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New palaeomagnetic data from the Palaeozoic carbonates of the Moravo-Silesian Zone (Czech Republic): evidence for a timing and origin of the late Variscan remagnetization

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Palaeomagnetic studies were carried out in the Devonian–Early Carboniferous carbonates of the Moravo-Silesian Zone — MSZ (Czech Republic) in order to evaluate the timing and origin of late Variscan magnetic overprinting. Sampling localities were spread out along the strike of the MSZ from the SW to NE. Previously published thermal maturity data have demonstrated a significant gradient from SW (burial temperatures 150–200°C) to NE of the region (250–300°C). A late Variscan remagnetization direction (component A), carried by magnetite, was identified in 6 localities. Three phases of the remagnetization in the MSZ might be distinguished which might be assigned to Early to Late Carboniferous, Late Carboniferous and Early Permian. They are coeval with remagnetization events distinguished in Ardennes. A correlation exists between thermal indices and unblocking temperature spectra of component A. Thermal activation nomograms show that component A might be either a thermoviscous or thermochemical remanent magnetization acquired due to a thermal event (deep burial) of 1–10 My duration and stabilized during subsequent uplift. A more ancient component B, identified in the SW part, previously interpreted as primary, is shown to be a synfolding remagnetisation. It indicates 70° clockwise rotations before the acquisition of the component A .

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Keywords: Czech Republic, Moravo-Silesian Zone, palaeomagnetism, remagnetization.

INTRODUCTION

Secondary magnetizations of variable age (pre-, syn- and post-folding) are the typical features of orogenic belts. They are, however, widely used for palaeotectonic reconstructions of mobile belts (e.g., Parés *et al*., 1994; Van der Voo *et al*., 1997; Márton *et al*., 2000; Szaniawski *et al*., 2003; Villalaìn *et al*., 2003). Investigations performed in the Moravo-Silesian Zone more than 10 years ago (Krs and Pruner, 1995; Tait *et al*., 1996) proved a strong late Variscan remagnetization of the Devonian carbonate rocks. It was claimed that the remagnetization took place when the Variscan tectonic structures existed in their present shape. The palaeopoles were roughly concordant with the Late Carboniferous–Permian sector of the European apparent polar wander path (APWP). In some localities Krs and Pruner (1995) and Tait *et al*. (1996) identified another direction which they interpreted as a primary Devonian magnetization. The direction of this magnetization indicates large clockwise tectonic rotations of the area during the Variscan orogeny (Hladil, 1995). Tait *et al.* (1996) interpreted it as evidence for an oroclinal bending around the NE flank of the Bohemian Massif. The orocline hypothesis was questioned by Edel *et al.* (2003) who argued that during the Devonian and Early Carboniferous, the Bohemian Massif was too weakly consolidated to act as an indenter, and to deform sedimentary formations in its direct foreland. Moreover, relatively high thermal maturities of the Moravo-Silesian Devonian (Krs *et al.,* 1995, palaeotemperatures 250–300°C) indicate that preservation of a primary magnetization is rather unlikely in magnetite-bearing rocks. In this paper, we present new palaeomagnetic data bringing more constraints for timing of the late Variscan remagnetization and a nature of the “primary” magnetizations in the carbonate rocks of the Moravo-Silesian Zone.

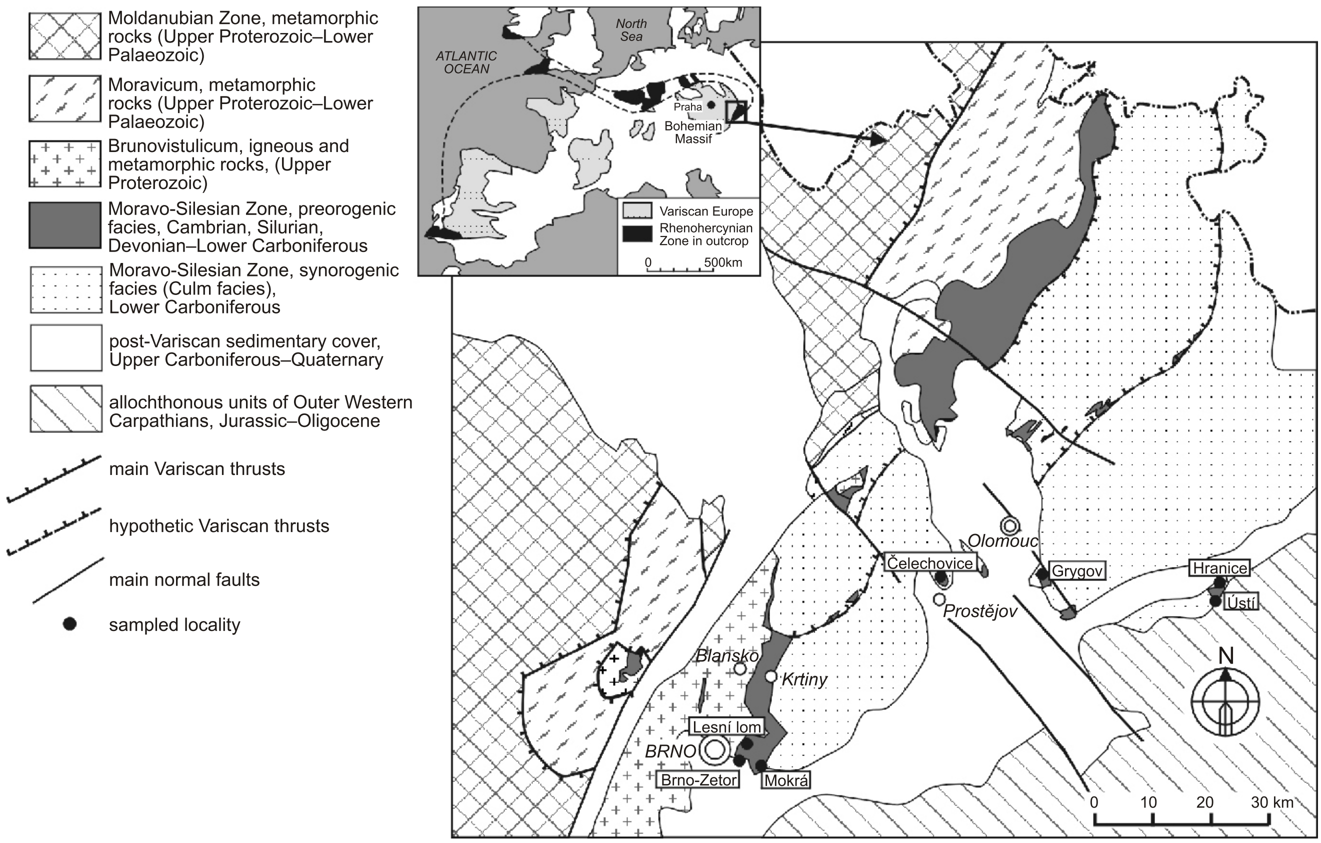


Fig. 1. Structural sketch map of the Moravo-Silesian Zone and adjacent areas, with sampling localities indicated

Insert in the upper left — location of the Moravo-Silesian Zone in the European Variscides

GEOLOGICAL SETTING

The Moravo-Silesian Zone (MSZ) is located at the eastern margin of the Bohemian Massif (Fig. 1), in the eastward extension of the Rhenohercynian and Subvariscan zones of the European Variscides (Dvořák and Paproth, 1969; Franke, 1995). To the west, the MSZ is bordered by Variscan crystalline nappes along the Moravo-Silesian Fault Zone (Schulmann *et al.*, 1991). To the east, it is covered by Mesozoic and Tertiary sediments of the Outer Western Carpathians. In the north, the MSZ extends to the Hamburg–Cracow Fault Zone in Southern Poland (Kalvoda *et al.*, 2003).

Rock successions of the MSZ can be divided into preorogenic and synorogenic facies. The preorogenic facies of Pragian to Viséan age were deposited during the extensional phase of the Moravo-Silesian Basin, a precursor of the MSZ (Ziegler, 1988; Franke, 1989; Hladil, 1994). The extension led to tectonic differentiation of the basin fill into the shelf part located to the east and the basinal part located to the west (Chlupáč, 1965, 1988; Hladil, 1994). The shelf part (so-called Moravian Karst facies domain) comprises a succession of rocks of Middle Devonian (Eifelian) to Early Carboniferous (Viséan) age (Fig. 2). These are terrigenous and shallow-marine siliciclastics, coral-stromatoporoid platform carbonates (Macocha Formation) and deep-water nodular limestones, calciturbidites and shales (Líšeň Fm.). The basinal part (so-called Drahany and Vrbno facies domains) comprises a succession of sandstones, fossiliferous shales, crinoidal limestones, carbonate turbidites, shales, radiolarian cherts and alkali- to subalkali basalts and basaltic tuffs of Early Devonian (Pragian) to Early Carboniferous (Tournaisian) age. The synorogenic facies comprise rhythmic alteration of turbidite sandstones, siltstones, mudstones and conglomerates (the so-called Culm facies) deposited in an Early Viséan trench basin to late Viséan to early Namurian marine foreland basin (Kumpera and Martinec, 1995; Hartley and Otava, 2001). The synorogenic flysch pass gradually upward to Namurian and Westphalian paralic and continental coal-bearing cyclothems of the Upper Silesian Coal Basin, representing the final depositional phase in the evolution of the Moravo-Silesian Basin.

The MSZ is considered to represent a Palaeozoic accretionary wedge, which developed between the overriding nappe stack of the Moldanubian and Tepla–Barrandian units, and the subducted Brunovistulian crystalline basement (Dallmeyer *et al.*, 1992; Fritz and Neubauer, 1995; Chadima *et al.*, 2006). Structure of the MSZ is interpreted as an imbricate stack of NW-dipping tectonic slices (Cháb, 1986; Čížek and Tomek, 1991; Bábek *et al.*, 2006). The main folding and thrusting events took place in the Late Carboniferous, most probably close to the Westphalian/Stephanian boundary ("Asturian phase").

There is a wide database of thermal-maturity data from the MSZ, including vitrinite reflectance, illite crystallinity and conodont colour alteration data (Dvořák and Wolf, 1979; Belka, 1993; Dvořák *et al.*, 1997; Franců *et al.*, 1999, 2002; Bábek and Franců, 2006). Two regional trends could be recog-

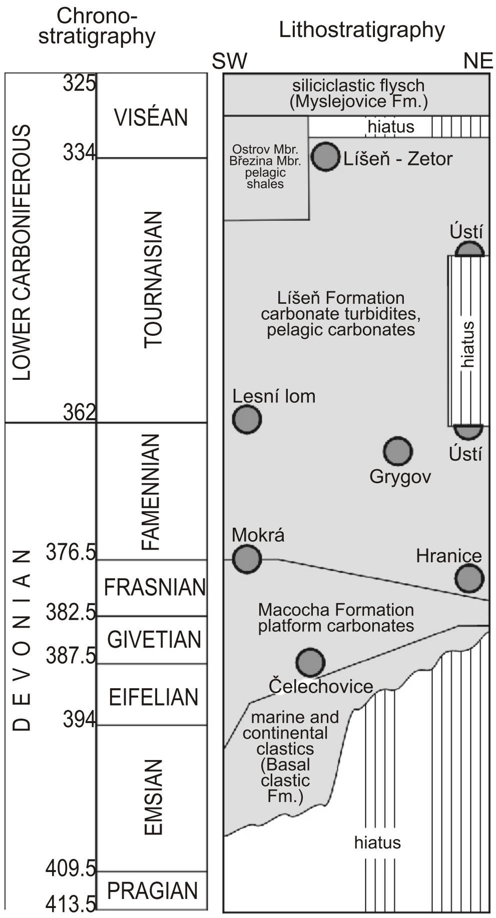


Fig. 2. Stratigraphical scheme of the Devonian and Lower Carboniferous in the Moravo-Silesian Zone

nized in the data. First, a to SE-to-NW trend of increasing thermal maturation is observed, from the outer to inner parts of the MSZ (Fig. 3A). To the SE of Brno (in the subsurface of the Western Carpathians in Moravia), the thermal overprint is relatively low, reaching dry-gas/oil-window zone (temperatures from 100 to 200°C). In the NW part of the MSZ in Moravia, the thermal maturity is much higher, reaching up to the anchimetamorphic grade (temperatures up to 330°C). The distribution of the R_r and illite crystallinity was explained in a model of a deep, mainly tectonically driven burial with lower heat flow in the inner part of the orogen and relatively shallow sedimentary burial with equal or slightly higher heat flow in the E foreland of the basin (Franců *et al*., 2002). However another trend seems to be observed along the strike of the orogen, from SW to NE: carbonates of the Brno area (SW) seem to be less heated (150 to 200°C) than the Olomouc region (probably more than 300°C, see Fig. 3B). The peak thermal maturation in the Moravia was achieved during the Late Carboniferous to earliest Permian (~300–310 Ma; Maluski *et al*., 1995). Isotherms in the thermal maturation maps cut across the Variscan fold-and-thrust structures, so they are younger than or synchronous to the Variscan deformation (~Westphalian). As there is a distinct outward-decreasing metamorphism in the whole Variscan orogen in Moravia including the thermal alteration of the MSZ (Franců *et al*., 2002), the source of heat must have been due to Variscan orogeny and not later. Analysis of late Variscan syntectonic calcite veins from the Brno area indicates vein formation from fluids of 120 to 170°C at a depth between 2.1 to 3.2 km, according to fluid inclusions data (Slobodník, 2002; Slobodník *et al*., 2006).

Table 1

Geological data for the sampled localities

Locality Geogr. coordinates	Lithology	Age	Microfacies	Thermal alteration
Hranice 49°33′7.10′′N; 17°45′58.45′′E	limestone, thin-bedded	middle–upper Frasnian	packstone-grainstone, mixed shallow/deep water biota, turbidite origin	CAI: 5; IC: 0.2 T: ~250 to >300°C
Ústí 49°31′25.84′′N; 17°45′19.0′′E	limestone, nodular and thick-bedded	upper Famennian to upper Tournaisian	pelagic lime mudstone, wackestone; grainstone with mixed shallow/deep water biota	CAI: 5; T: ~250 to >300°C
Grygov 49°31′41.78′′N; 17°18′55.5′′E	limestone, thick-bedded	upper Famennian	packstone/grainstone, mixed shallow/deep water biota, grain-flow origin	CAI: 5 to 5.5; IC: 0.16 to 0.2 ; T: ~250 to >300°C
Čelechovice 49°31′54.9′′N; 17°5′9.86′′E	dolomite, limestone, thick-bedded	upper Eifelian/lower Givetian	coarse crystalline dolomite, subordinately lime mudstone, algal lamination, fenestral fabric	CAI: 5; T: </~ 300°C
Lesní lom 49°13′17.77′′N; 16°41′38.88′′E	limestone, thin-bedded	Famennian–lower Tournaisian	grainstone-packstone, shallow water biota, turbidite origin	CAI: 3.5 to 4; IC: 0.72 °2 T: ~150 to 200°C
Zetor 49°11′41.85′′N; 16°41′33.83′′E	limestone, thin-to thick bedded	upper Tournaisian to middle Viséan	wacke/packstone, shallow water biota, turbidite origin	CAI: 3.5 to 4; T: ~150 to 200°C
Mokrá 49°13′57.47′′N; 16°45′20.20′′E	limestone, thick-bedded and nodular	upper Frasnian to upper Fammenian	peritidal limestones (wacke/packstone, fenestral fabric, algal lamination) passing upwards into deep subtidal/pelagic lime mudstones	CAI 3.5 to 4; R_r: 1.38 to 1.5%; T: ~150 to ~200°C

CAI — Conodont Alteration Index; IC — Illite Crystallinity; R_r — vitrinite reflectance; T — maximum burial temperature estimated form thermal indexes

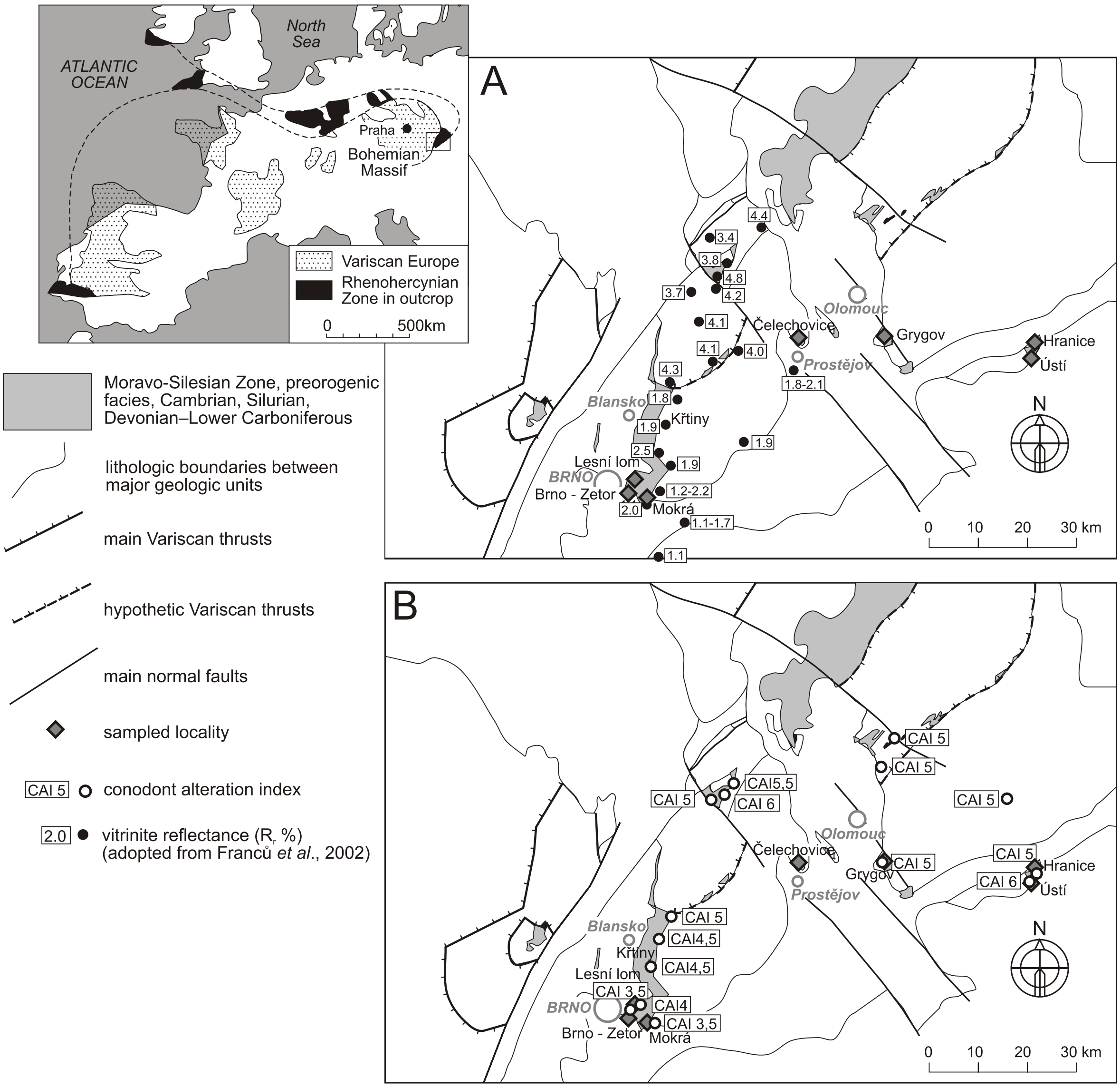


Fig. 3. Thermal maturity data in the Moravo-Silesian Zone: vitrinite reflectance (A) and CAI indexes (B)

SAMPLING AND METHODS

39 hand samples and 52 drill cores taken with a gasoline powered drill were collected from 7 localities (Table 1). They were distributed along the strike of the MSZ structures, from the SW (Brno area) to NE (Olomouc area) and further to E, up to the Carpathian overthrust (Figs. 1 and 3). The localities were either active (Hranice, Mokrá) or abandoned quarries. The rocks sampled were predominantly shallow-water limestones of the Macocha and and pelagic limestones of the Líšeň Formation (Fig. 2). Dolomitic rocks (Macocha Fm.) were sampled in the abandoned quarry at Čelechovice (Fig. 1). More detailed litho- and chronostratigraphic data are included in the Figure 2. Thin sections were prepared from representative samples from each locality, in order to evaluate microfacies, mineralization, and internal deformations. Ductile deformation in northeasterly localities (Hranice, Ústí, Grygov) can be inferred from curved twin lamellae in sparry calcite, sheared peloids and deformation of conodont elements. Rocks from localities Čelechovice and Lesní lom are not internally deformed as can be seen in the microscope. Localites Čelechovice and Mokrá were studied palaeomagnetically by Krs and Pruner (1995; see Table 2).

Natural remanent magnetisation (NRM) was measured with a *JR-5* spinner magnetometer (AGICO, Brno; noise level 10^{-5} A/m) in the palaeomagnetic laboratory of Polish Geological Institute (PGI) in Warsaw. Samples were demagnetised thermally using the non-magnetic oven MMTD (Magnetic

Table 2

Palaeomagnetic results from the localities Čelechovice and Mokrá (after Krs and Pruner, 1995)

Locality	component	D	I	α_{95}	k	Dc	Ic	α_{95}	k
Čelechovice	A	222	10	6	68	222	3	6	67
	B	107	–41	11	45	105	–33	10	59
Mokrá	A	214	2	3	60	no data			

D/I — declination/inclination before tectonic correction; Dc/Ic — declination/inclination after tectonic correction; α_{95}, k — Fisher statistics parameters

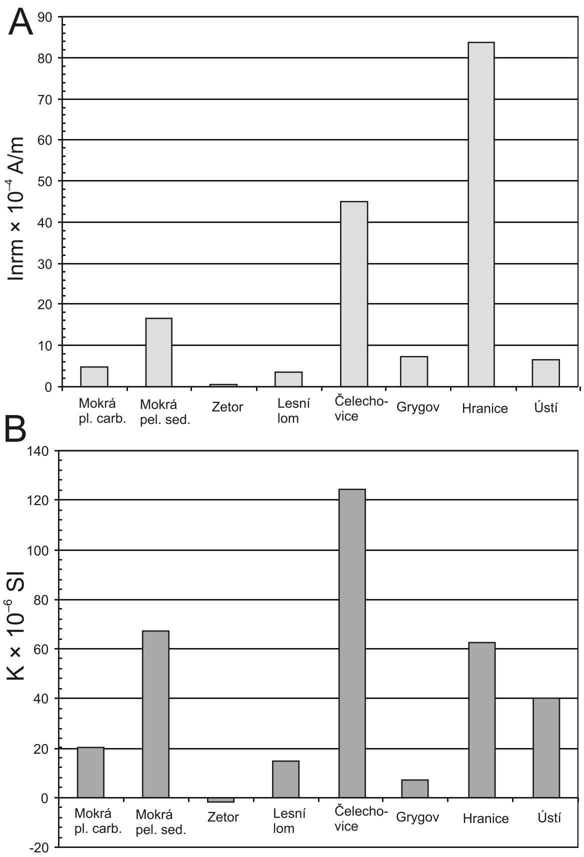


Fig. 4. NRM intensities (A) and bulk susceptibility data (B) in the studied localities

pl.carb — platform carbonates; pel. sed.— pelagic sediments

Measurements, UK, rest field <10 nT). The NRM measurements and demagnetisation experiments were carried in the magnetically shielded space (a low-field cage, Magnetic Measurements, UK, which reduces the ambient geomagnetic field by about 95%). Magnetic susceptibility was monitored with a KLY-2 bridge (AGICO, Brno; sensitivity 10^{-8} SI units) after each thermal demagnetisation step. Characteristic remanence magnetisation (ChRM) directions were calculated by principal component analysis (Kirschvink, 1980) using the PALMAG package of Lewandowski *et al.* (1997). Mean directions were calculated at the sample level (usually three specimens) and then sample means were used for calculation of site or locality mean direction. Fold tests were performed using the method of Watson and Enkin (1993). Rock magnetic studies included stepwise acquisition of the isothermal remanent magnetisation (IRM) and thermal demagnetisation of a composite IRMs acquired along 3 perpendicular axes (Lowrie, 1990). The IRM was imparted using the MMPM1 pulse magnetiser produced by Magnetic Measurements (UK). Palaeopoles and Apparent polar Wander Paths were plotted and constructed with GMAP softwere (Torsvik, 2002).

ROCK MAGNETISM

The rocks revealed quite a broad range of bulk susceptibility and NRM values. The highest NRM values of several mA/m were observed in Hranice and Čelechovice (Fig. 4A). Quite strong NRM intensities were found in the pelagic limestones in the Mokrá Quarry (site 6). In other localities, mean NRM values

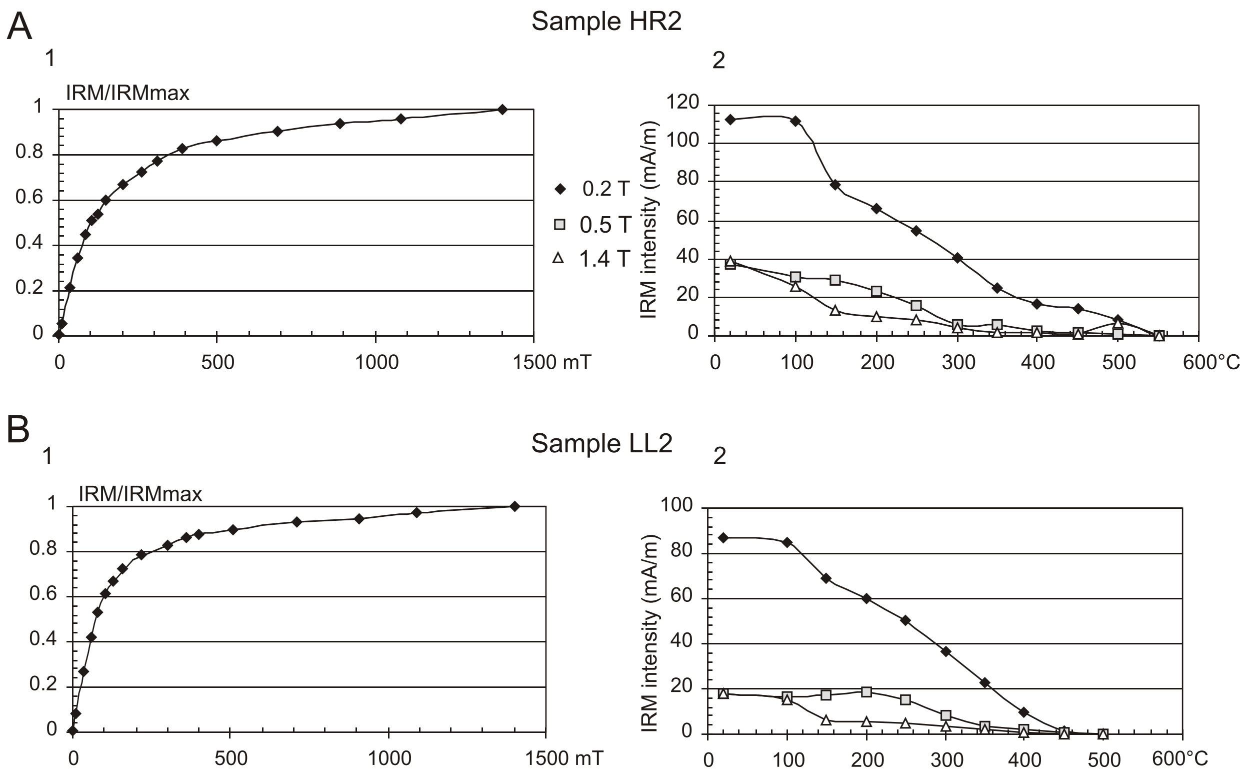


Fig. 5. Rock magnetic data of representative specimens

Locality Hranice (A) and Lesní lom (B); 1 — stepwise IRM acquisition; 2 — thermal demagnetization of the 3 axes IRM did not exceed 1 mA/m, and in Zetor, they were even below 0.1 mA/m.

The highest susceptibility values were revealed in dolomitised rocks at Čelechovice (well above 100 × 10^{-6} SI units) and in pelagic limestones at Mokrá (Fig. 4B).

IRM acquisition curves indicate that low and high coercivity minerals occur in the studied rocks: the saturation magnetization is not fully achieved in the fields as high as 1.4 T (Fig. 5), although a low coercivity fraction predominates. Three-axis thermal demagnetization reveals that the low coercivity fraction is magnetite, because maximum unblocking temperatures are between 500–580°C (Fig. 5). The medium coercivity fraction unblocks largely in the temperatures between 250 and 350°C, which might be interpreted as pyrrhotite. Presence of this mineral is not unlikely due to high thermal alterations (e.g., Rochette *et al*., 1992; Crouzet *et al*., 2003). Subordinate presence of pyrrhotite in the magnetite, dominated remagnetized Palaeozoic carbonates was recently reported by Zwing *et al.* (2005). A major kink in the demagnetization curve of the high coercivity fraction between 100 and 150°C indicates goethite which might be a product of recent weathering.

CHARACTERISTIC DIRECTIONS

The Devonian and Lower Carboniferous carbonates proved to be quite suitable rocks for palaeomagnetic studies. Only in Zetor the rocks were too weakly magnetized. Thermal demagnetization revealed the presence of a dominant component A in all localities (Table 3). The component was most strongly developed in Hranice. This was the only component of magnetization isolated in this locality. It was stable between 250 and 500°C (Fig. 6A). The component, in geographic coordinates, reveals SW declinations and equatorial inclinations (Fig. 7A). The Watson and Enkin (1993) fold test gave negative results, which indicates a post-folding age, at least in the site 2 (Table 3). The component A was documented also in other localities. The fold test could not be performed in Ústí, due to very small differences in the bedding attitude, however, the characteristic magnetization isolated between 200 and 450°C (Fig. 6B) was quite similar to that in Hranice (Fig. 7B). The same results were obtained in the rocks from Grygov (Figs. 6C and 7C), and Čelechovice, (Figs. 6D and 7D), where the fold

Table 3

Characteristic magnetizations — component A (this study)

Locality	Site	D/I	α_{95}	k	Dc/Ic	α_{95}	k	Palaeopole (long. E/ lat. N)	Dp/Dm	N/N_o
Hranice	Site 1	222/–3	10.5	78	221/1	10.5	78			4/4
	Site 2	216/4	5.1	92	214/5	13.4	13.9			10/10
	Combined	**218/2**	4.5	79	216/6	9.6	18	332/–30	2/4	14/14
Ústí	Site 1	214/–9	6.2	118	217/–24	6.2	118			6/9
	Site 2	212/–7	12.5	38	213/–26	12.5	38			5/5
	Site 3	215/–5	11.8	27	216/–26	11.8	27			7/7
	Combined	**214/–7**	5.2	45	216/–26	5.2	45	333/–36	3/5	18/21*
Grygov		216/–9	6.3	386	235/23	11.2	123	330/–36	3/6	3/3
Čelechovice		**213/12**	7.9	73	213/–10	9.8	47	339/–28	4/8	6/6
Lesní lom	Site 1	202/7	11.9	108	201/–24	16.6	56			3/3
	Site 2	206/–7	8.3	222	177/42	10.0	153			3/3
	Site 3	208/–2	–	–	209/–17	–	–			1/4
	Site 4	205/9	6.9	321	205/–6	7.4	279			3/3
	Combined	205/3	5.4	79.5	197/1	20.1	6.7	–	–	10/13
		16% tect. corr.	**205/3**	3.8	159.2	346/–35	2/4			
Mokrá	Site 1	210/15	13.0	35	199/29	13.0	35			5/6*
	Site 2	196/7	–	–	192/6	–	–			2/2*
	Site 3	207/5	5.6	272	201/26	5.6	272			4/4*
	Site 4	209/2	–	–	206/7	–	–			2/2*
	Site 5	219/21	7.7	33	212/1	7.7	33			12/12*
	Site 6	205/22	6.8	58	205/–8	6.8	58			9/9*
	Combined	208/12	9.3	52	203/10	13.4	26	–	–	6 sites
		34% tect. corr.	**206/12**	7.3	86	347/–30	4/7			

Dp/Dm — parameters of 95% confidence of palaeopole estimation; N/N_o — number of hand samples used for calculation of the mean direction/number of samples evaluated; *number of cylindrical samples; directions accepted for geological interpretations due to result of fold tests and used for a calculation of palaeopole are indicated with bold; other explanations as in Table 2

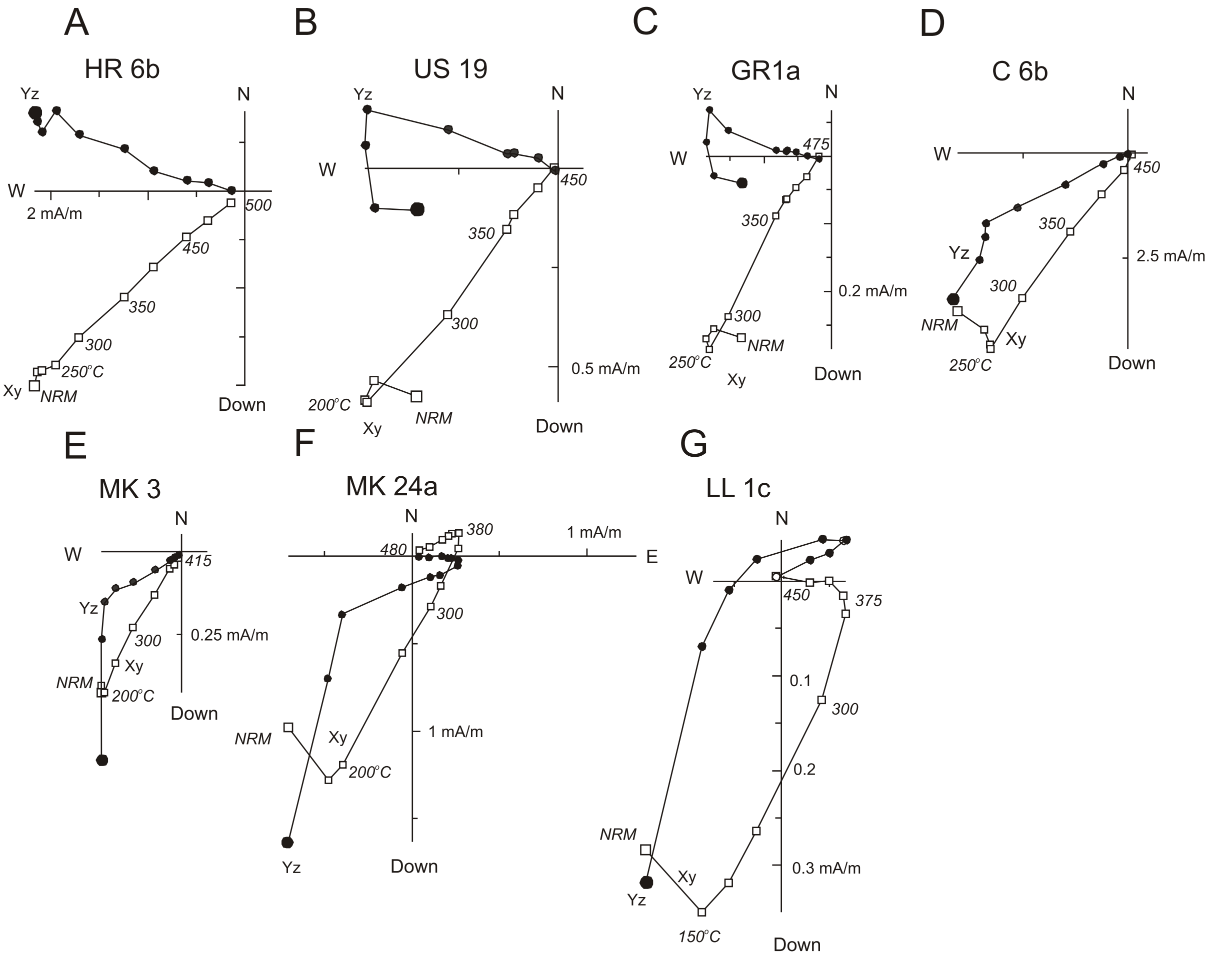


Fig. 6. Thermal demagnetization of the representative specimens from the studied localities (before tectonic correction) — orthogonal projections

squares — horizontal plane projection, dots — vertical plane projection; A — Hranice; B — Ústí; C — Grygov; D — Čelechovice; E — Mokrá, platform carbonates; F — Mokrá, pelagic carbonates; G — Lesní lom

tests indicate post-folding age of the component A. The fold tests performed in the localities Mokrá and Lesní lom (Figs. 6E–G and 7E–F) gave a late synfolding age (after 33 and 16% of unfolding respectively) for component A (Table 3). In the Mokrá sites 1–5, the NRM consisted exclusively of the component A with maximum unblocking temperatures up to 415–480°C (Fig. 6E). The component A was more easily removed (between 200 and 380°C) in the site 6 of this locality. Subsequently, a component B appeared with easterly declination and shallow negative inclination (Fig. 6F). Unfortunately the end points were not reached during thermal demagnetization and the component could not be statistically evaluated. However, in the Lesní lom locality, after subtraction of the component A at the temperatures 350–375°C (Fig. 6G) a component B emerged which was statistically significant in the sites 1 and 2 from this locality (Table 4). Total number of 6 samples (18 cylindrical specimens) was evaluated in these sites. In most specimens (15), it was possible to evaluate component B using the Kirschvink's algorithm (1980). In three cases the method of remagnetization circles (McFadden and McElhinny, 1988) was applied. It appeared that best clustering is obtained after 33% tectonic correction (Fig. 8), thus the component B is interpreted as synfolding.

Table 4

Characteristic magnetizations — component B (this study), Lesní lom Quarry, sites 1 and 2 combined

Locality	D/I	α_{95}	k	Dc/Ic	α_{95}	k	Palaeopole (long. E/ lat. N)	Dp/Dm	N/N$_o$
Lesní lom	98/–18	17.4	15.8	105/–45	34.5	4.7			6/6
	33% tect. corr.			**97/–28**	9.6	49.2	292/15	6/11	

Other explanations as in Tables 2 and 3

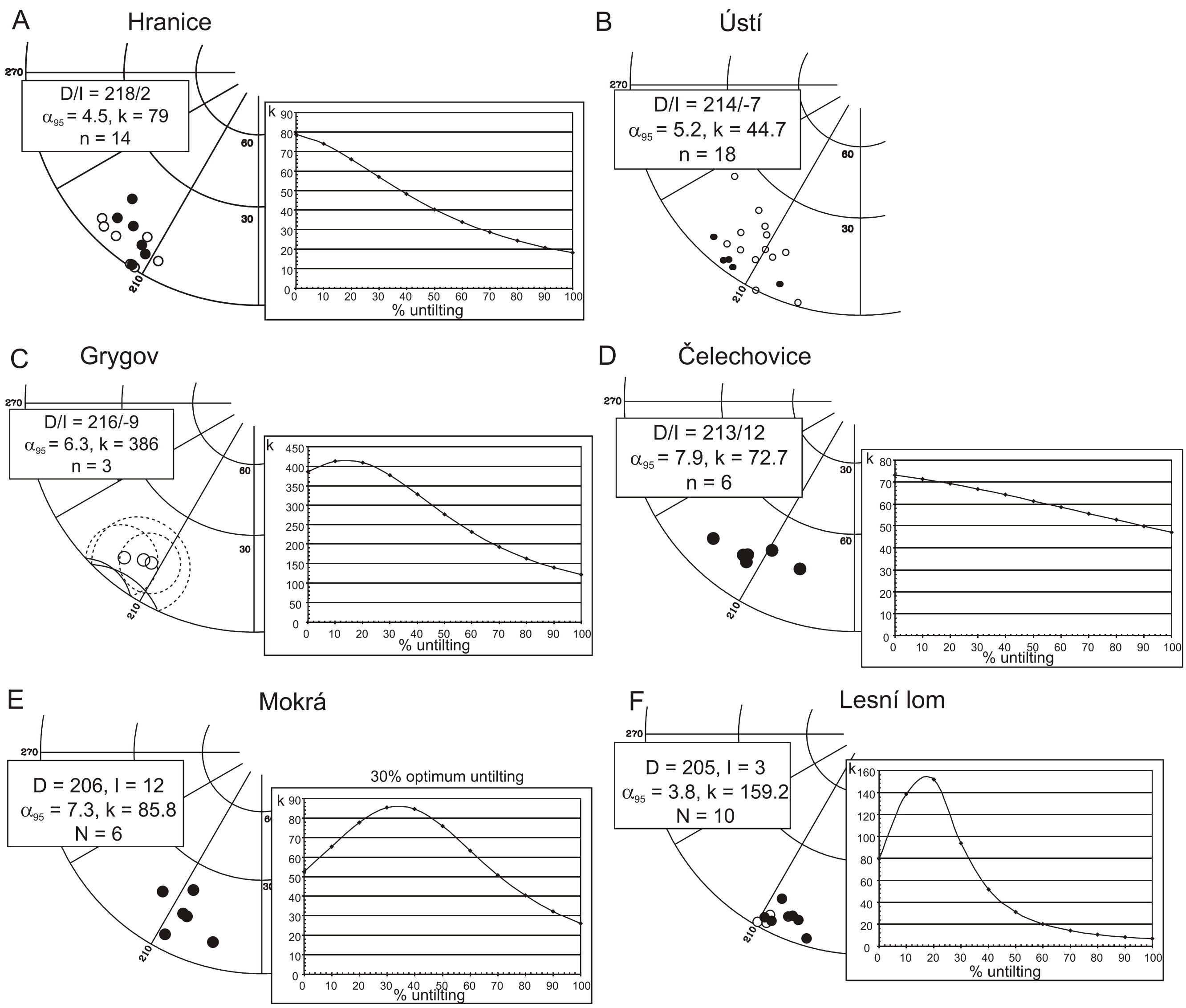


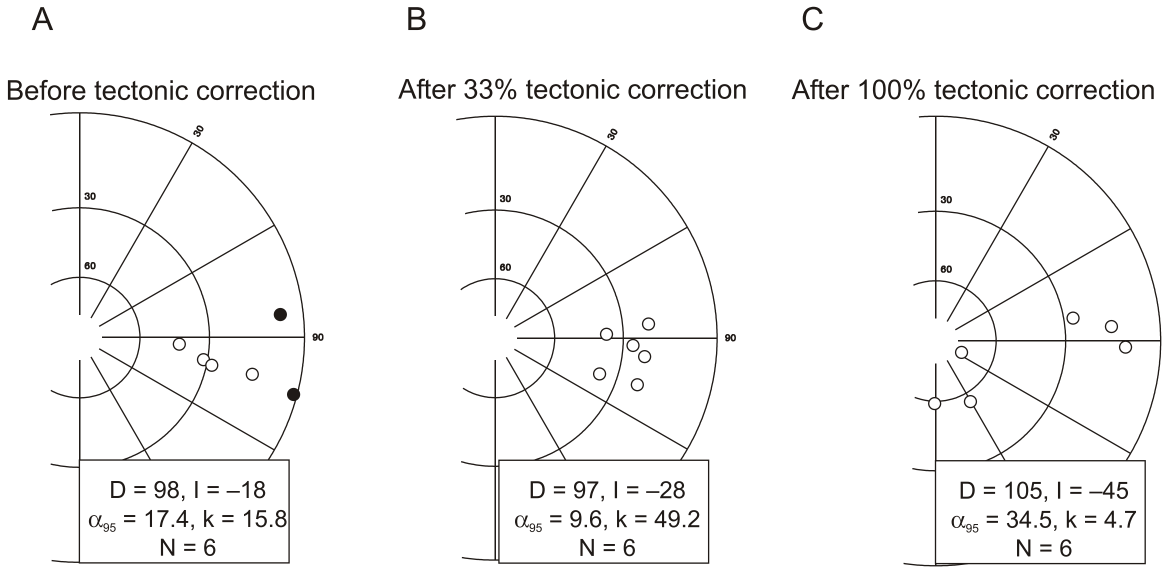
Fig. 7. Stereographic projection of the component A from the studied localities

A–**D** — before tectonic correction; **E** — after 34% tectonic correction; **F** — after 16% tectonic correction; results of incremental tilt test are shown (except B); open (full) symbols — upper (lower) hemisphere projection

AGE OF THE COMPONENT A

Palaeopoles of the component A fall in the vicinity of the Late Carboniferous–Early Permian section of the Apparent Polar Wander Path for the European plate (Fig. 9). They undoubtedly represent the late Variscan remagnetization acquired during the Permo-Carboniferous reversed superchron and already noted in the studied area by Krs and Pruner (1995, their component B) and Tait *et al.* (1996, their component A). The NE localities (Hranice, Ústí, Grygov) are apparently rotated more to the NW from the reference curve (Fig. 9), which might account for a minor tectonic rotation of the MSZ to the E and SE of Olomouc. We attempt to date the late Variscan overprint in our study area in a more detailed way. It is usually done by comparison of the reference inclination curve with palaeoinclinations observed. Use of a reference palaeoinclination curve is quite a sensitive tool for dating of the Late Carboniferous–Permian magnetizations, since the European plate generally drifted northward at that time, and in the Permian the latitudinal velocity of this drift was as high as 4 cm/yr (Torsvik and Cocks, 2005). Our reference curve in the interval 300–250 Ma was constructed using data from well dated and demagnetized volcanic rocks (Van der Voo and Torsvik, 2004), while between 350 and 300 Ma Baltic APW of Torsvik and Cocks (2005) was applied. It is evident that remagnetization phenomena started as early as in the Late Carboniferous (Westphalian) in Čelechovice and Mokrá, and continued up to the Early Permian in Grygov and Ústí (Fig. 10A).

The late Variscan (Late Carboniferous/Early Permian) remagnetization seems to be ubiquitous all over the Variscan Europe. It was noted in the Holy Cross Mts. and Lublin Basin in Poland (Lewandowski, 1981; Grabowski and Nawrocki, 1996; Grabowski *et al.*, 2002, 2006; Szaniawski, 2008), Rheinish Massif in Germany (Nowaczyk and Bleil, 1985;



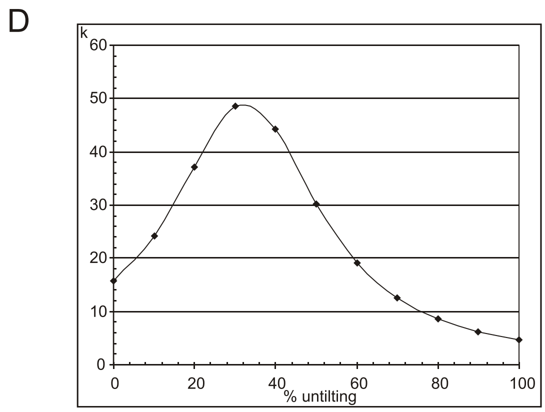


Fig. 8. Lesní lom, characteristic directions of component B calculated from hand samples

A — before tectonic correction; **B** — after 33% tectonic correction; **C** — after 100% tectonic correction; **D** — incremental fold test for component B; other explanations as in Figure 7

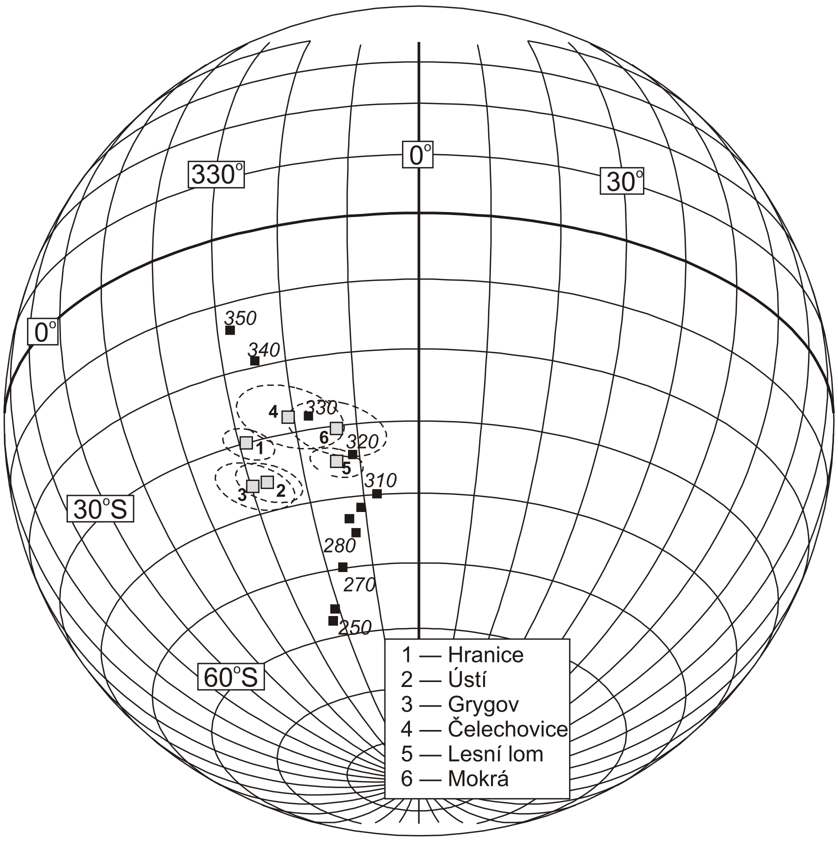


Fig. 9. Palaeopoles of the component A obtained in this study (grey squares, 1–6) at the background of the Carboniferous–Permian segment of APWP for Baltica (after Torsvik and Cocks, 2005)

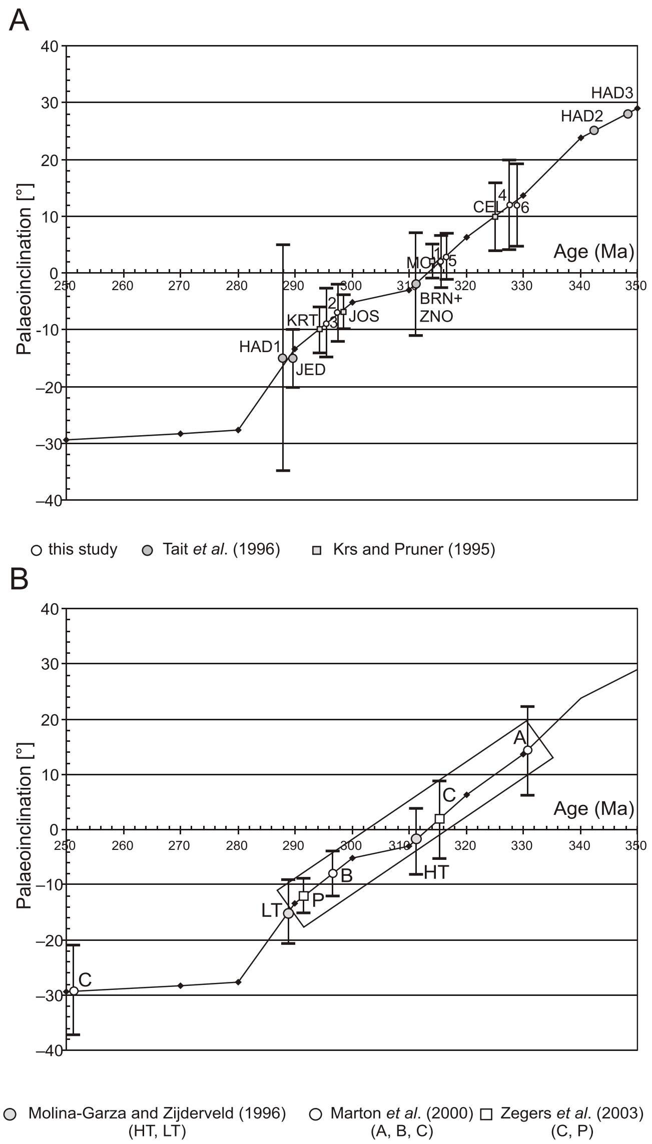


Fig. 10. Dating of Late Variscan remagnetizations in the MSZ (A) and Ardennes (B)

A — palaeoinclinations of the component A from localities studied in the MSZ (this study, Krs and Pruner, 1995; Tait *et al*., 1996) compared to the reference palaeoinclination curve for the European plate (350–300, after Torsvik and Cocks, 2005; 300–250 Ma, after Van der Voo and Torsvik, 2004); 1 — Hranice, 2 — Ústí, 3 — Grygov, 4 — Čelechovice, 5 — Lesní lom, 6 — Mokrá (this study); HAD1–3 — Hady limestone, JED — Josefov limestone, BRN, ZNO — Devonian clastics (Tait *et al*., 1996); KRT — Krtiny, JOS — Josefov, MOK — Mokrá, CEL — Čelechovice (Krs and Pruner, 1995); **B** — palaeoinclinations of the late Variscan remagnetizations from Ardennes (after Molina-Garza and Zijderveld, 1996; Marton *et al*., 2000; Zegers *et al*., 2003), recalculated for the geographic coordinates of the Moravian Karst, compared to the reference palaeoinclination curve for the European plate

Zwing *et al*., 2002; Zwing *et al*., 2005) Ardennes (Molina-Garza and Zijderveld, 1996; Márton *et al*., 2000; Szaniawski *et al*., 2003; Zegers *et al*., 2003), Craven Basin in England (McCabe and Channell, 1994) and Cantabrian/Asturian arc in Northern Spain (Van der Voo *et al*., 1997). Most of data fall within the interval between 320 and 286 Ma, as in the case of Ardennes (Fig. 10B).

The remagnetization in Moravian Karst is coeval with late Variscan magnetite remagnetizations in other parts of Europe. Most authors report distinct phases of remagnetizations that were identified by the magnetic carriers and time of their acquisition in relation to deformations. In Ardennes, all authors mention remagnetization at least two remagnetization phases: (1) early Variscan remagetization between 320 and 310 Ma (components C and HT in the Fig. 10B), which is mostly pre-folding, (Molina-Garza and Zijderveld, 1996; Zegers *et al*., 2003); (2) Late Variscan remagnetization, between 300 and 286 Ma (components B, P and LT in the Fig. 10B) which is post-folding (Molina-Garza and Zijderveld, 1996; Márton *et al*., 2000; Zegers *et al*., 2003). In results from Moravian Karst, component A from Ústí and Grygov (2 and 3 in the Fig. 10A), and old results of Krs and Pruner (1995) and Tait *et al*. (1996) from Josefov area (JED and JOS in the Fig. 10A) might be assigned to the late Variscan remagnetization phase. This phase is post-folding in Ardennes, as well as in Moravian Karst.

We do not take into account the results of Tait *et al*. (1996) from Hady limestones. The late Variscan overprint is poorly defined in these rocks. Mean of sites HAD2 and HAD3 was based on two samples only (out of seven and eight taken respectively), while mean direction of site HAD1 (based on four out of eight samples taken) has very large error (α_{95} = 19.8°). This dispersal is surprising because usually a component A is ubiquitous and relatively well clustered (see Table 3 and Fig. 7).

Results from Hranice and Lesní lom (1 and 5 in the Fig. 10A) and older results from Mokrá (Krs and Pruner, 1995; MOK in Fig. 10A) as well as red clastics from Brno and Znojmo (Tait *et al*., 1996; BRN + ZNO in Fig. 10A) seem coeval with the early Variscan remagnetization in Ardennes. This phase is late synfolding (Lesní lom) to post-folding in our area. This might indicate that deformation processes in the Moravian Karst were more advanced at this time than in the Ardennes, where this phase is mostly pre-folding. Secondary magnetizations reported from Cantabrian Arc (Van de Voo *et al*., 1997; Weil *et al*., 2001) seem to correspond to that phase, they are however syn- to post-tilting in age, similarly as our Moravian data.

Remagnetization in Čelechovice (4 and CEL in Fig. 10A) and our results from Mokrá is apparently coeval with phase A of Márton *et al*. (2000). This phase, in Ardennes, was reported only from the Boulonnais area and interpreted as post-folding. This interpretation was questioned by Zegers *et al*. (2003) who interpreted it as primary Devonian component. In our area, posfolding age of this magnetization is well established in Čelechovice. As to Mokrá Quarry, our results are not fully concordant with those of Krs and Pruner (1995), their results indicate slightly younger age of remagnetization. This might result from inaccuracies in tectonic correction: our result indicate synfolding age in Mokrá, while according to Krs and Pruner (1995) remagnetization is post-folding, however they have not checked the possibility of its synfolding age.

ORIGIN OF THE COMPONENT A

Two modes of remagnetization are usually considered in magnetite-bearing carbonates (McCabe and Elmore, 1989): (1) Thermoviscuous remagnetization (TVRM) is acquired in elevated temperatures during deep burial and uplift, regional or contact metamorphism. TVRM resets the magnetization in existing magnetite grains. (2) Chemical remagnetization (CRM) is related to growth of a new magnetic phase due to some chemical alterations usually caused by fluid flow. Typical examples of CRM were documented in rocks which were not heated to temperatures higher than 80–120°C. Origin of CRM due to burial diagenesis (e.g., Banerjee *et al.*, 1997; Katz *et al.*, 2000; Blumstein *et al.*, 2004) is also possible. Recently a thermochemical remagnetization (TCRM) is mentioned as viable remagnetization mechanism, resulting from chemical transformation of magnetic carriers promoted by elevated temperatures (e.g., Costanzo-Alvarez *et al.*, 2000; Woods *et al.*, 2002).

It should be noted that stability of component A against thermal demagnetization is higher in the rocks with elevated thermal maturity. Maximum unblocking temperatures in the localities Hranice, Ústí, Grygov and Čelechovice are up to 450–500°C (see Fig. 6A–D), while in Lesní lom and Mokrá rarely exceed 400°C (Fig. 6E–G).

Correlation of the thermal indexes with stability of magnetization would imply that component A might have been acquired during deep burial and stabilized during uplift. This would support the model of Hladil *et al.* (1998) who argued that the late Variscan remagnetization in the area of Mokrá was acquired during an isostatic uplift of the area during the latest phases of the orogeny. Two models for origin of the component A might be considered:

1. Component A is a typical TVRM that originated due to thermal resetting of existing magnetite grains.
2. Component A is a TCRM acquired e.g. due to oxidation of pyrite to magnetite in elevated temperatures.

The commonly applied method to distinguish between pure TVRM and CRM is a usage of thermal activation nomograms showing dependence between unblocking temperatures and relaxation time (see Fig. 11). The laboratory unblocking temperature for a TVRM acquired at a given time and temperature might be predicted. Nomograms published by Pullaiah *et al.* (1975) and Middleton and Schmidt (1982) were elaborated for SD magnetite but using different single domain theories (see McCabe and Elmore, 1989). The nomograms of Middleton and Schmidt (1982) appear to fit better experimental data for rocks containing mixture of magnetite grains of variable size (Kent, 1985). Therefore this nomogram is used here. Maximum unblocking temperatures of component A amount to 450 and 500°C in localities with higher thermal alteration (Hranice, Ústí, Grygov, Čelechovice) and 380–420°C in localities less altered (Mokrá, Lesní lom). If component A is of thermoviscous origin, the observed unblocking temperatures would correspond to 1–10 My lasting thermal event of magnitude 250–300°C in the former and 150–200°C in the latter localities. This is in a very good agreement with estimated maximum palaeotemperatures from the Table 1. The difference in thermal alteration explains why in less altered localities (Mokrá and Lesní lom) component B, was preserved. Therefore model 1 might be acceptable. However correlation of thermal indexes with stability of magnetization might imply that secondary fine grained magnetite was formed in elevated temperatures. High susceptibilities in the dolomitic rocks in locality Čelechovice (Fig. 4) might account for presence of ultra fine magnetite which is considered as a fingerprint of chemical

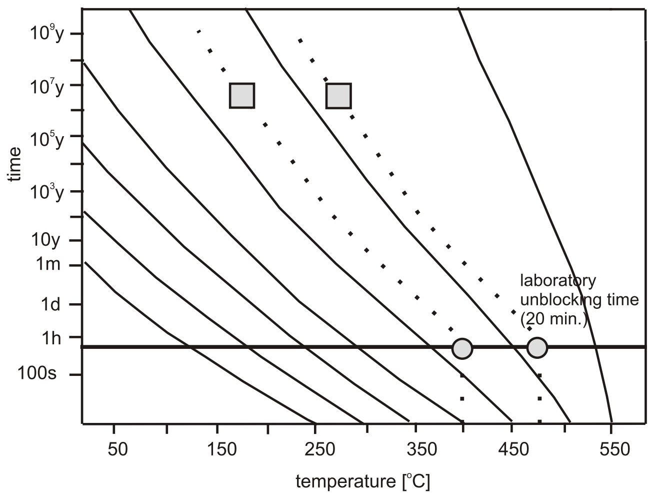


Fig. 11. Thermal activation nomogram for SD magnetite (after Middleton and Schmidt, 1982)

Stippled lines represent a TVRM components with laboratory unblocking temperatures 400 and 475°C (grey circles) and which were acquired in 1–10 My time span (grey squares)

remagnetization mechanism (e.g., Zwing *et al.*, 2005). Therefore a thermally conditioned mineralogical changes might be also responsible for the remagnetization (model 2), We can not distinguish now which model (or the combination of both) was responsible for the remagnetizations in the MSZ. Nevertheless all data prove strong link between thermal history and acquisition of the component A.

It seems that in the southern part of the MSZ , if data of Tait *et al.* (1996) from Hady limestone (HAD1–3) are not taken into account (for reasons, see above), there is a trend of younger age of component A towards the north, from Brno (localities Mokrá, Lesní lom and ZNO + BRN of Tait *et al.* 1996, and localities of Krs and Pruner, 1995) to the Krtiny–Blansko area. It also follows a trend of increasing thermal maturation (see Fig. 3), what again might support that component A is somehow correlated with thermal phenomena. This model however needs confirmation from a more extensive data set. Component A from Hady limestone (Tait *et al.*, 1996) might account that remagnetization in the Brno area was significantly extended in time (Fig. 10A). Component A in the northern part of the MSZ does not show any trend, broad spectrum of remagnetization direction is present from apparently the oldest in Čelechovice, through “intermediate” in Hranice to the youngest in Grygov and Ústí (Fig. 10A).

DISCUSSION — COMPONENT B

The synfolding nature of the component B implies that it must be of Carboniferous (pre-Namurian age). Its direction obtained here is quite concordant with the previous studies (Fig. 12). It should be noted that component B was reported only from the Brno area thus from the SW part of the Moravo-Silesian Zone (Krs and Pruner, 1995; Tait *et al.*, 1996).

Tait *et al.* (1996) reported a positive result of the McFadden (1990) fold test for the component B. However, they averaged

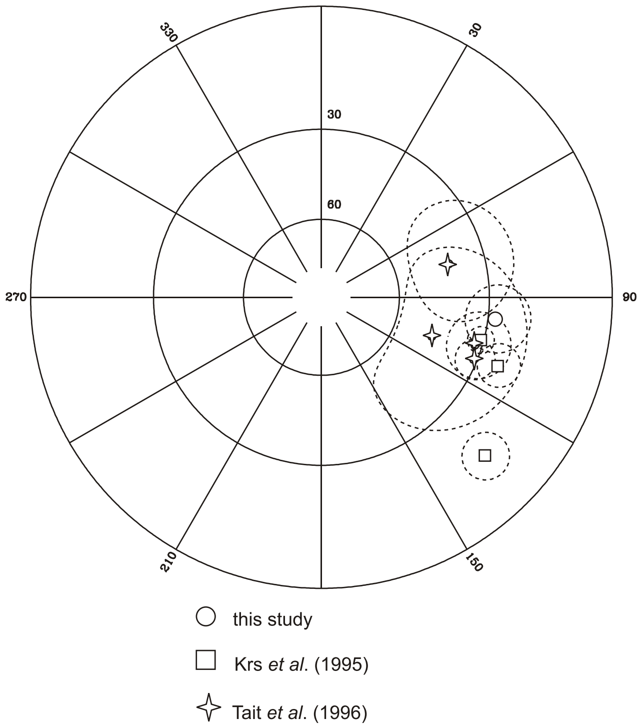


Fig. 12. Stereographic projections of the locality mean component B in various localities of the Moravo-Silesian Zone

This study — after 33% tectonic correction (see Table 4); Tait *et al*. (1996) and Krs *et al*. (1995) — after full tectonic correction

results from the clastic Old Red and carbonate Middle–Upper Devonian localities. When the fold test is performed for 4 carbonate localities only, the results indicate the synfolding nature of component B (79% of unfolding). Even if only the Fammenian Hady limestones localities are considered (3 localities), the component B also appears to be synfolding (78%). This means that a synfolding geometry of the component B obtained by Tait *et al.* (1996) is not caused by averaging components from a broad stratigraphic interval but is a real feature pointing to the secondary character of component B, at least in the carbonate rocks. Interpretation of synfolding components poses some problems for palaeomagnetists, and it is not evident whether they correspond to any true field direction at any stage of deformation (e.g., Dinares-Turell and McClelland, 1991; Stamatakos and Kodama, 1991; Halim *et al*., 1996; Shipunov 1997). The palaeopole of the component B is situated far from the reference APWP for Baltica. The origin of the component B in the MSZ is unclear and its firm geological interpretation is not possible at this time. It is assumed that the tectonic position of the crustal blocks at the SE margin of the Bohemian Massif was firmly established by the Visean/Namurian boundary (*ca*. 326 Ma), which is the age of the Moldanubian thrust (Franke and Żelaźniewicz, 2002). Edel *et al*. (2003) argue, based on palaeomagnetic evidence, for *ca*. 45° clockwise rotations as late as in the late Namurian–Westphalian (320–305 Ma). If component B is a real synfolding magnetization of Carboniferous age, the large almost 70° clockwise tectonic rotation must have occurred during the Carboniferous (Edel *et al*., 2003). This might have happened during the underthrusting of the Brunovistulicum towards the SW.

CONCLUSIONS

1. Late Variscan overprint (component A) of Carboniferous–Early Permian age is ubiquitous in carbonate rocks of MSZ in Czech Republic. Its age is roughly similar as in the other parts of Variscan Europe (e.g., Ardennes and Cantabrian/Asturian arc). Three phases of Variscan remagnetizations might be distinguished in the MSZ, which are easily correlated with their counterparts in Ardennes. The youngest phase of Early Permian age (*ca*. 300–290 Ma) is post-folding in MSZ as well as in Ardennes. The middle phase of Late Carboniferous age is late syn- to post-folding in the MSZ and Cantabria, but mostly pre-folding in Ardennes. The oldest phase of remagnetization in the MSZ is also syn- to postfolding and its age might be Early/Late Carboniferous. Altogether the data would indicate diachronism of Variscan folding in the MSZ area, as well as between MSZ and Ardennes.

2. Component A is carried by magnetite and it might be related to a thermal event (deep burial and uplift). Its unblocking temperatures correlate with degree of thermal alteration. The unblocking temperatures 450–500°C were observed in the more thermally affected NE and central part of the MSZ (Olomouc–Hranice area), while unblocking spectra 385–425°C are typical for less thermally altered SW part (Brno area). Also in this area older component B was preserved.

3. The presence of primary magnetizations, previously reported from the carbonates of the MSZ (Krs and Pruner, 1995; Tait *et al*., 1996) has not been confirmed. The component B that accounts for large tectonic rotations in the MSZ (“orocline hypothesis” of Tait *et al*., 1996) reveals a synfolding geometry and it might represent an Early Carboniferous overprint.

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