRM intensity is measured after each step of magnetisation. Rapid saturation of the specimen in fields up to 300 mT is indicative of the presence of low coercivity minerals: magnetite-titanomagnetite or maghemite-titanomaghemite series. Saturation fields between 0.5–1.0 T are characteristic for pyrrhotite, 1.5–5.0 T for haematite, while goethite saturates in fields higher than 5 T. Thermal demagnetisation of the 3 axes IRM is used for determining unblocking temperatures of magnetic minerals of different coercivities. The strongest field of 1.4 T is applied along the *Z* axis (hard component), an intermediate field of 0.4 T along the *Y* axis (intermediate component) and the weakest field of 0.1 T along the *X* axis (soft compo-

Table 2

Characteristic palaeomagnetic directions and their poles obtained in this study

Component	*D*/*I* btc	α_{95}**	*k***	*D*/*I* atc	α_{95}**	*k***	Pole		*dp*	*dm*	*n*/*N*
							lat. N	long. E			
MG	245/–4	11.6	44	252/6 244/–1 26% unfolding	24.5 8.1	10.5 92.9	–16	312	4	8	48/14
JO	78/14	9.0	105	79/–18	11.5	64.6	0	306	6	12	9/4*
ZC	108/–1	5.7	65.9	107/3	5.4	71.7	10	277	3	6	11 cores
SK	85/7	5.7	94.1	87/–13	5.7	94.1	3	298	3	6	43/8
DO	50/–58	5.8	249	33/–22	5.8	249	–21	346	3	6	14/4

* — dolomite samples only; ** — statistic parameters calculated for hand samples

Component A

Locality	*D*/*I* btc	α_{95}*	*k**	*D*/*I* atc	α_{95}*	*k**	*n*/*N*
DO	204/–13	9.5	65.1	211/–51	9.5	65.1	5/1
SK	211/–28	5	59.9	210/12	5	59.9	15/2

* — statistic parameters calculated for specimens component A mean, after 19% unfolding; $D = 208$, $I = -20$, pole: –43° lat. N, 341° long. E

D/*I* btc (atc) — declination/inclination of the ChRM before (after) tectonic correction; α_{95} , *k* — Fisher statistics parameters; lat. N — northern latitude; long. E — eastern longitude; parameters of the palaeomagnetic pole refer to the palaeomagnetic direction typed in bold font; *dp*, *dm* — semiaxes of the 95% confidence ellipse associated with the mean poles; *n* — number of specimens used for calculation of the mean direction; *N* — number of hand samples used for calculation of the mean direction

nent). The magnetised specimen is then subjected to thermal demagnetisation and the intensity decay of each component is plotted separately. The hard component is carried either by goethite (unblocking temperature $T_{ub} < 150°C$) or haematite ($T_{ub} > 600°C$). Soft and intermediate components are usually related to magnetite (T_{ub} between 450 and 580°C), titanomagnetite (any T_{ub} between room temperature and 580°C), maghemite (T_{ub} between 300 and 350°C related to transformation of maghemite to haematite) and pyrrhotite (T_{ub} between 300 and 325°C). The results of the method are sometimes ambiguous, because unblocking temperatures are dependant on grain size or titanium content of magnetite and haematite, thus very fine-grained magnetite could reveal the same unblocking temperature as titanomagnetite.

The analysis of AMS is now a widely used method for studying petrofabrics (see Tarling and Hrouda, 1993; Borradaile and Henry, 1997). It reflects the preferred orientation of dia-, para- and ferromagnetic grains. Geometrically the AMS is represented as an ellipsoid the three axes of which characterise values of maximum ($K1$), intermediate ($K2$) and minimum susceptibility ($K3$). The following parameters characterise the AMS ellipsoid:

1 — mean susceptibility $K_m = (K1 + K2 + K3)/3$ calculated for normalised volume 10 cm^3, in 10^{-6} SI units;

2 — parameters defining the shape of the anisotropy ellipsoid: lineation $L = K1/K2$ and foliation $F = K2/K3$. The ellipsoid is prolate if $L > F$ and oblate if $F > L$;

3 — degree of anisotropy $P' = \exp\{2[(\eta_1 - \eta)^2 + (\eta_2 - \eta)^2 + (\eta_3 - \eta)^2]\}^{1/2}$

where: $\eta_1 = \ln K1$; $\eta_2 = \ln K2$; $\eta_3 = \ln K3$; $\eta = (\eta_1 + \eta_2 + \eta_3)/3$;

4 — the shape parameter $T = 2(\eta_2 - \eta_3)/(\eta_1 - \eta_3) - 1$.

The values of *T* are between 0 and 1 if the AMS ellipsoid is oblate (foliation prevails) and between –1 and 0 if the AMS ellipsoid is prolate (lineation prevails).

In undeformed sediments the *K*3 axes are directed perpendicular to the bedding while *K*1 axes are either randomly oriented or indicate the direction of palaeocurrent flow. Such magnetic fabric is called **depositional** or **sedimentary**. In deformed rocks the AMS ellipsoid is quite often co-axial with the finite strain ellipsoid. This makes AMS a useful tool for investigating internal deformation of the rock structure. In most weakly deformed sediments, magnetic fabric reflects mostly the effects of compaction — the *K*3 axes are still perpendicular to the bedding, *K*1 axes cluster parallel to the tectonic stretching direction and the $T > 0$. This kind of fabric is called **relict sedimentary fabric** (Borradaile and Henry, 1997). As deformation increases the **deformational magnetic fabrics** develop. The AMS ellipsoid becomes more prolate (*T* decreases) and subsequently foliation poles create a girdle perpendicular to the lineation direction. Further increase in deformation results in clustering of *K*3 axes perpendicular to cleavage, while *K*1 and *K*2 axes lie within the cleavage plane. The scheme is valid for normal magnetic fabric. In carbonate rocks an inverse

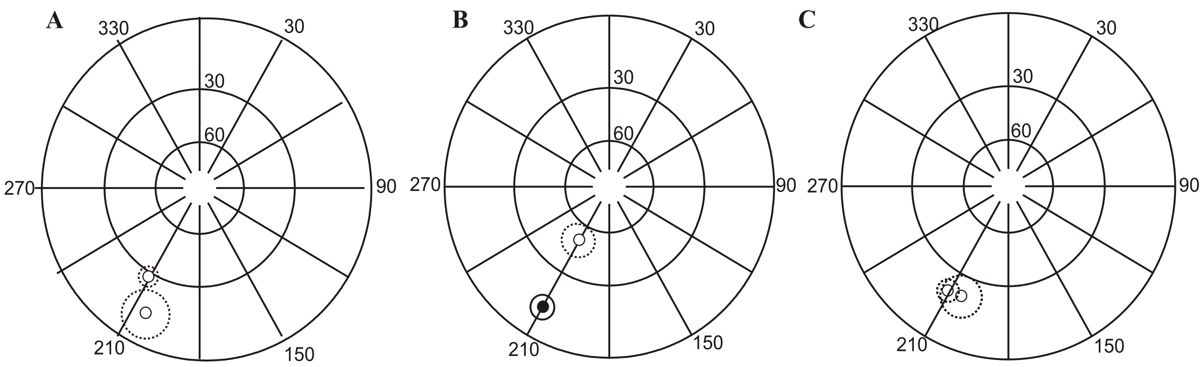

Fig. 6. Fold test for the high temperature component A from localities DO and SK; **A** — before tectonic correction, **B** — after tectonic correction, **C** — after 19% unfolding; note the syn-folding nature of the component; ovals of 95% confidence are indicated around each direction

Other explanations as in Fig. 4

or intermediate tectonic fabric sometimes occurs (Rochette, 1988; Rochette *et al*., 1992). The *K*1 and *K*3, *K*2 and *K*3 or *K*1 and *K*2 axes might exchange their positions due to mineralogical effects and not tectonic deformations. This is commonly reported from carbonate rocks and may arise from a magnetic fabric related to iron bearing carbonate minerals (ferroan calcite or dolomite) and single domain magnetite. An intermediate fabric might be observed when a mixture of minerals with normal and inverse magnetic fabric occur in the rocks, for example multi-domain (MD) and single-domain (SD) magnetite. An inverse or intermediate nature of magnetic fabric must be taken into account while interpreting the AMS data.

RESULTS

CHARACTERISTIC COMPONENTS AND FOLD TESTS

Initial NRM intensities range between 0.55 and 47 x 10^{-4} A/m. The intensities were lower in light limestones (between 1 and 3 x 10^{-4} A/m) and higher in dark carbonates and those containing a reddish pigment (generally close to 10^{-3} A/m or more). Thermal demagnetisation was applied to the entire collection. In all samples a low temperature characteristic remanent magnetisation (ChRM) occurred which was unblocked between 250 and 350°C (Fig. 3). It is exclusively of normal polarity and its direction is very similar to the present day field direction. Therefore it is most probably a recent viscous remanent magnetisation of no palaeomagnetic importance. Afterwards, in 90% of the collection, a well defined component appeared which was unblocked between 350 and 450°C (Fig. 3A1, B–E).The component clusters well within a single locality (Tab. 2, Figs. 4 and 5). However, the directions between localities are dispersed before as well as after tectonic correction. Therefore the magnetisation from each locality is treated as a separate component (Tab. 2).

About 10% of the collection revealed different behaviour during demagnetisation. After unblocking of the viscous overprint a hard component A appeared which was stable up to 610–630°C. It occurred in one sample from locality DO (Fig. 3A2), in two samples from locality SK and some cores from locality ZC. In the latter locality, a stable end point was not reached during thermal demagnetisation, probably because of overlapping blocking temperature spectra of two anti-parallel magnetisations.

A McFadden's (1990) fold test reveals, that the best clustering of component A is obtained after 19% unfolding of both limbs of the syncline (Fig. 6) thus component A reveals a syn-folding geometry. A fold test for the components with an unblocking temperature range of 350–450°C could be applied only for locality MG. Also, there, the best cluster of directions (maximum value of the parameter *k*) occurs after 26% of unfolding (Fig. 5). Both tests are significant at the 95% confidence level. It is difficult to speculate about the age of components DO, JO, ZC and SK because fold tests could not be applied within these localities. Their age must be inferred from geological constraints and comparison with the APWP of EEC and Variscan Europe.

MAGNETIC CARRIERS AND ANISOTROPY OF MAGNETIC SUSCEPTIBILITY (AMS)

Low minerals prevail in the samples where components occur with unblocking temperatures of 350–450°C of syn-folding or undefined age (Fig. 7A1, B1 — IRM acquisition curves reveal rapid saturation of the specimens). High coercivity minerals are of minor importance. The maximum unblocking temperatures of 500–550°C, obtained during thermal demagnetisation of the 3 axes IRM (Fig. 7A2, B2) are indicative of magnetite.

Rock magnetic properties of the samples that revealed hard component A are different. High coercivity minerals constitute the majority of the magnetic fraction (Fig. 7C1). Haematite with a maximum unblocking temperature of 650°C is the most important magnetic mineral in sample DO7 (Fig. 7C2), with a minor contribution of a magnetic phase with an unblocking temperature of 500–550°C. Component A in this sample (Fig. 3A2) is undisputably carried by haematite.

The magnetic fabric in dolomites from the localities SK, ZC, DO and JO is poorly developed and is not discussed here. The dark limestones from locality MG reveal mostly a sedimentary/compactional magnetic fabric with *K*3 axes mostly a perpendicular to the bedding (Fig. 8A). The anisotropy degree *P*' is always less than 10%. Mean susceptibility values are no

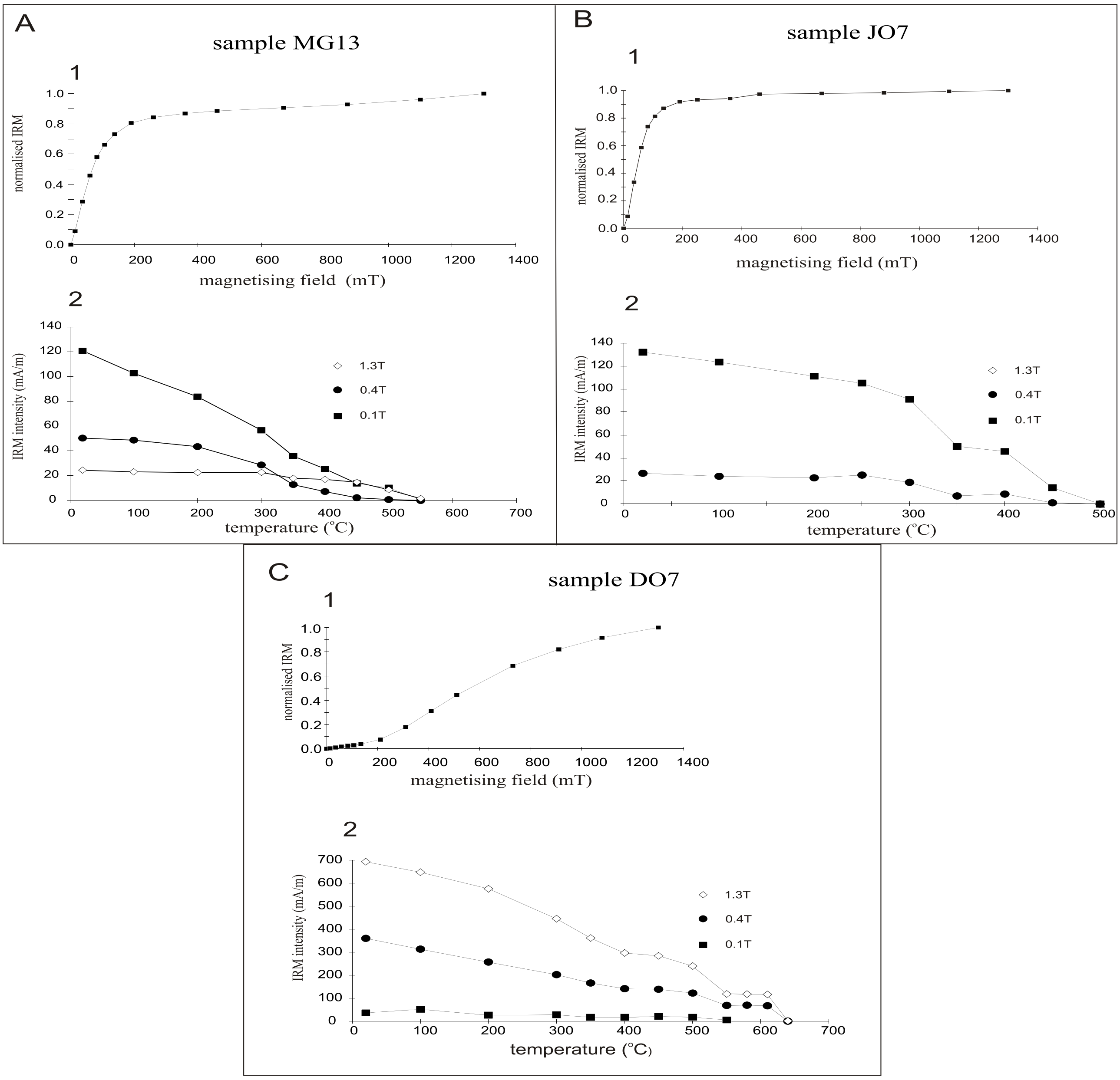

Fig. 7. IRM properties of representative specimens: 1 — IRM acquisition curve; 2 — thermal demagnetisation of the 3 axis IRM (Lowrie, 1990); **A** — locality MG, dark limestone, **B** — locality JO, dark dolomite, **C** — locality DO, reddish dolomite

more than 100 x 10^{-6} SI units therefore its anisotropy could be related to a paramagnetic matrix. Magnetic foliation generally prevails (positive values of parameter *T* — see Fig. 8B). Lineation is also developed, preferentially along N–S and E–W directions which are sub-parallel and sub-perpendicular to the fold axes. This magnetic fabric accounts for the relatively weak internal deformation of the host rock (Borradaile and Henry, 1997). In two samples (MG12 and MG14) an anomalous magnetic fabric was observed with *K*2 and *K*1 axes at steep angles to the bedding (Fig. 8A). This might indicate either development of a secondary foliation plane, perpendicular to the bedding, or a mineralogical effect common in limestones (Rochette, 1988; Rochette *et al*., 1992), related to interchanging anisotropy axes due to the presence of an inverse magnetic fabric. The latter seems more likely, since the samples MG12 and MG14 were taken from beds that do not differ macroscopically from the neighbouring beds MG13 and MG15 which reveal a normal magnetic fabric.

DISCUSSION

PALAEOMAGNETIC DATA BASE FOR THE HOLY CROSS MTS. — A REVIEW

Before interpreting the new palaeomagnetic results obtained in this study, a brief comment on the existing palaeomagnetic data base from the HCM is necessary. The most reliable results (quality index $Q \geq 3$, see Van der Voo, 1993) are listed in Table 3 and plotted in Figure 9 against the reference APWP for Baltica (Torsvik *et al*., 1992, 1996). It should be noted that the interpre-

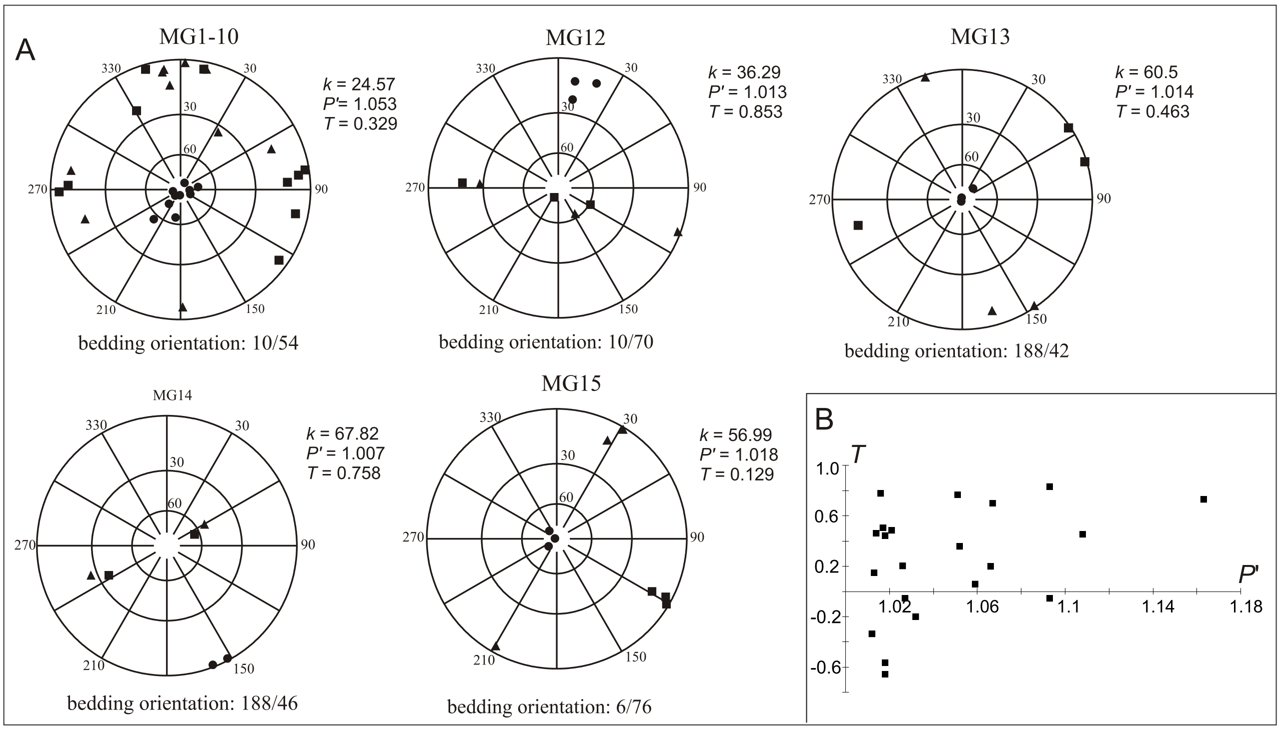

Fig. 8. Magnetic fabric at the locality MG

A — stereographic projection of the principal susceptibility axes (after tectonic correction); squares — maximum, triangles — intermediate, circles — minimum susceptibility axes, each stereogram denotes single site (MG1-10) or hand sample (MG12–15) with distinct bedding orientation; **B** — a plot of the shape parameter *T* and degree of anisotropy *P*’ for specimens revealing normal magnetic fabric (site MG1-10, MG13, MG15)

tation of these data is strongly dependent on the reliability of the reference APWP. The APWP of Torsvik *et al.* (*op. cit.*) is now widely used (e.g. Zwing and Bachtadse, 2000). Its Late Carboniferous and later segments are well documented. On the other hand the entire Mid to Late Devonian segment is an extrapolation between the Early Devonian palaeopoles from the Ukraine (Smethurst and Khramov, 1992) and Spitsbergen (Jeleńska and Lewandowski, 1986) and the Early Carboniferous poles from Spitsbergen (Watts, 1985). It is believed that the Early Carboniferous poles from Spitsbergen are representative for the EEC, because the Early Devonian and Permian palaeomagnetic poles from this area are fully convergent with those from the EEC (Nawrocki, 1999).

The palaeomagnetic data in Figure 9 indicate that, since the Late Carboniferous, only minor rotations in the HCM might disturb their position in relation to the EEC (see also Lewandowski, 1999). Late Palaeozoic remagnetisation, a well known phenomenon reported widely from North America (McCabe and Elmore, 1989) and Variscan Europe with its foreland (Edel and Coulon, 1984; Nowaczyk and Bleil, 1985; Thominski *et al.*, 1993; McCabe and Channell, 1994; Molina-Garza and Zijderveld, 1996) also affected both regions of the HCM. Secondary poles obtained in the Devonian and Carboniferous carbonates of the Kielce Unit (Tab. 3, entries 1–3) and Upper Cambrian clastics of the Łysogóry Unit (entries 8b, c) are situated roughly along the reference APWP. Some minor uncertainties and inconsequencies, however, still exist in their interpretation. For example palaeopole 8b from Wiśniówka, interpreted as pre-folding by Lewandowski (1993), seems to be younger than the post-folding palaeopole 8c from the same locality. Palaeopole 3, interpreted by Grabowski and Nawrocki (1996) as Early Permian remagnetisation, is slightly rotated from the reference APWP. This was interpreted as an effect of local tectonic rotation, which probably affected also palaeopole 2 (both localities are situated in neighbouring quarries) — that is why two alternative ages of the pole 2 are given in the Table 3.

Interpretation of pre-Late Carboniferous palaeomagnetic results is also a matter of serious debate. Investigations in the Łysogóry (Lewandowski *et al*., 1987; Lewandowski, 1993) apparently confirm the assumption that this block constituted a part of the EEC at least since the Silurian. Upper Cambrian and Lower Devonian quartzites (Tab. 3, entries 7–9) revealed stable pre-folding directions comparable with the palaeodirections expected for the EEC. This conclusion is still valid although the age of some poles given by Lewandowski (1993) is not exactly the same as the age interpreted from the APWP used here (e.g. the “Silurian” palaeopole 8a is very close to the Carboniferous segment of the APWP, while palaeopole 7 matches rather the inferred Late Devonian age). On the other hand the Early Devonian palaeopoles from the Kielce Unit (Tab. 3, entries 4 and 5) strongly deviate from the reference APWP of EEC. This was interpreted as evidence for large scale dextral strike-slip movement of the Kielce Unit along the SW margin of the EEC (Lewandowski, 1993) that took place between Emsian and Late Carboniferous times. However, the new palaeopole from the Silurian diabases of the Kielce Unit (Nawrocki, 2000; Tab. 3, entry 6b) fits well the coeval segment of the reference APWP for the EEC, indicating a relative stability of the Kielce Unit at least since Early Devo-

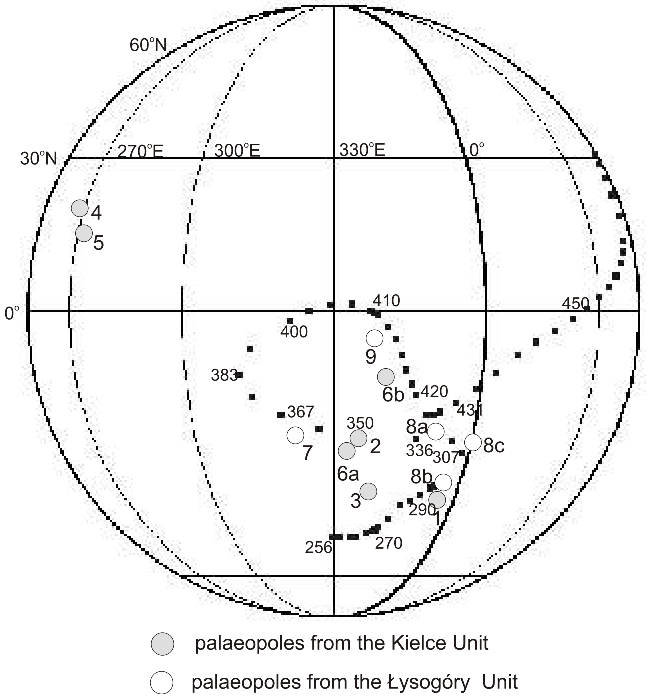

Fig. 9. Silurian-Late Carboniferous palaeomagnetic poles from the HCM (listed in the Tab. 3) at the background of the APWP for the EEC (after Torsvik *et al*., 1996); centre of projection 0°N, 330°E; age calibration of the APWP after Palmer's (1983) time scale

nian and thus setting serious constraints to more mobilistic interpretations.

AGE OF CHARACTERISTIC MAGNETISATIONS

All characteristic components obtained in this study are summarised in Table 2. Stereographic projection of characteristic directions is presented in Figure 10. An attempt at their dating might be performed by direct comparison with the existing APWP for Baltica (Torsvik *et al*., 1992, 1996). Palaeomagnetic poles are plotted against a background of the reference path (Fig. 11).

Palaeomagnetic poles of hard component A are situated on the Early Permian (280–260 Ma) segment of the APWP (Fig. 11). Therefore its age might be assigned to that time span. It confirms the results of previous palaeomagnetic studies which indicate that the Late Carboniferous and later palaeopoles from the HCM are situated close to the APWP of the EEP (Lewandowski, 1981, 1993, 1999; Nawrocki, 1984; Grabowski and Nawrocki, 1996).

The pole of the syn-folding MG component is located far from the Frasnian and younger poles (Fig. 11) and its interpretation is not straightforward. Its inclination is concordant with expected Early Permian (294–282 Ma) and Middle Devonian-Early Carboniferous (384–356 Ma) palaeoinclinations. However, an Early Permian age of component MG is hardly acceptable. This would imply a tectonic rotation by almost 40° after remagnetisation. As trends of Variscan folds in Mogiłki are roughly the same as in the other parts of the HCM (W–E to WNW–ESE) the post-Early Permian rotation of such magnitude must be excluded. Thus the Late Devonian-Early Carboniferous age of the MG component is favoured here (see next section for more discussion).

The component DO is most likely a pre-folding Early Carboniferous remagnetisation as could be inferred from the pole position (Fig. 11). Its post-folding age ($D = 50$, $I = -57$) cannot be accepted because this would situate the area in a high southerly latitude in the Late Paleozoic which does not agree with palaeomagnetic and facies data (e.g. Lewandowski, 1999). Components ZC, SK and JO should be considered as pre- or syn-folding Variscan (Eifelian-Visean). Were they post-folding or syn-folding younger than the Late Carboniferous, a large 70–90° clockwise rotation should be introduced in the Kielce and Łysogóry units after their acquisition. Abundant Late Palaeozoic palaeomagnetic data from the HCM (Lewandowski, 1981, 1993; Nawrocki, 1984; Grabowski and Nawrocki, 1996) as well as the position of palaeopole A, of presumed Early Permian age, on the APWP contradict this option.

Observations could be summarised as follows:

1. The syn-folding palaeopole A of the Early Permian age and pre-folding Early Carboniferous palaeopole DO are situated more or less on the predicted APWP.

2. Middle Devonian-Early Carboniferous palaeopoles MG, SK, JO and ZC of pre- or syn-folding origin are shifted to the NW from the Baltic APWP.

GEOLOGICAL CONSIDERATIONS

Remagnetisations of Early Permian age (component A) occur in the rocks containing significant amounts of haematite. Then it is very likely that these remagnetisations are related to

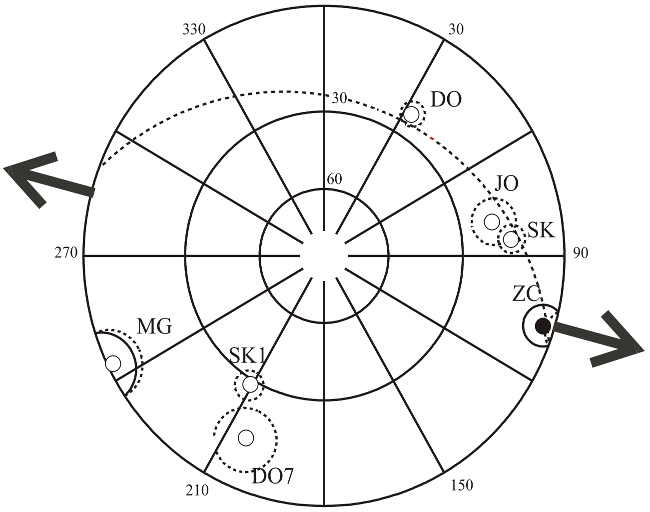

Fig. 10. Stereographic projection of characteristic components obtained in this study (after Tab. 3); arrows indicate the predominant direction of fold axes in the HCM; note the great circle distribution of components DO, JO, SK and ZC; 95% confidence ovals are indicated for each component; other explanations as in the Fig. 4

Table 3

Summary of the Late Silurian-Late Carboniferous palaeomagnetic data from the Holy Cross Mts.Palaeomagnetism of some Devonian carbonates from the Holy Cross Mts.

KIELCE UNIT (southern part of the HCM)

No.	Rock unit and locality	Pole		Age of pole (Ma)	Fold test	References
		lat. N	long. E			
1	C_1, limestone, Ostrówka	−38	355	315 (B)	not applied	Lewandowski (1985)
2	D_3, limestone, Kostomłoty	−24 −33	335 333	340–316 (B) 305 (B)	negative negative	Lewandowski (1981) Grabowski and Nawrocki (1996)
3	D_2, dolomite, Laskowa	−36	338	300 (B)	not applied	Grabowski and Nawrocki (1996)
4	D_1, quartzite, Świnia	20	267	385 (A)	not applied	Lewandowski (1993)
5	D_1, quartzite Poręba	15	272	385 (A)	not applied	Lewandowski (1993)
6a	S_2, diabase, Zalesie and Pragowice	27	333	350–340 (A)	not applied	Nawrocki (2000)
6b	S_2, diabase, Zalesie	−12	340	420 (A)	positive	Nawrocki (2000)

ŁYSOGÓRY UNIT (northern part of the HCM)

No.	Rock unit and locality	Pole		Age of pole (Ma)	Fold test	References
		lat. N	long. E			
7	D_1, quartzite, Bukowa	−24	322	380 (A)	not applied	Lewandowski *et al.* (1987)
8a	Cm_3, quartzite, Wiśniówka	−23	351	420 (A)	positive	Lewandowski (1993)
8b	Cm_3, quartzite, Wiśniówka	−34	156	320 (A)	not applied	Lewandowski (1993)
8c	Cm_3, quartzite, Wiśniówka	−26	0	300 (B)	negative	Lewandowski (1993)
9	Cm_3, quartzite, Wąworków	−5	338	410 (A)	not applied	Lewandowski (1993)

Cm_3 — Upper Cambrian, S_2 — Upper Silurian, D_1, D_2, D_3 — (Lower, Middle and Upper) Devonian, C_1— Lower Carboniferous; indexes A and B indicate if the magnetisation is interpreted as pre-folding (A) or post-folding (B); numbering of localities refers to Fig. 2

an increase in Eh caused by migration of oxidising fluids or subaerial exposure of the rocks after the Variscan orogeny. Apparently older directions are encountered in dark rocks with magnetite which were not subjected to extensive oxidation. The syn-folding origin of the component A implies a steepening of dips in the Bodzentyn Syncline that might have taken place after the Early Permian, probably during the Alpine uplift of the HCM in the Maastrichtian-Paleocene (Kutek and Głazek, 1972; Lamarche *et al.*, 1999 and references therein). The conclusion about Alpine modification of Variscan structures in the Łysogóry Unit must be treated as preliminary, since the palaeomagnetic evidence is based on three hand samples only. Nevertheless it requires some attention because Alpine involvement of the Palaeozoic basement of the HCM has already been postulated (Kutek and Głazek, 1972; Lamarche *et al.*, 2000).

The interpretation of the magnetite-related component is somewhat ambiguous. A problem arises from the apparent syn-folding age of the MG component. As already pointed out, it does not fall on the Carboniferous segment of the APWP, as should be expected from the presumed Visean/Namurian age of the Variscan folding in the HCM, but is located near the inferred date 383–375 Ma (Eifelian-Givetian). On the other hand post-folding magnetisations of Late Carboniferous age in the Kostomłoty (Tab. 3, entry 2) and pre-folding DO component fit quite well to the reference APWP. Pre-folding components concordant with the Late Silurian and Early Carboniferous directions of the EEC were reported also from Silurian diabases in the Kielce Unit (Nawrocki, 2000; Tab. 3, entries 6a, b).

A possible explanation for anomalous position of the MG pole might be that the locality was affected by local tectonic rotation. Earlier palaeomagnetic studies of the area adjacent to local-

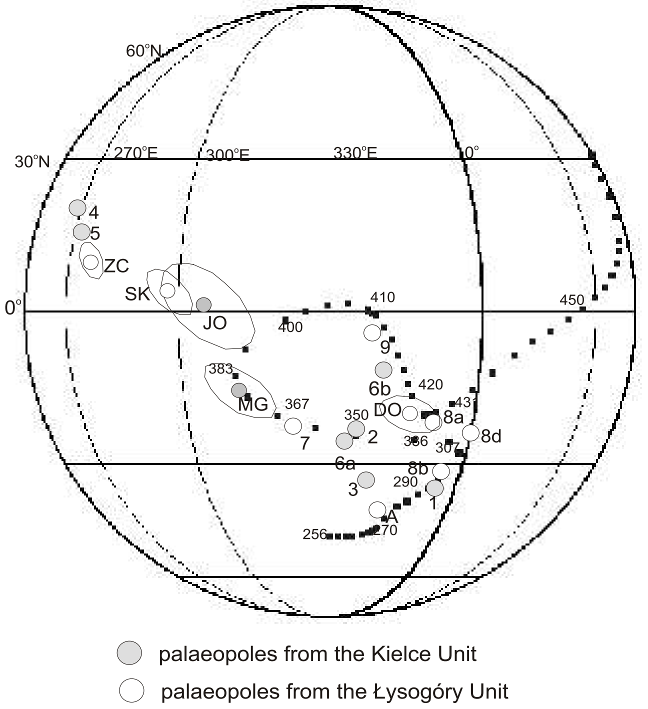

Fig. 11. Palaeomagnetic poles of characteristic components obtained in this study (after Tab. 2) and other poles from the HCM (listed in the Tab. 3) at the background of the APWP for the EEP (after Torsvik *et al*., 1996); centre of projection 0°N, 330°E; age calibration of the APWP after Palmer's (1983) time scale

ity MG, in the NW part of the Kielce Unit (Kostomłoty and Laskowa quarries) (Grabowski and Nawrocki, 1996; Tab. 3, entries 2 and 3) indicated the possibility of local post-Variscan clockwise rotations of magnitude *ca.* 13° (20° if compared with the reference APWP applied here). Indeed the MG palaeopole might be matched with the reference path after 16–23° rotation dating at 358–350 Ma (Tournaisian/Viséan). This date might be interpreted as the onset of Variscan folding in this locality. It would imply significant diachronism of folding between locality MG (NW part of the Kielce Unit) and DO (northern part of the Łysogóry Unit). In the latter locality the pre-folding ChRM might be dated as 335 Ma old (Late Viséan). The possibility of diachronous Variscan folding in the HCM has already been suggested by Lewandowski (1997). However, because the entire Late Devonian-Early Carboniferous segment of the reference APWP is poorly constrained, the considerations above are no more than speculations to be tested by more extensive studies.

Rotation of magnetic minerals due to internal deformation of host rocks might be an alternative interpretation of the MG component. Strain was reported to be a factor affecting the characteristic magnetisation in some Permo-Triassic red beds in the Swiss Alps at the Glarus overthrust (Hirt *et al*., 1986), in the Silurian Bloomsburg Formation (Stamatakos and Kodama, 1991*a*) and Mississipian Mauch Chunk Formation in the Appalachians (Stamatakos and Kodama, 1991*b*). Strong suspicion of strain modified palaeomagnetic directions was also suggested for some sites in the Lower Old Red Sandstone of southern Wales (Setiabudidaya *et al*., 1994; Kirker and McClelland, 1997). Molina-Garza and Zijderveld (1996) described a syn-folding magnetisation from Devonian red beds in Belgium. Its pole (long. 302°E, lat. 19°S) is surprisingly close to the MG pole. They rejected this direction as an artefact of remanence acquisition or deformation processes. In studies of Appalachian red beds, Stamatakos and Kodama (1991*a*, *b*) proved that the pre-folding characteristic magnetisation was reoriented during deformation and mimicked the apparent syn-folding magnetisation. Zwart and Oele (1966) observed, in phyllites, magnetite grains that had been mechanically rotated due to tectonic stress. It might be that the same mechanisms could have disturbed the magnetisation at locality MG. This hypothesis is not supported by the AMS studies. Investigations of magnetic fabric in most samples revealed apparently low degrees of internal deformation. However, it is not certain whether preservation of the "primary" (presumably paramagnetic) fabric definitely implies that ferromagnetic minerals were not affected by stress. The hypothesis of strain modification is not likely in the case of syn-folding component A of Early Permian age because the Alpine deformations of Palaeozoic rocks were much weaker than those of the Variscan.

Palaeopoles of the ZC, SK and JO components are situated far from the reference APWP. However, they fill the gap between the rotated, presumably Early Devonian palaeopoles of Lewandowski (1993) from the Kielce Unit (Tab. 3, entries 4 and 5, Fig. 11) and non-rotated post-folding remagnetisations in both HCM units (Fig. 11). They might be interpreted in two ways. First, they might reflect local tectonic rotation. We do not favour here the model of dextral strike-slip movement of the entire HCM or of its southern part along the EEC margin (Lewandowski, 1993) because of the occurrence of non-rotated pre-folding directions of Early Carboniferous or earlier age, isolated in both regions of the HCM (Tab. 3, entries 6–9, palaeopole DO — this work). The rotations that affected the localities SK and ZC (possibly also JO) must have taken place between the Middle-Late Devonian and Early Permian. A post-folding non-rotated Early Permian component is documented in the localities SK and DO in this paper (component A), while Lower Triassic strata unconformably overlying dolomites at locality ZC also yielded a primary component concordant with the reference APWP (Nawrocki and Kuleta, pers. comm.). This implies that a possible Alpine age of tectonic rotation must be excluded. In almost all localities (except JO) the bedding strike is concordant with the general trend of Variscan structures in the HCM (WNW–ESE) so, it is very unlikely that these rotation were younger than Variscan folding in the area. The lower age limit for the rotation is not certain, because it is not known if the components are pre- or syn-folding. Nevertheless a rotation between 40–60° is required to match the pre-folding palaeopoles ZC, SK and JO with the reference APWP. Up till now, no structural evidences for such pre-folding rotations of Middle-Upper Devonian rocks are known.

Alternatively, the SK, JO and ZC components might be strain modified or resultant directions. A peculiar feature of these components is the stepwise shallowing of their inclinations towards the WNW–ESE which is the direction of the local fold axes (Fig. 10). Together with component DO they form a perfect great circle. This might be interpreted either as stepwise rotation of the palaeomagnetic vector towards the tectonic stretching direction or an effect of the distribution of resultant vectors between two anti-parallel components similar to DO.

CONCLUSIONS

Syn-folding haematite-related palaeomagnetic directions are of Early Permian age. They confirm the presence of extensive post-Variscan remagnetisation in the HCM and the possibility of slight modification of some Variscan folds during Alpine uplift of the HCM.

Definite tectonic interpretation of some Devonian and Early Carboniferous palaeomagnetic directions from the Devonian carbonates in the HCM is not possible. The palaeomagnetic data apparently indicate large tectonic rotations of pre-Early Permian age in both regions of the HCM, but no structural data exist to support this conclusion. Alternatively, palaeomagnetic directions might be interpreted as strain modified or resultant vectors.

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