Acta Geologica Polonica, Vol. 59 (2009), No. 2, pp. 137–155

Synthrusting remagnetization of the Krížna nappe: high resolution palaeo- and rock magnetic study in the Strážovce section, Strážovské vrchy Mts, Central West Carpathians (Slovakia)

JACEK GRABOWSKI[1,*], JOZEF MICHALÍK[2], RAFAŁ SZANIAWSKI[3] AND IZABELLA GROTEK[1]

[1]*Polish Geological Institute, Rakowiecka 4, 00-975 Warszawa, Poland. *E-mail: jgra@pgi.gov.pl*
[2]*Institute of Geology, Slovak Academy of Sciences, Dúbravská cesta 9, 842 26 Bratislava, Slovakia*
[3]*Institute of Geophysics, Polish Academy of Sciences, Ks. Janusza 64, 01-452 Warszawa, Poland*

ABSTRACT:

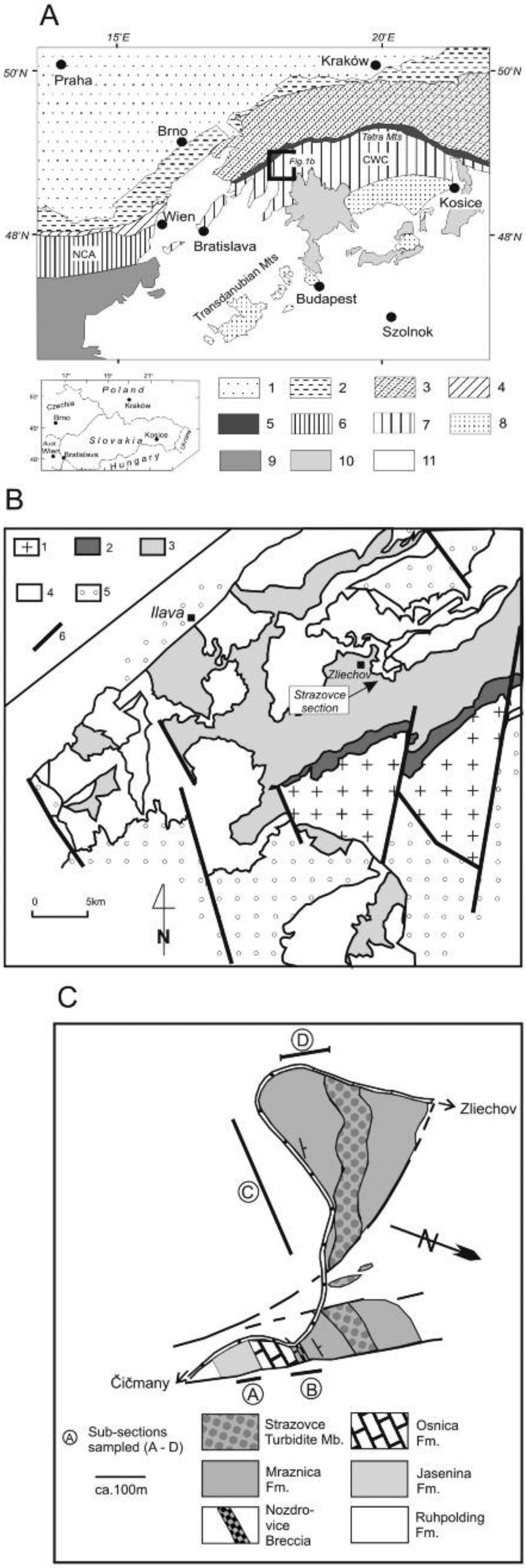
Grabowski, J., Michalík, J., Szaniawski, R. and Grotek, I. 2009. Synthrusting remagnetization of the Krížna nappe: high resolution palaeo- and rock magnetic study in the Strážovce section, Strážovské vrchy Mts, Central West Carpathians (Slovakia). *Acta Geologica Polonica*, **59** (2), 137–155. Warszawa.

Palaeomagnetic studies of the uppermost Jurassic to Lower Cretaceous pelagic carbonates in the Krížna nappe in the Strážovske vrchy Mts (Central West Carpathians, Slovakia) revealed the presence of secondary magnetite-related magnetization of exclusively normal polarity (component B), which was most probably acquired during the thrusting episode in the Late Cretaceous. Three formations exposed in the Strážovce section were the subject of investigation: Jasenina (Kimmeridgian–Tithonian), Osnica (Lower–Middle Berriasian) and Mraznica (Upper Berriasian–Hauterivian). Component B is ubiquitous throughout the section but is strongest in the Mraznica Formation. This formation contains a lot of superparamagnetic particles and shows rock magnetic characteristics typical of chemically remagnetized carbonates. The remaining two formations, although also remagnetized, bear traces of an older, probably primary magnetization (component C). The fold test for component B is apparently positive; however the inclination in pre-folding coordinates is too steep for any expected palaeoinclination of Jurassic to Recent age. Additional tectonic correction must be applied to match the palaeoinclinations with expected values. Although there is some uncertainty in this additional correction, all plausible options suggest that the rocks must have been magnetized when they dipped in the opposite direction to the thrusting direction. This interpretation is concordant with the internal tectonics of the Krížna nappe, consisting of imbricated units of duplex-type structure.

Key words: Palaeomagnetism; Remagnetization; Mesozoic; Carbonates; Slovakia; Carpathians; Strážovske vrchy Mts.

INTRODUCTION

It is now well established that secondary magnetizations in carbonate rocks might be acquired in a variety of ways (McCabe and Elmore 1989). Thermoviscuous remagnetization originates through resetting of magnetization due to increased burial temperature and subsequent cooling (Pullaiah *et al*. 1975; Kent 1985). Chemical remagnetization (through growth of a new magnetic phase) might be expected for rocks with low thermal alteration indexes (maximum burial temperature 100ºC or less, e.g. Hillegeist *et al*. 1992; Elmore *et al*. 1993; Katz *et al*. 2000). Remagnetizations are commonly reported from fold and thrust belts of Meso- and

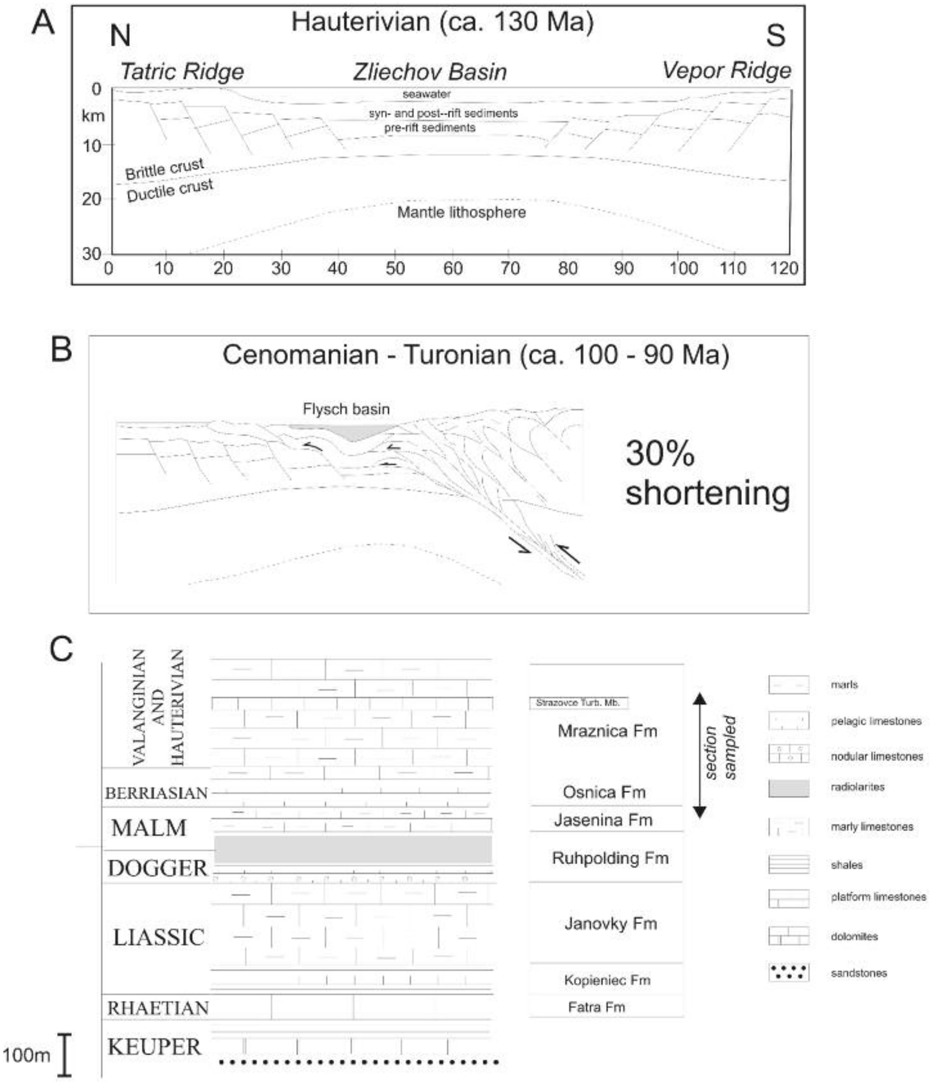


Cenozoic age (e.g. McCaig and McClelland 1992; Enkin *et al*. 2000). They were documented in Alpine Europe from the Betics (e.g. Kirker and McClelland 1996; Villalain *et al*. 1996), Iberian range (Juarez *et al.* 1996; 1998) and Pyrenees of Spain (Dinarés – Turell and García – Senz 2000; Oliva-Urcia *et al*. 2008), the Western Alps (Aubourg and Chabert-Pelline 1999), the Alpine foreland of southeast France (Katz *et al*. 2000; Henry *et al*. 2001; Kechra *et al*. 2003), the Northern Appenines (Aiello *et al*. 2004), the Eastern Alps of Austria (Pueyo *et al*. 2007) up to the Balkan Mts in Bulgaria (Jordanova *et al*. 2001). The data were used mostly to constrain local structural history; however, if the origin of remagnetization is properly interpreted, the data might give constraints for dating diagenetic (Katz *et al.* 2000; Elmore *et al*. 1998; Lewchuk *et al*. 2000), mineralizing (Henry *et al*. 2001), structural (Oliva-Urcia *et al*. 2008) or thermal events (Fruit *et al*. 1995). In the case of syntilting remagnetizations, they also supply quantitative data on intermediate deformation stages, which are difficult to obtain using structural methods (e.g. Villalain *et al*. 2003). Special problems are presented by remagnetizations where an orogen consists of nappes which were subjected to several deformation events, like in the case of the Northern Calcareous Alps (Pueyo *et al*. 2007). It is virtually impossible to suggest a proper coordinate system in which remagnetization took place, since the nappe might have been subjected to multiple axis rotations, not necessarily around horizontal and vertical axes (Kirker and McClelland 1996; Pueyo *et al*. 2003). It is usually not possible to date the remagnetization due to the uncertainty of tectonic correction. Thus, its timing must be interpreted indirectly, based on geological knowledge (age of the most important deformation events) and the mutual geometry of palaeomagnetic vectors. Moreover, the phenomena responsible for the remagnetization cannot be deduced without extensive rock magnetic and, sometimes, geochemical studies (e.g. Elmore *et al*. 1994). In this paper we present detailed palaeomagnetic and petromagnetic data

Text-fig. 1. (A) Tectonic sketch map of the Western Carpathians and Eastern Alps. 1 – Foreland; 2 – Neogene Molasse Zone; 3 – Outer West Carpathians; 4 – Rhenodanubian Flysch; 5 – Pieniny Klippen Belt; 6 – Northern Calcareous Alps (NCA); 7 – Central West Carpathians (CWC); 8 – Inner West Carpathians and North Pannonian Mesozoic rocks; 9 – Austroalpine basement; 10 – Neogene volcanics; 11 – Neogene basins. Rectangle indicates the area of Text-fig. 1b. (B) Tectonic sketch map of the Strážovské vrchy (after Maheľ 1985). 1 – Tatric crystalline core; 2 – Tatric sedimentary cover; 3 – Krížna nappe (Fatricum); 4 – higher nappes (Choč, Strážov, – Hronicum; Manín); 5 – Tertiary basins; 6 – major faults. (C) detailed sketch of the Strážovce section (modified after Michalik *et al.* 1990) from the remagnetized uppermost Jurassic–Lower Cretaceous pelagic carbonates in the Strážovce section of the Central West Carpathians (Strážovske vrchy Mts, Krížna nappe, Slovakia) and try to solve the puzzle of the mechanism of the magnetic overprint and the structural context of its acquisition.

GEOLOGICAL SETTING

The Central West Carpathians (CWC) constitute a thick-skinned fold and thrust belt situated south of the Pieniny Klippen Belt, mostly in the territory of Slovakia (Text-fig. 1a). Tectonic units of two types are recognized there (Plašienka *et al*. 1997). The first type comprises units with crystalline pre-Mesozoic rocks and their Upper Palaeozoic and Mesozoic sedimentary cover (e.g. Tatricum, see Text-fig. 1b). The second type comprises thin-skinned nappes, consisting mainly of sedimentary Mesozoic rocks, thrust over the parautochthonous substratum. To this type belong the Fatric units (e.g. Krížna and Manín nappes) and higher nappes (i.e Choč, Strážov – Hronicum) (Text-fig. 1b). The Krížna nappe, where our section is located (Text-fig. 1c), is a highly differentiated structure that consists of numerous smaller imbricated units. An extensional Zliechov basin was situated in the central part of the Krížna basin in the Mesozoic (Michalík 2007) (Text-fig. 2a–b). The synrift sedimentary cycle started at the end of the Triassic (Michalík *et al*. 2007). In the Rhaetian–Hettangian, the basin was filled with dark-coloured neritic carbonates and shales of the Fatra



Text-fig. 2. Idealized extensional (A) and compressional (B) stage of the Zliechov basin development (after Plašienka and Prokešová 1996, slightly modified). (C) Synthetic lithostratigraphic scheme of the Zliechov basin

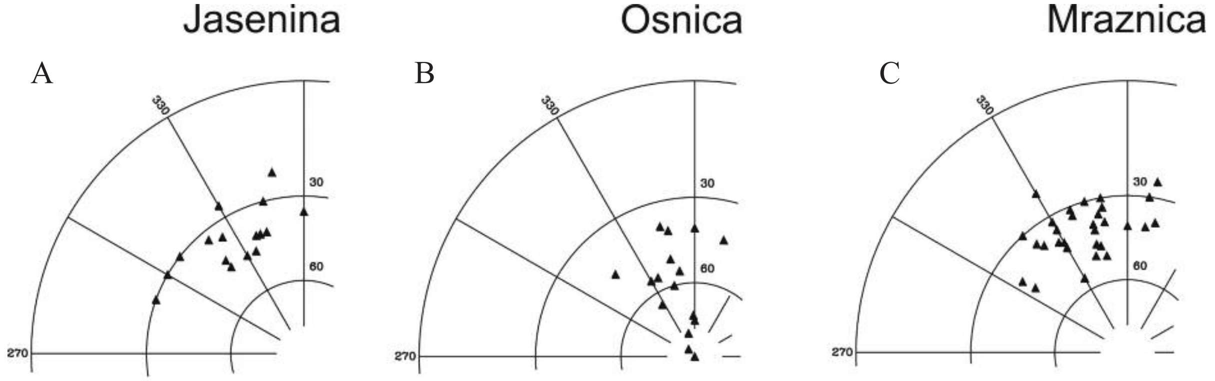
Formation, with a significant input of clastic material in the Kopieniec Formation (Text-fig. 2c). The slow and gradual subsidence of the basin resulted in deposition of spotty limestones (Janovky Formation = Fleckenmergel) in the greater part of the Early Jurassic. More rapid subsidence in the Middle Jurassic was related to deposition of deep-water sediments: nodular limestones and radiolarites of the Ruhpolding Formation (Ždiar Formation of Polák *et al.* 1998). The marly Jasenina Formation, developed in the Kimmeridgian, is an equivalent of the Ammonitico Rosso facies in the swell facies (Vašíček *et al*. 1994). With the bloom of calpionellid plankton, the thick-bedded pelagic limestones of the Osnica Formation were deposited in the Early and Middle Berriasian. In the Late Berriasian, the deposition of grey marly micritic limestones of the Mraznica Formation took place, continuing until the Aptian. It was occasionally interrupted by extensive carbonate debris-flow bodies (e.g. the Strážovce Member, see Text-fig. 1c, 2c). The Zliechov basin was strongly assymmetrical during Valanginian and Hauterivian, being affected by an active fault along its southern limb (see Michalik 2007). In the Aptian, black shales of Parnica Formation were deposited. The sedimentation in the Zliechov basin finished with the deposition of Albian–Cenomanian flysch of the Poruba Formation (Michalík 1995).

Mesozoic orogenic processes in the CWC advanced from the south to the north (Plašienka 1995; Jurewicz 2005). The thrust of the Veporicum over the Tatricum occurred in the early Late Cretaceous (90–80 Ma) (Text-fig. 2b). Also around 90 Ma emplacement of the Fatric and Hronic nappe systems occurred (Plašienka 1996). The original substratum of the Krížna nappe is now buried below the Veporic overthrust. Pre-Cenozoic basement of the CWC occurs now in the form of tectonic horsts (as in the Tatra, Strážov Mts and other massifs) surrounded by Tertiary basins and volcanites (Text-fig. 1a, b). These features result from various transpressional and transtensional stress regimes in the Neogene (Kováč *et al*. 1994). Uplift of the basement rocks must have changed the geometry of the Mesozoic structures, which now dip mostly to the north (Text-fig. 1c, 3). However, the attitudes of the strata and the thrust surfaces during the Cretaceous thrusting were poorly known until now. Plašienka and Prokešová (1996) developed a structural model of the Krížna nappe emplacement, in which imbricated units (duplexes) are thrust over the ramp produced by the Tatric ridge (Text-fig. 2b). The authors indicated the importance of high pore-fluid pressure during thrusting, especially in the sole parts of the nappe (Jaroszewski 1982). This is evidenced by the abundance of rauhwackized tectonic breccias (Plašienka and Soták 1996) and by the fact that the overthrusts apparently did not affect the structures of the substratum (Bac-Moszaszwili *et al*. 1981). Jurewicz (2005) and Jurewicz *et al*. (2007) argued for a considerable mass reduction and for pressure-solution phenomena along the thrust planes. In the last stages of thrusting the frontal parts of the Krížna nappe glided gravitationally from the Tatric ridge towards unconstrained foreland areas (Plašienka and Prokešova 1996).

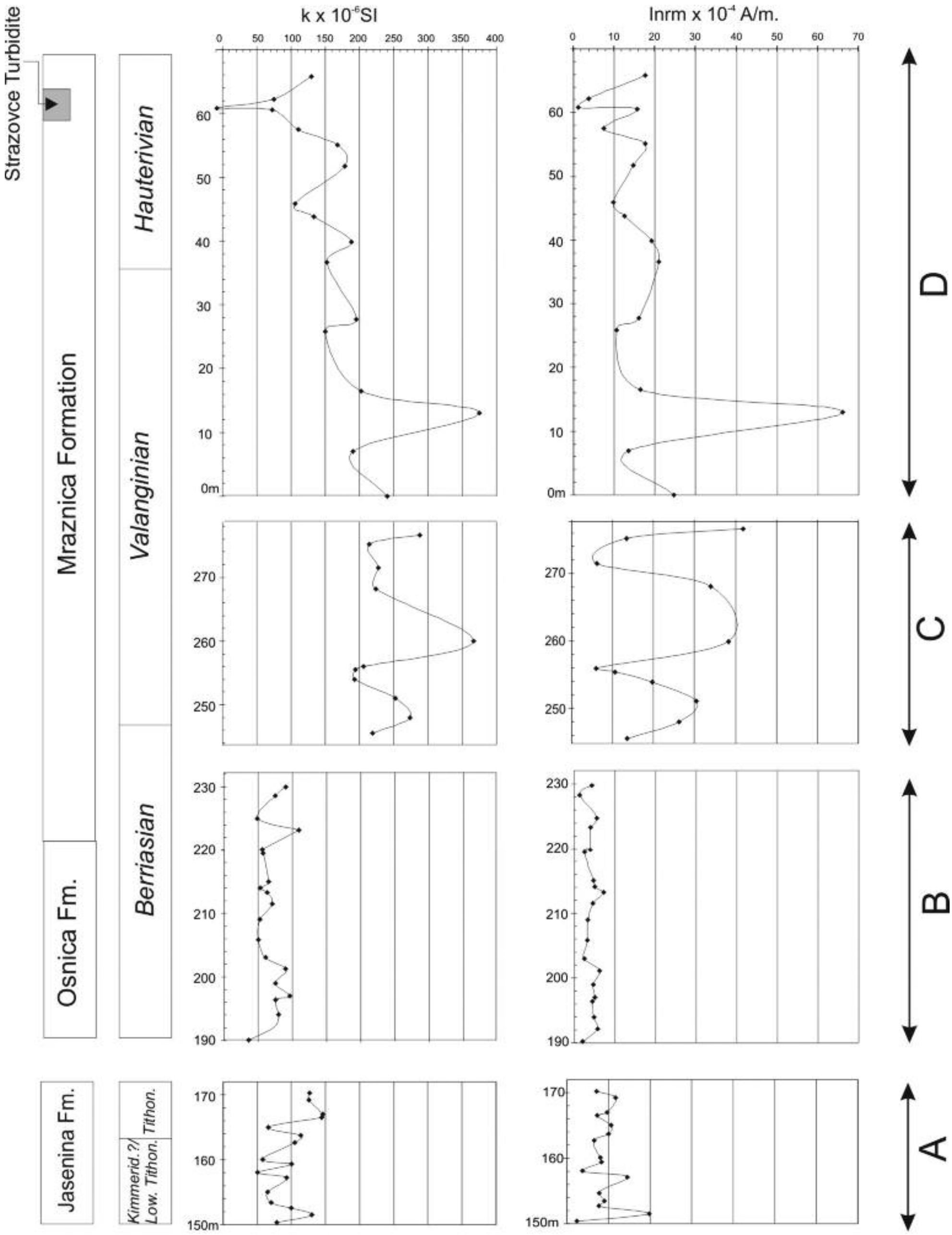
SAMPLING AND METHODS

The Strážovce section is situated in Western Slovakia, in the northern part of the Strážovské vrchy Mts (Text-fig. 1a, b). It is exposed along the escarpment of the Zliechov–Čičmany road (Text-fig. 1c), on the southern slope of Mt. Strážov (1245 m). The section embraces a complete succession from the uppermost Triassic (Rhaetian) up to the Barremian. The lithology and biostratigraphy are described in detail in numerous papers (e.g. Michalík *et al*. 1990; Vašíček *et al*. 1994).

A total number of 65 hand samples were investi-



Text-fig. 3. Stereographic projection of bedding attitude variations in the Strážovce section, indicated as bedding azimuth vs. bedding dip. (A) – Jasenina Formation; (B) – Osnica Formation; (C) – Mraznica Formation



Text-fig. 4. Magnetic susceptibility and NRM logs of the Strážovce section

gated throughout the Upper Jurassic–Lower Cretaceous part of the section (16 from the Jasenina Formation; 16 from the Osnica Formation; and 33 from the Mraznica Formation). Each hand sample was taken from a different bed. A primary goal of the study was magnetostratigraphy, since the Jasenina and Osnica formations yielded a reliable magnetostratigraphy in the Tatra Mts (Grabowski and Pszczółkowski 2006). The positions of the samples collected are shown in Text-fig. 4. They were taken from four sub-sections (Text-fig. 1c and 4). The Jasenina Formation was sampled in the interval between 150 and 170 m (sub-section A[1]), the Osnica Formation between 190 and 220 m (sub-section B). Microbiostratigraphical studies revealed that the sampled intervals belong to the Kimmeridgian?/Tithonian and Middle–Upper Berriasian respectively. The

---

[1] Metric callibration of sub-sections A, B and C refers to old bed numbering along the section (still visible), which starts from the lowermost beds exposed, of Late Triassic age.

Mraznica Formation was sampled more systematically, between 220 and 280 m in the uppermost part of sub-section B and in sub-section C (Upper Berriasian–Valanginian, 15 samples), as well as in the highest sub-section (D), embracing ca. 70 m of Valanginian and Hauterivian age (17 samples), up to the Strážovce Turbidite Member (Text-fig. 1c). The part of the section containing sub-sections A and B is more or less continuously exposed. Sub-section B is separated from C by a fault zone (valley), where the strata are covered. However, the topmost beds of sub-section B and the lowermost beds of sub-section C belong to the same calpionellid zone (*Calpionellopsis*, Upper Berriasian). Sub-sections C and D overlap due to the curves of the Zliechov–Čičmany road (Text-fig. 1c). Two to four standard cylindrical specimens were obtained from each hand sample. At least one specimen from each hand sample was used specifically for petromagnetic studies. These comprised acquisition of the isothermal remanent magnetization of the magnitude of 1T (IRM_{1T}) along the Z axis, and the subsequent imparting of the IRM of magnitude 100mT (IRM_{100mT}) in the antiparallel direction (-Z). The S-ratio, calculated as IRM_{100mT} / IRM_{1T}, enabled evaluation of the presence of high vs. low coercivity minerals within a sample. The values of the S-ratio, plotted along the section, show a vertical variation of rock magnetic properties. Samples displaying contrasting S-ratio were subjected to further IRM experiments, such as stepwise acquisition of the IRM and thermal demagnetization of the IRM acquired along three perpendicular directions in the fields of 0.1T, 0.4T and 1.4T (Lowrie 1990). The IRM was imparted using the MMPM1 pulse magnetiser produced by Magnetic Measurements (UK). Low- and high-frequency susceptibility was studied for specimens from all sampled beds to estimate the contribution of the very fine (close to superparamagnetic state – SP) magnetic fraction. Additional rock magnetic study was performed in the Paleomagnetic Laboratory of the Institute of Geophysics (Polish Academy of Sciences), using a Vibrating Sample Magnetometer (VSM) (mod. 2900-02, Princeton Measurements) to determine the parameters of the hysteresis loops and the coercivity of remanence (Hcr).

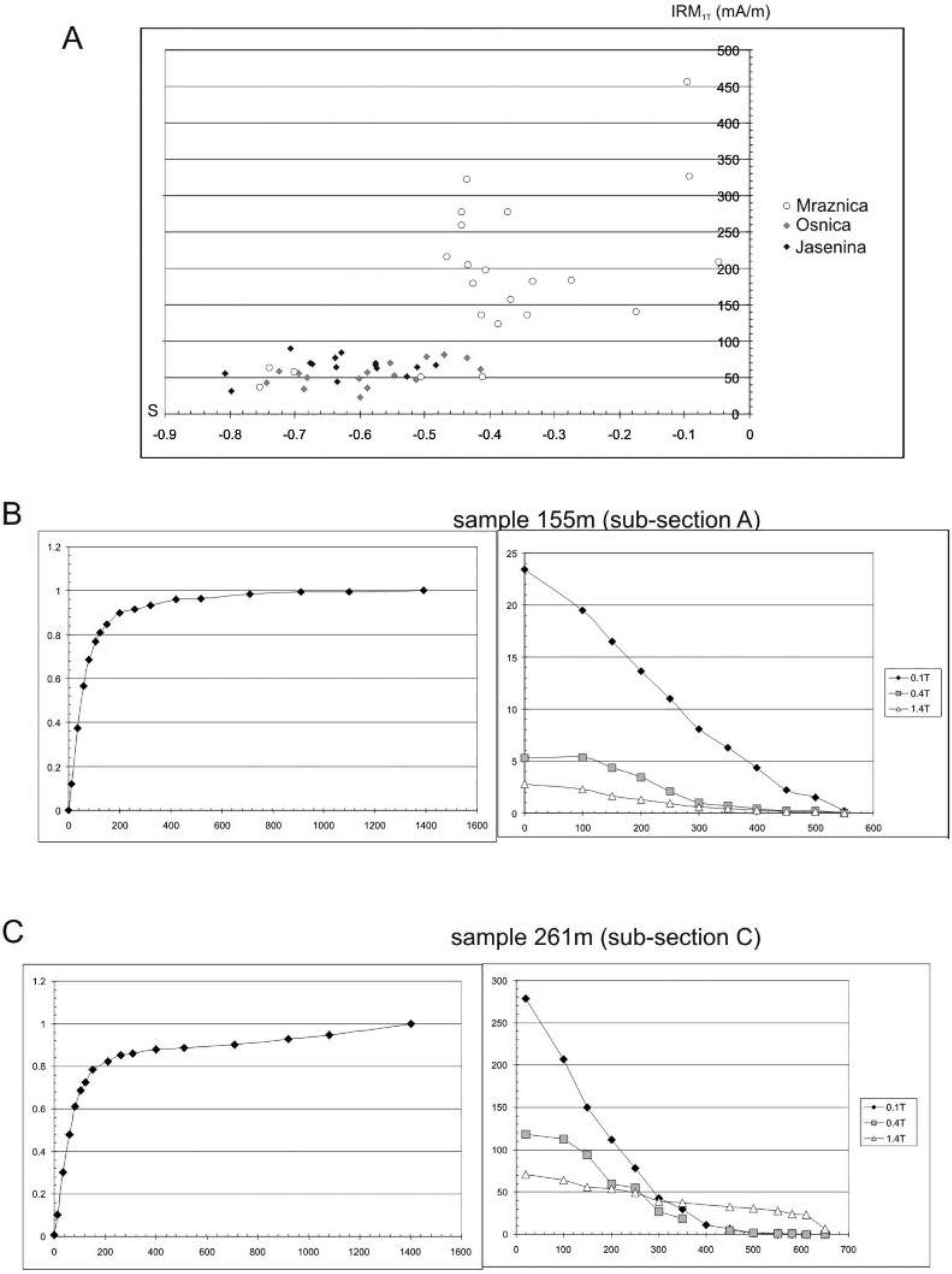
Natural remanent magnetisation (NRM) was measured with a JR-5 spinner magnetometer (AGICO, Brno; noise level 10^{-5} A/m) in the paleomagnetic laboratory of the Polish Geological Institute (PGI) in Warsaw. Samples were demagnetised thermally using the non-magnetic oven MMTD (Magnetic Measurements, UK, rest field < 10 nT). NRM measurements and demagnetization experiments were carried out in a 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 demagnetization step. The same instrument was used for measurements of the anisotropy of magnetic susceptibility (AMS). AMS parameters were determined using the ANISO software supplied by AGICO (Jelinek 1977). Characteristic remanence magnetization (ChRM) directions were calculated by principal component analysis (Kirschvink 1980) using the PALMAG package of Lewandowski *et al.* (1997). Fold tests were performed using the McFadden (1990) method. A fold test is a standard palaeomagnetic procedure which checks the age of magnetization in relation to folding processes. If magnetic vectors cluster better in situ (without any tectonic correction), the magnetization is post-folding. When the clustering is better after restoration of the beds to a horizontal position (full or 100% tectonic correction), magnetization must be considered as pre-folding. A syn-folding age of magnetization (clustering best between 0 and 100% tectonic correction) is also possible (see also Introduction). During the process of tectonic correction each vector is rotated around a horizontal axis with the azimuth and angle that of the bedding azimuth and dip of a bed from which the palaeomagnetic sample was collected.

Nine samples from the Mraznica Formation (sub-sections C and D) were examined for the thermal maturity of organic matter. The reflectance of authigenic vitrinite (*Ro*) amounts to 1.15–1.70%, with mean values of 1.3–1.5%. It corresponds to the main phase of gas generation and to maximum burial temperatures of 130–150°C, locally even 170°C.

ROCK MAGNETISM

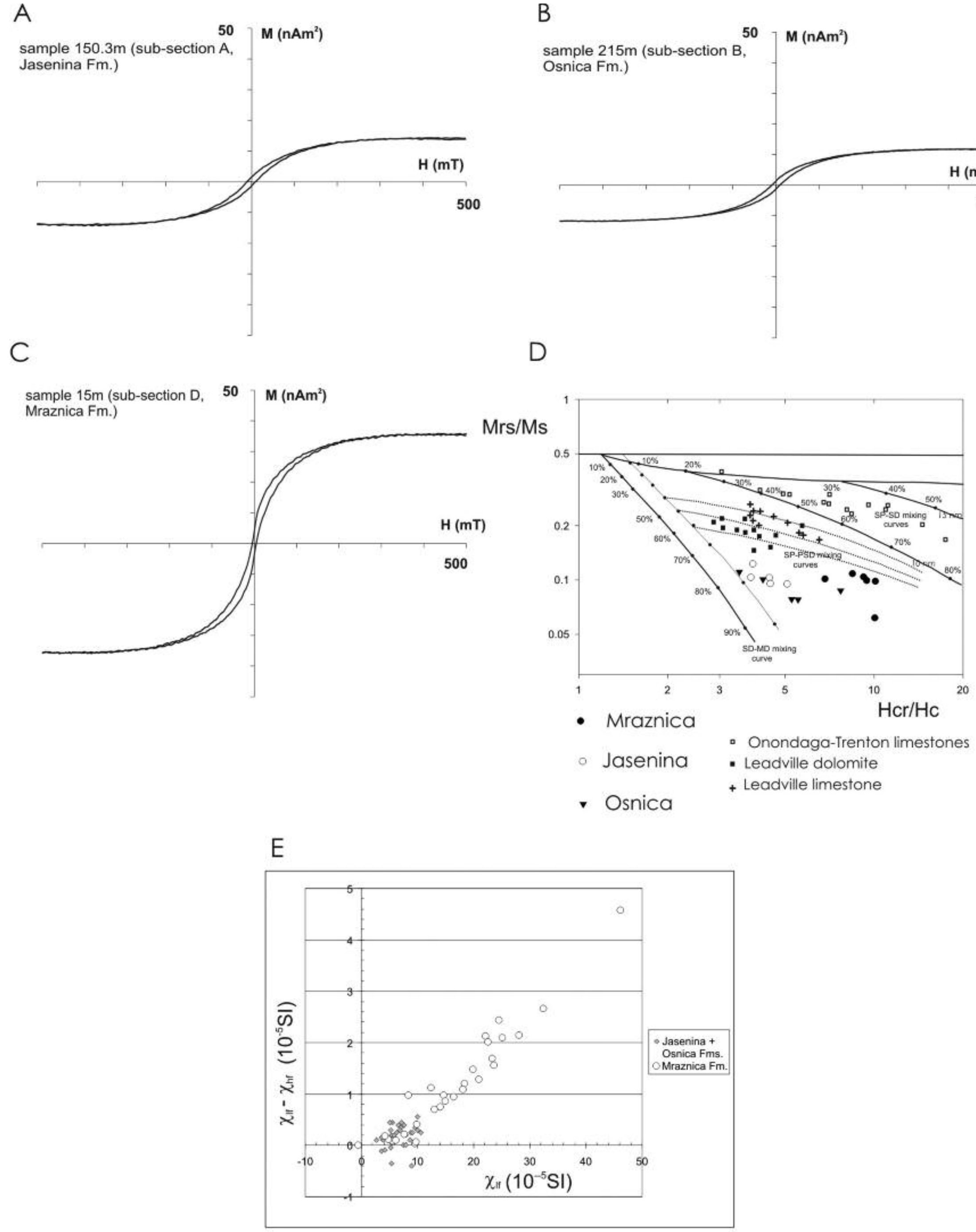
Magnetic susceptibility and NRM intensities seem to correlate with lithostratigraphical units. The lowest values of both parameters were observed at the top of the section within the Strážovce Turbidite Member (Text-fig. 4). They result from an abundance of organodetrital debris containing pure calcite. Within the Osnica and lowermost part of the Mraznica Formation susceptibility values were mostly between 50 and 100 × 10^{-6} SI units, while the NRM intensities were between 2 and 7 × 10^{-4} A/m. Slightly higher values were noted within the marly Jasenina Formation: susceptibility up to 150 × 10^{-6} SI units and NRM intensities mostly between 5 and 20 × 10^{-4} A/m. Surprisingly strong magnetic properties were shown by the bulk of the Mraznica Formation: susceptibility between 100 and 380 × 10^{-6} SI, with NRM intensities mostly higher than

10^{-3} A/m (Text-fig. 4). Substantial difference in mineral magnetism seems to occur between the Jasenina–Osnica–lowermost Mraznica formations and the bulk of the Mraznica Formation. The former is characterized by relatively low values of IRM_{1T} and S-ratios between –0.8 and –0.4 (Text-fig. 5a), which indicates the prevalence of low coercivity minerals. Thermal demagnetization of the 3 axes IRM confirm the predominance of a low coercivity fraction with a maximum unblocking temperature of 550ºC, which is interpreted as magnetite (Text-fig. 5b). On the other hand, strongly magnetic specimens of the Mraznica Formation with high values of the IRM_{1T} prove a significant admixture of a high coercivity fraction manifested by an S-ratio be-



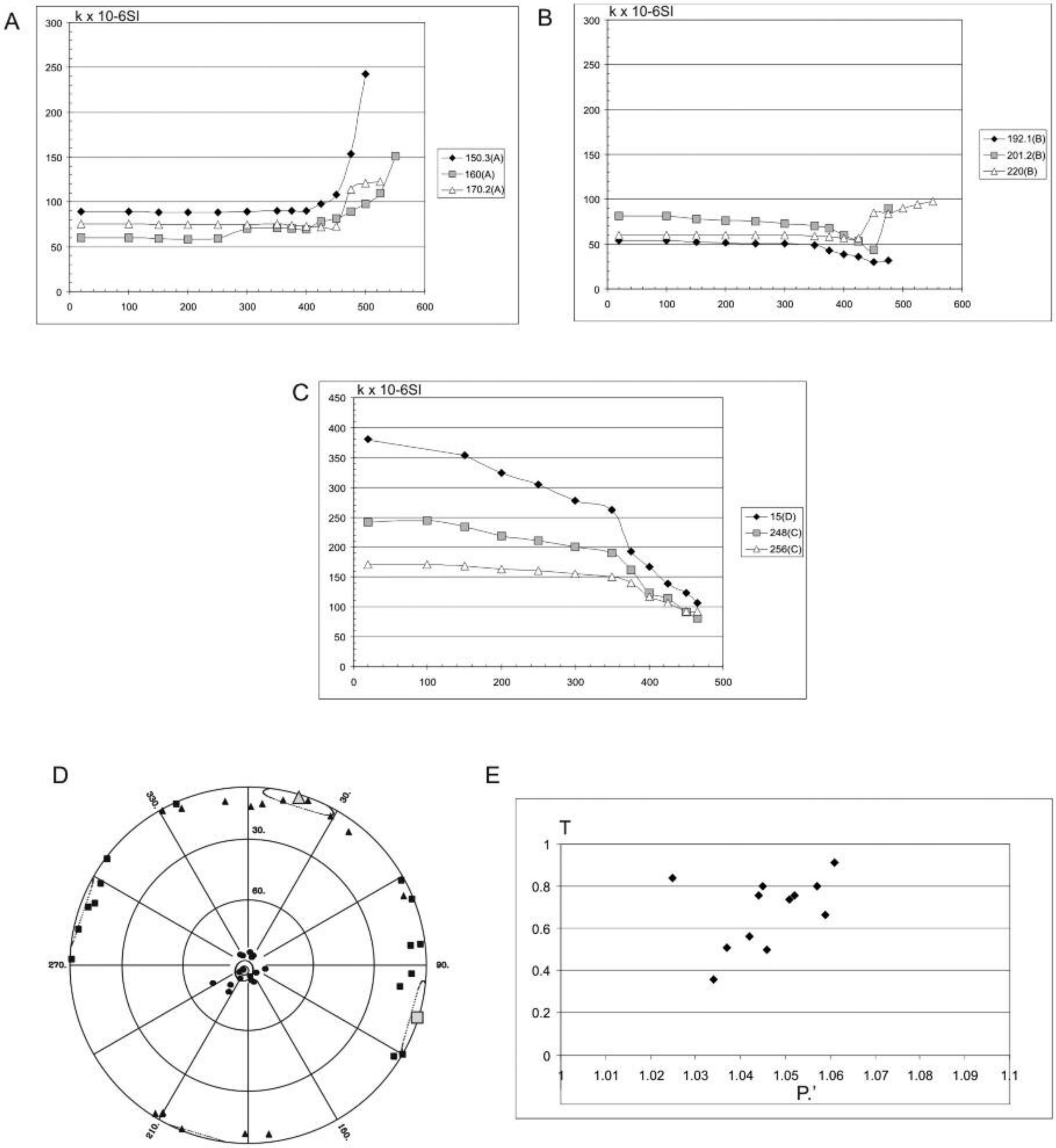
Text-fig. 5. (A) Cross-plot of S-ratio and IRM_{1T} for the Strážovce section. (B) and (C) – stepwise acquisition of the IRM (left diagrams) and thermal demagnetization of the 3 axes IRM acquired in the fields of 0.1T, 0.4T and 1.4 T. (a) sample 155 m, sub-section A – Jasenina Formation; (b) sample 261 m, sub-section C – Mraznica Formation tween –0.4 and 0 (Text-fig. 5a). In this case, IRM experiments (Text-fig. 5c) reveal a mixture of magnetic minerals with high coercivities and high unblocking temperatures (more than 600ºC: hematite) and lower coercivities and unblocking temperatures (magnetite).

The shapes of the hysteresis loops differed slightly between the formations investigated. In the Osnica and Jasenina formations the saturation magnetization (Ms) values were generally smaller than in the Mraznica Formation (Text-fig. 6a–c). In the latter, most of the ob-



Text-fig. 6. Hysteresis curves for representative samples of Jasenina (A), Osnica (B) and Mraznica formations (C). (D) Plot of the hysteresis ratios Mrs/Ms and Hcr/Hc for Mraznica, Osnica and Jasenina sites compared with theoretical curves (after Dunlop 2002a, b). Results from Onondaga – Trenton limestones and Leadville limestone and dolomite (after Suk *et al.* 1993 and Xu *et al.* 1998) are shown for comparison. (e) Susceptibility differences χ_{lf}-χ_{hf} measured at low (0.47 kHz; χ_{lf}) and high frequency (4.7 kHz; χ_{hf}) plotted as a function of a low frequency susceptibility χ_{lf}

served hysteresis loops were characterized by a slightly wasp-waisted shape (evidence of a mixture of different sizes of magnetite grains) that was not as common in the Osnica and Jasenina formations. Hysteresis and remanent coercivity (Hcr) parameters summarized in the Day diagram (Day *et al.* 1977, modified by Dunlop 2002a, b) are indicative of the occurrence of a pseudo-single domain (PSD) and SP magnetite grains, with a larger contribution of the SP fraction in the Mraznica Formation (Text-fig. 6d). It seems that differences in magnetic properties in particular formations are largely governed by the relative abundance of a very fine-grained (perhaps SP) ferromagnetic fraction. Its presence is evidenced by frequency dependence of susceptibility in the bulk of the Mraznica formation (Text-fig. 6e). On the other hand, the SP fraction seems



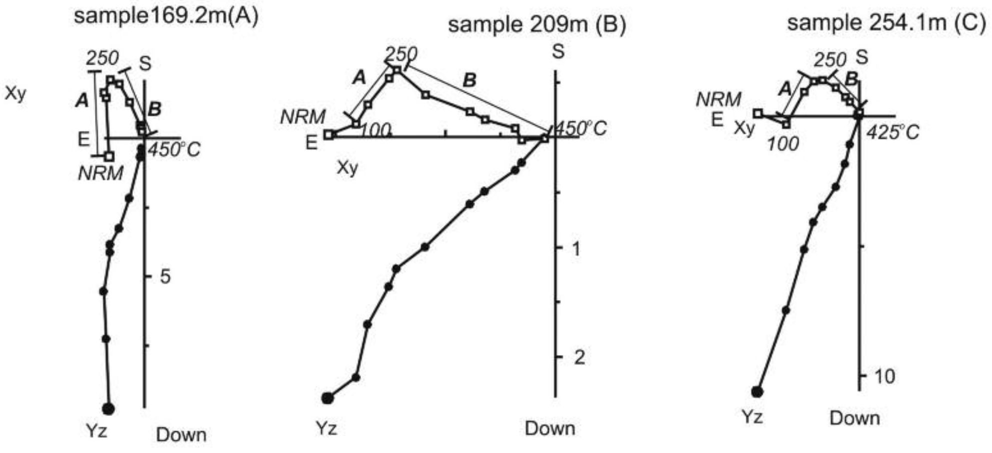
Text-fig. 7. Magnetic susceptibility changes during thermal demagnetization. Strážovce section. (A) – Jasenina Formation; (B) – Osnica Formation; (C) – Mraznica Formation. (D) Magnetic fabric of the Jasenina formation, presented after tectonic correction (in bedding coordinates). Circles (triangles, squares) - minimum (intermediate, maximum) susceptibility axes. Grey – mean susceptibility axes; (E) – plot of degree of anisotropy (P') and shape parameter (T) to be absent in the samples of the Jasenina and Osnica formations.

Two types of behaviour of magnetic susceptibility during thermal treatment are observed. In the first type, susceptibility is rather stable between 20 and 350ºC, then a slight decrease is observed, followed by a sharp rise above 425–450ºC. This type comprises all the Jasenina Formation samples (Text-fig. 7a) and some of the Osnica Formation samples (Text-fig. 7b, sample 220B). A susceptibility decrease between 350 and 425ºC is commonly attributed to the transformation of maghemite to hematite (Opdyke and Channell 1995), while an increase above 425ºC results from the oxidation of pyrite to magnetite (Van Velzen 1992). In the second type, a gentle decrease of magnetic susceptibility is observed between 100 and 350ºC, followed by a quite sharp decrease that continues up to 470ºC. This type is found in part of the Osnica Formation (Text-fig. 7b, samples 192.1(B) and 201.2(B)) and in the bulk of the Mraznica Formation (Text-fig. 7c). Pyrite is apparently absent. A sharp decrease in magnetic susceptibility between 350 and 470ºC seems to be correlated with an abundance of the SP fraction.

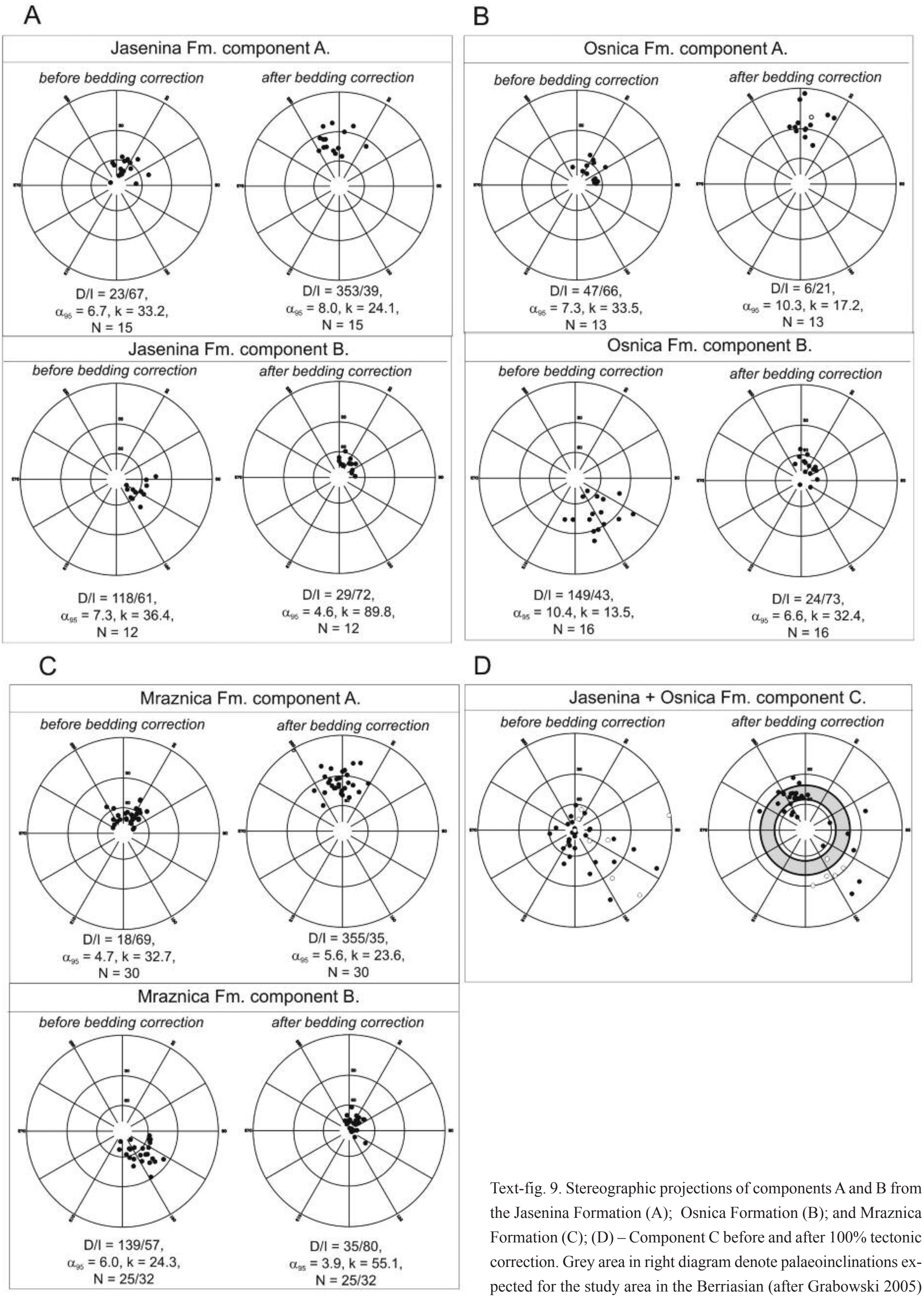
The Jasenina Formation showed a well-defined normal magnetic fabric. An almost perfect planar magnetic fabric is developed, with magnetic foliation within the bedding plane. There is a weak WNW–ESE magnetic lineation (Text-fig. 7d). An almost linear dependence between degree of anisotropy (P') and shape parameter (T) (Text-fig. 7e) indicates that the magnetic anisotropy is related mostly to a single mineral phase with predominating planar features. In our opinion, these are most probably paramagnetic phyllosilicates. In the other formations a more complex and not easily interpretable magnetic fabric is observed, which most probably results from the superposition of para- and ferromagnetic subfabrics.

DEMAGNETIZATION

Samples of all the formations revealed two components of magnetization, A and B, with well-separated unblocking temperature spectra. Additionally, a third component C was present in some samples of the Jasenina, Osnica and lowermost Mraznica formations (Table 1). Component A, with unblocking temperatures between 100 and 250ºC (Text-fig. 8), is better clustered in the present day coordinates, which implies its post-folding age (Text-fig. 9). Its direction is close to the present-day geomagnetic field in the area and hence it is most probably a recent viscous remanent magnetization. Component B unblocks between 250–300 and 450ºC (Text-fig. 8). It is better clustered after full tectonic correction (i.e. restoring beds to horizontal position, see Text-fig. 9) with positive results of the McFadden (1990) fold test for the Jasenina and Mraznica formations. In the Osnica Formation, the fold test indicates an early synfolding origin of component B (80% unfolding) (Table 1). This difference might result from the fact that the Osnica Formation beds were more strained than those of the other formations, which is evidenced by differences in bedding attitude (Text-fig. 3). Some studies in tectonically deformed beds proved that strain might rotate the prefolding remanence into an apparent synfolding position (Stamatakos and Kodama 1991; Lewchuk *et al*. 2003; Elmore *et al*. 2006). The inclination of component B after full bedding correction is very steep and polarity is exclusively normal. This component cannot be interpreted as primary because in the Neocomian a lot of magnetic inversions must be expected (Gradstein *et al*. 2004). Also the inclination is too steep, not only for the expected Early Cretaceous palaeoinclination, but for any later periods (Text-fig. 10). The secondary component B must have been acquired when the strata were



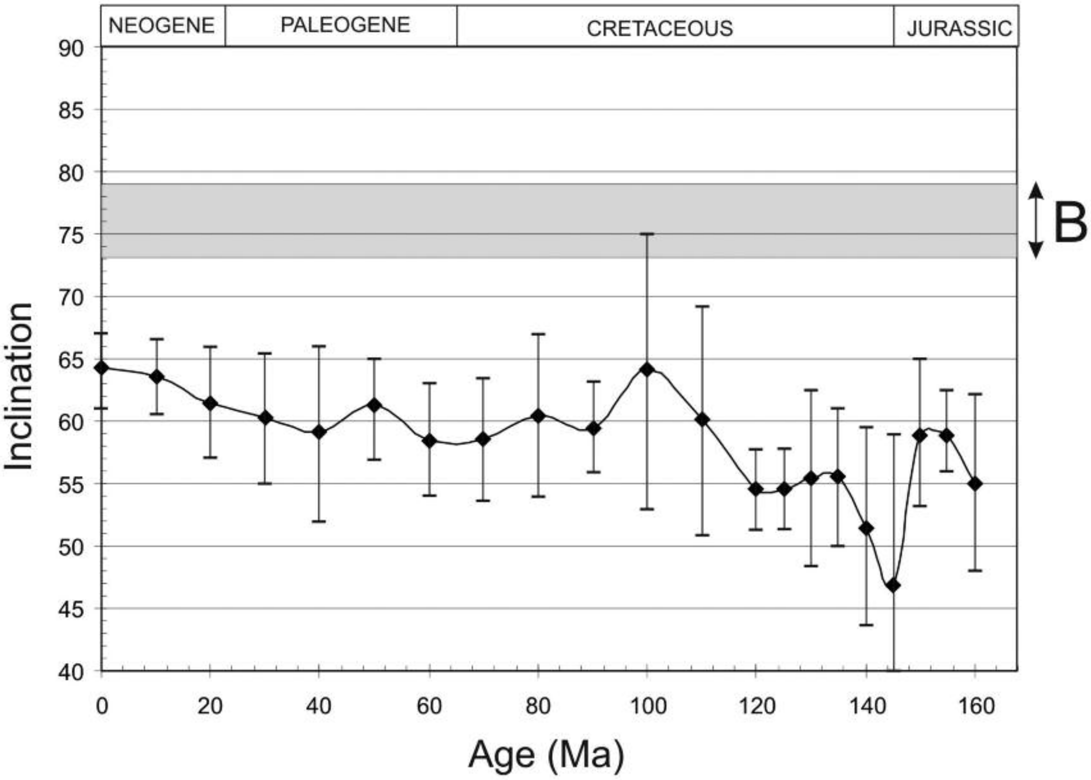
Text-fig. 8. Typical orthogonal plots of thermal demagnetization paths. All diagrams before tectonic correction. Open squares – horizontal (xy) plane; solid circles – vertical (yz) plane. NRM intensities in 10^{-4}A/m



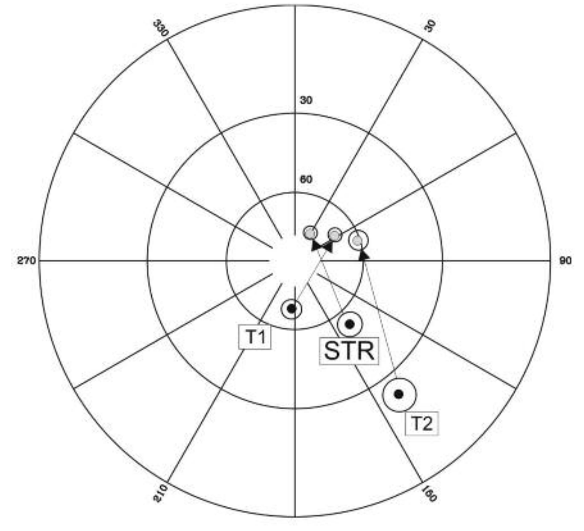
Text-fig. 9. Stereographic projections of components A and B from the Jasenina Formation (A); Osnica Formation (B); and Mraznica Formation (C); (D) – Component C before and after 100% tectonic correction. Grey area in right diagram denote palaeoinclinations expected for the study area in the Berriasian (after Grabowski 2005)

Formation	Component	D/I	α_{95}	k	Dc/Ic	α_{95}	k	N/No
Jasenina	A	23/67	6.7	33.2	353/39	8.0	24.1	15/16
	B	118/61	7.3	36.4	29/72	4.6	89.8	12/16
Osnica	A	47/66	7.3	33.5	6/21	10.3	17.2	13/16
	B	149/43	10.4	13.5	24/73	6.6	32.4	16/16
Mraznica	A	18/69	4.7	32.7	355/35	5.6	22.6	30/32
	B	139/57	6.0	24.3	35/80	3.9	55.1	25/32
Mean	A	30/68	4.4	172.7	358/32	17.2	52.2	Mean of 3 formations
	B	137/54	20.1	38.1	28/75	6.9	317	Mean of 3 formations
	C	177/84	10.3	12.1	338/49	4.0	75.3	18/64

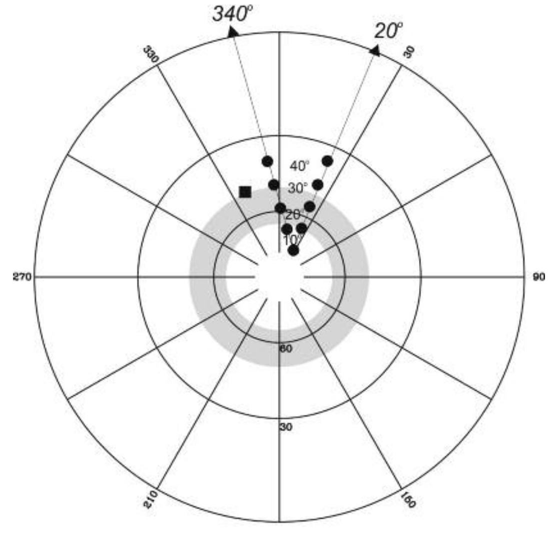
Table 1. Characteristic remanent magnetizations, Strážovce section. Explanations: D, I – declination, inclination before tectonic correction; Dc, Ic – declination, inclination after 100% tectonic correction (to the horizontal); α_{95}, k – Fisher statistics parameters; No – number of hand samples collected; N – number of hand samples used for calculation of mean direction



Text-fig. 10. “Expected” palaeoinclinations for the study area between 160 and 0 Ma, calculated from the European APWP (after Besse and Courtillot 2002; 2003) with inclination of component B (this study) indicated parallel to each other but not necessarily in a horizontal position. Discussion about the origin of this component is presented in the next chapters. Component C usually coexists with component B in samples that reveal a susceptibility rise between 400 and 450ºC (see Text-fig. 7a, b). Therefore it cannot be defined using the Kirschvink's (1980) algorithm. It can be approximated using a stereographic projection of the NRM vectors, these being the last logical points of the demagnetization path (Text-fig. 9d). Component C is somewhat streaked; however, after full tectonic correction, the NRM vectors tend to group in the NW and SE quadrants of the stereonet, with a positive inclination in the former case and a negative inclination in the latter.



Text-fig. 11. Component of "B" type in the Mesozoic of the Central West Carpathians. STR – component B, Strážovce section (this study); T1 – Skupniów Upłaz section, Tatra Mts; T2 – Siklawica section, Tatra Mts (after Grabowski 2000). Black dots – before tectonic correction (*in situ*); grey dots – after 100% tectonic correction (to horizontal position of beds). Ovals of 95% confidence are indicated

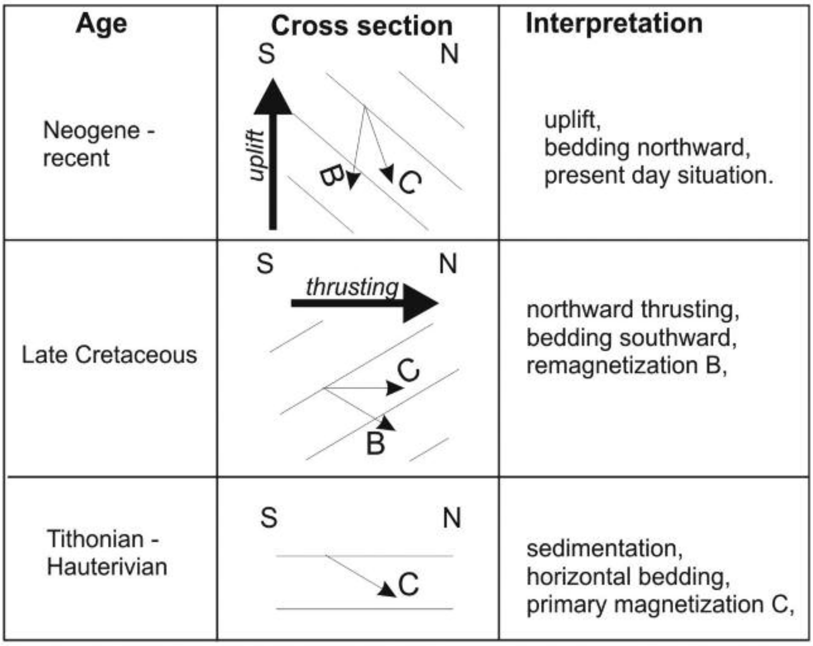


Text-fig. 12. Stepwise tectonic correction of component B. Two option are presented: untilting towards SSE (around mean present-day dip direction) and towards SSW (according to magnetic lineations in the Jasenina Formation). Grey ring indicates "expected" palaeoinclinations for the area in the Late Cretaceous–Early Tertiary. Square – position of the primary component C (see Table 1)

TECTONIC CORRECTION AND AGE OF MAGNETIZATION

Component C represents, in our opinion, a resultant vector between component B and a primary magnetization of dual (normal and reversed) polarity. It is noteworthy that the inclination of the main cluster of component C after 100% tectonic correction (restoring beds to a horizontal position), is concordant with the Berriasian palaeoinclination obtained for the Krížna unit in the Tatra Mts (Grabowski 2005, see Text-fig. 9d). If so, the primary palaeodeclination for the study area would be close to 340º, indicating a mild counterclockwise rotation in relation to the European platform and the Tatra Mts. A tentative directional evaluation of this component is presented in Table 1.

Acquisition of component B took place when the strata were relatively undeformed, albeit definitely not in the horizontal position. This means that component B must be interpreted as syn-deformational magnetization and its proper tectonic correction and age are a matter of interpretation. A very similar magnetization, based on magnetite with very high NRM intensities and susceptibilities more than 100 × 10^{-6}SI units caused by abundant SP magnetite grains was described from the Middle Triassic dolomites of the Krížna nappe (Suchy Wierch sub-unit) in the Tatra Mts (Grabowski 2000). Moreover, its direction was very similar to our component B, being apparently "pre-folding" (Text-fig. 11) but requiring additional tectonic correction to match it with the "expected" Mesozoic–Tertiary inclination of the area. Its origin was interpreted as fluid-related chemical remagnetization, which, beside SP magnetite, was evidenced by findings of authigenic potassium feldspar within the dolomites (Skiba and Michalik 1999). The occurrence of feldspars and SP magnetite are evidence for late diagenetic brine migration in carbonate rocks that might be coeval with nappe overthrusting, as is in the case of Northern Calcareous Alps (Spötl *et al.* 1998). In this case, the magnetization was interpreted as synthrusting of Cretaceous age (Grabowski 2000). The



Text-fig. 13. Schematic diagram illustrating tectonic evolution and magnetization of the Strážovce section

"expected" palaeoinclination for the Late Cretaceous–Early Tertiary of the Central West Carpathians would be around 60º, thus almost 15º less than observed in component B in the Strážovce section (Text-fig. 10). The simplest approach to match the inclination of component B with that expected would be to untilt it back, according to the regional bedding strike (see Text-fig. 1b-c and 3), in a SSE direction. This additional correction brings the component B close to component C. The bedding dip would be around 20–30º towards the SSE (Text-fig. 12). This might imply that the section might have been magnetized as a part of a contractional duplex during a NNW-directed thrusting episode dipping in an opposite direction to the thrusting direction (hinterland dipping duplex). The geometrical solution for tectonic correction of the Strážovce section towards the SSE is, however, not unique since we do not have independent structural evidences that Cretaceous compression of the area was indeed directed towards the NNW. The present-day bedding position of the Mesozoic units in the CWC was finally established after Neogene uplift of the crystalline massifs (Kováč *et al*. 1994). The axis of the uplift was directed WSW–ENE in the NW–SE-directed compression in the Early Miocene (Kováč *et al*. 1990). However, the magnetic lineation in the samples of the Jasenina Formation reveals a predominant WNW–ESE-directed lineation (Text-fig. 7d) which, in a case of normal magnetic fabric, is commonly attributed to the first pre-folding shortening (e.g. Lowrie and Hirt 1987; Tarling and Hrouda 1993). The Late Cretaceous compression that resulted in the inversion of the Zliechov basin and nappe stacking might have been directed NNE–SSW, thus obliquely to the present-day geometry of the structures. In this case, component B should be untilted to the SSW rather than to the SSE (Text-fig. 12). Although there is some uncertainty in the tectonic correction, it is quite clear that remagnetization took place during thrusting, with a bedding attitude opposite to the direction of thrusting (Text-fig. 13). This observation is in good agreement with tectonic models developed by Bac-Moszaszwili *et al*. (1984) and Jurewicz (2005) for the Mesozoic structures in the Tatra Mts. They argued that after untilting the Tatra block to a position prior to the Miocene uplift, the Mesozoic thrust planes attain southerly dips. It is very likely that the same model might be applied to the other "core mountains" of the CWC, particularly the Strážovske Vrchy Mts. To the best of our knowledge, our study is a second report (the first being Hillegeist *et al*. 1992) of syn-thrusting remagnetization related to imbricated structures of "duplex type". Although the fold test is apparently positive, the magnetization is not only secondary, but in fact "syn-deformational".

ORIGIN OF COMPONENT B

Preliminary results of vitrinite reflectance study in the Strážovce section indicate mean values of Ro 1.3–1.4%. This corresponds to maximum values of burial temperatures of 130–150ºC. These values are too low to cause a thermal resetting of magnetite grains according to the Pullaiah *et al*. (1975) diagrams; however, using the nomograms of Middleton and Schmidt (1982), thermally-activated remagnetization cannot be totally excluded. The Middleton and Schmidt (1982) nomogram fits better to experimental data for rocks containing a mixture of magnetite grains of variable grain size. On the other hand, an abundance of SP magnetite is a typical feature of chemically remagnetized carbonates (Jackson *et al*. 1993; Channell and McCabe 1994; Weil and Van der Voo 2002; Zwing *et al*. 2005). The largest amounts of SP magnetite in the Mraznica Formation correlate with the strongest remagnetization evidenced in analysis of the NRM (Text-fig. 4). This makes a strong argument in support of the chemical remagnetisation model. Hysteresis parameters from the Mraznica Formation (Text-fig. 6d) coincide with those from remagnetized Neocomian limestones of the Southern Pyrenees (Dinarés-Turell and García-Senz 2000) and the North American–northern England trend of remagnetized limestones which are considered as typical examples of chemical remagnetizations. The chemical event (oxidizing fluid flow?) might have caused the precipitation of new magnetite by oxidation of pyrite (which is a common mechanism of magnetite-related chemical remagnetizations see e.g. Suk *et al*. 1990). It can be easily imagined that fluid flow might have been triggered during thrusting e.g. in the situation presented in Text-fig. 2b. The presence of fluids, at least in the sole part of the Krížna nappe, is well supported by the geological data (Plašienka and Prokešová 1996; Jurewicz 2005; see also Geological setting, above).

Post-pyrite origin of secondary magnetite might explain why the most strongly remagnetized rocks of the Mraznica Formation are devoid of pyrite, while in the Jasenina Formation and partly in the Osnica Formation, which are not so heavily overprinted, the pyrite was still preserved. In those formations, the mechanism of remagnetization might be different from that in the Mraznica Formation. Hysteresis parameters of those formations (Text-fig. 7d) are close to the main cluster of Katz *et al*. (2000) from the Vocontian Basin (SE France), where smectite–illite transformation was postulated as the remagnetization factor. This mode of remagnetization was, however, questioned by Henry *et al*. (2001) and therefore it cannot be excluded that the Jasenina and Osnica Formations were either remagnetized thermally or were affected by the same fluid flow as the Mraznica Formation, but that its effects were weaker, resulting in only partial remagnetization of those formations. Linking of fluid circulation with remagnetization phenomena would require an integrated palaeomagnetic, structural and geochemical study of the wider area. It is noteworthy that, in our section, total remagnetization of the beds and a fundamental change of rock magnetic properties occurred above a fault-zone separating sampled sub-sections B and C (Text-fig. 1c and 4). This might indicate that the fault zone might be a migrating pathway of for hydrothermal solutions (e.g. Jurewicz and Słaby 2004), which might have been important remagnetization factors. It is a further confirmation that the palaeomagnetic method might be useful for tracing palaeofluid circulation in orogenic belts.

CONCLUSIONS

Uppermost Jurassic–Lower Cretaceous pelagic carbonates from the Strážovce section (Strážovské vrchy Mts, Central West Carpathians) reveal the presence of pervasive remagnetization (component B) related to magnetite. It was revealed in all of the three formations studied, albeit they differ in their rock magnetic characteristics, especially in the contribution of SP grains. The petromagnetic properties of the most strongly remagnetized Mraznica Formation are dominated by SP grains, this being a typical fingerprint for chemical remagnetization; however a thermoviscous mechanism cannot be excluded. Remagnetization is apparently "pre-folding", according to the fold test; however, this implies only that the beds were not deformed in relation to each other. In pre-folding coordinates, component B reveals an abnormally steep inclination and, to match it with the Eurasian "reference" inclination, additional tectonic correction is required. Its application implies that during remagnetization the strata must have dipped 20–30º to SSW or SSE, while the present-day dip is 30–80º to the NNW. As the section is located in one of the thrust sheets within the allochthonous Krížna unit, the magnetization B brings evidence for an intermediate stage of deformation. Component B was most probably acquired during the episode of Late Cretaceous thrusting when the regional dip of the rocks studied was toward the hinterland, in an opposite direction to the direction of tectonic transport. Remagnetization might have been promoted by the activity of a syn-deformational fault (shear?) zone which served as a migration pathway for hydrothermal solutions.

Acknowledgements

The authors are grateful to Prof. A. Pszczółkowski (Institute of Geological Sciences, Polish Academy of Sciences) for determination of the biostratigraphic age of the studied rocks from thin sections. Thanks are also due to Ing. T. Sztyrak for preparation of thin sections and technical assistance in the field, as well as K. Wolański and K. Sobień for laboratory measurements. Critical remarks of R. D. Elmore, E. Jurewicz and D. Plašienka are gratefully acknowledged. The investigations were supported by the Polish Committee for Scientific Research (project no. 6.14.0005.00.0 of the Polish Geological Institute and research grant 3 P04D 012 24 to JG).

REFERENCES

Aiello, I.W., Hagstrum, J.T. and Principi, G. 2004. Late Miocene remagnetization within the internal sector of the Northern Appenines, Italy. *Tectonophysics*, **383**, 1–14.

Aubourg, C. and Chabert-Pellline, C. 1999. Neogene remagnetization of normal polarity in the Late Jurassic black shales from the southern Subalpine Chains (French Alps). Evidence for late anticlockwise rotations. *Tectonophysics*, **308**, 473–486.

Bac-Moszaszwili, M., Gamkrelidze, I.P., Jaroszewski, W., Schroeder, E., Stojanov, S.S. and Tzankov, T.V. 1981. Thrust zone of the Križna nappe at Stoły in the Tatra Mts (Poland). *Studia Geologica Polonica*, **68**, 61–73.

Bac-Moszaszwili, M., Jaroszewski, W. and Passendorfer, E. 1984. W sprawie tektoniki Czerwonych Wierchów i Giewontu w Tatrach (On the tectonics of Czerwone Wierchy and Giewont area in the Tatra Mts, Poland), *Annales Societatis Geologorum Poloniae,* **52**, 67–88.

Besse, J. and Courtillot, V. 2002. Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr. *Journal of Geophysical Research*, **107**(B11), 2300, doi: 10.1029/2000JB000050. EPM 6.

Besse, J. and Courtillot, V. 2003. Correction to "Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr". *Journal of Geophysical Research*, **108**(B10), 2469, doi: 10.1029/2003JB002684. EPM 3.

Channell, J.E.T. and McCabe, C. 1994. Comparison of magnetic hysteresis parameters of unremagnetized and remagnetized limestones. *Journal of Geophysical Research*, **99**, B3, 4613–4623.

Day, R., Fuller, M.D. and Schmidt, V.A. 1977. Hysteresis properties of titanomagnetites: grain size and composition dependent. *Physics of the Earth and Planetary Interiors,* **13**, 260–266.

Dinarés-Turell, J. and García-Senz, J. 2000. Remagnetization of Lower Cretaceous limestones from the southern Pyrenees and relation to the Iberian plate geodynamic evolution. *Journal of Geophysical Research*, **105**, B8, 19405–19418.

Dunlop, D. 2002a. Theory and application of the Day plot (Mrs/Ms versus Hcr/Hc), 1, Theoretical curves and tests using titanomagnetite data. *Journal of Geophysical Research*., **107**, 10.1029/2001JB000486, 2002.

Dunlop, D. 2002b. Theory and application of the Day plot (Mrs/Ms versus Hcr/Hc), 2, Application to data for rocks, sediments, and soils, *Journal of Geophysical Research*, **107**, 10.1029/2001JB000487, 2002.

Elmore, R. D., Campbell, S., Banerjee, S. and Bixler, G. 1998. Paleomagnetic dating of ancient fluid flow events in the Arbuckle Mointains, S. Oklahoma. In: Parnell, J. (Ed.), Dating and duration of fluid flow and fluid rock interaction. *Geological Society, London, Special Publications*, **144**, 9–25.

Elmore, R.D., Cates, K., Gao, G. and Land, L. 1994. Geochemical constraints on the origin of secondary magnetizations in the Cambro–Ordovician Royer Dolomite, Arbuckle Mountains, southern Oklahoma. *Physics of the Earth and Planetary Interiors*, **85**, 3–14.

Elmore, R.D., Lee-Egger Foucher, J., Evans, M., Lewchuk M. and Cox, E. 2006. Remagnetization of the Tonoloway Formation and the Helderberg Group in the Central Appalachians: testing the origin of syntilting magnetizations. *Geophysical Journal International*, **166**, 1062–1076.

Elmore, R.D., London, D., Bagley, D. and Gao, G. 1993. Remagnetization by basinal fluids. Testing the hypothesis in the Viola Liumestone, southern Oklahoma. *Journal of Geophysical Research,* **98**, 6237–6254.

Enkin, R. J., Osadetz, K. G., Beker, J. and Kisilevsky, G. 2000. Orogenic remagnetizations in the Front Ganges and inner Foothills of the southern Canadian Cordillera: Chemical harbinger and thermal handmaiden of Cordilleran deformatons. *Geological Society of America, Bulletin*, **112**, 6, 929–942.

Fruit, D., Elmore, R.D. and Halgedahl, S. 1995. Remagnetization of the folded Belden Formation. Northwest Colorado. *Journal of Geophysical Research*, **100**, B8, 15009–15023.

Grabowski, J. 2000. Palaeo- and rock magnetism of Mesozoic carbonate rocks in the Sub-Tatric series (Central West Carpathians) – palaeotectonic implications. *Polish Geological Institute, Special Papers,* **5**, 1–88.

Grabowski, J. 2005. New Berriasian palaeopole from the Central West Carpathians (Tatra Mountains, southern Poland): does it look Apulian? *Geophysical Journal International,* **161**, 65–80.

Grabowski, J. and Pszczółkowski, A. 2006. Magneto- and biostratigraphy of the Tithonian – Berriasian pelagic sediments In the Tatra Mountains (central Western Carpathians, Poland): sedimentary and rock magnetic changes At the Jurassic/Cretaceous boundary. *Cretaceous Research*, **27**, 398–417.

Gradstein, F., Ogg, J. and Smith, A. 2004. A Geologic Time Scale 2004, 589 pp. Cambridge University Press.

Henry, B., Rouvier, H., le Goff, M., Leach, D., Macquar, J-D., Thibieroz, J. and Lewchuk, M.T. 2001. Palaeomagnetic dating of widespread remagnetization on the southeastern border of the French Massif Central and implications for fluid flow and Mississippi Valley-type mineralization. *Geophysical Journal. International*, **145**, 368–380.

Hillegeist, T. K., Fruit, D.J. and Elmore, R.D. 1992. Syndeformational magnetization in the Ordovician Bigfork Chert at Black Knob Ridge, western Ouachita Mountains, southern Oklahoma. *Earth and Planetary Science Letters*, **109**, 531–542.

Jackson, M., Rochette, P., Fillion, G., Banerjee, S. and Marvin, J. 1993. Rock magnetism of remagnetized Paleozoic carbonates: Lowe Temperature behaviour and susceptibility characteristics. *Journal of Geophysical Research*, **98**, B4, 6217–6225.

Jelínek, V. 1977. The statistical theory of measuring anisotropy of magnetic susceptibility of rocks and its application. Geofyzika Brno, 1–88.

Jaroszewski, W. 1982. Hydrotectonic phenomena at the base of the Križna nappe, Tatra Mts. In: M. Maheľ (Ed.), Alpine structural elements: Carpathian – Balkan – Caucasus – Pamir orogene zone. Veda, Bratislava, 137–148.

Jordanova, N., Henry, B., Jordanova, D., Ivanov, Z., Dimov, D. and Bergerat, F. 2001. Paleomagnetism in northwestern Bulgaria: geological implications of widespread remagnetization. *Tectonophysics*, **343**, 79–92.

Juárez, M.T., Lowrie, W., Osete, M.L. and Meléndez, F. 1998. Evidence for widespread Cretaceous remagnetization in the Iberian Range and its relation with the rotation of Iberia. *Earth and Planetary Science Letters*, **160**, 729–743.

Juárez, M.T., Osete, M.L., Vegas, R., Langereis, C.G. and Meléndez, G. 1996. Palaeomagnetic study of Jurassic limestones from the Iberian Range (Spain): tectonic implications. In: Morris, A. and Tarling, D.H. (Eds), Palaeomagnetism and Tectonics of the Mediterranean Region, *Geological Society, London, Special Publications*, **105**, 83–90.

Jurewicz, E. 2005. Geodynamic evolution of the Tatra Mts. And the Pieniny Klippen Belt (Western Carpathians): problems and comments. *Acta Geologica Polonica*, **55**, 295–338.

Jurewicz, E., Gireń, B. and Steller, J. 2007. Cavitation erosion – a possible cause of the mass loss within thrust zones in the Tatra Mts., Poland. *Acta Geologica Polonica*, **57**, 305–323.

Jurewicz, E. and Słaby, E. 2005. The Zadnie Kamienne "ravenous" shear zone (High-Tatric Nappe) – conditions of deformation. *Geological Quarterly*, **48**, 371–382.

Katz, B., Elmore, R.D., Cogoini, M., Engel, M.H. and Ferry, S. 2000. Associations between burial diagenesis of smectite, chemical remagnetization and magnetite authigenesis in the Vocontian trough, SE France. *Journal of Geophysical Research*, **105**, B1, 851–868.

Kechra, F., Vandamme, D. and Rochette, P. 2003. Tertiary remagnetization of normal polarity in Mesozoic marly limestone from SE France. *Tectonophysics*, **362**, 219–238.

Kent, D.V. 1985. Thermoviscous remagnetization in some Appalachian limestones. *Geophysical Research Letters*, **12**, 805–808.

Kirschvink, J.L. 1980. The least square line and plane and the analysis of paleomagnetic data. *Journal of Royal Astronomical Society*, **62**, 699–718.

Kirker, A. and McClelland, E. 1996. Application of nand tectonic rotations and inclination analysis to a high-resolution palaeomagnetic study in the Betic Cordillera. In: Morris, A. and Tarling, D.H. (Eds), Palaeomagnetism and Tectonics of the Mediterranean Region, *Geological Society, London, Special Publication*, **105**, 19–32.

Kováč, M., Kráľ, J., Márton, E., Plašienka D. and Uher, P. 1994. Alpine uplift history of the Central Western Carpathians: geochronological, paleomagnetic, sedimentary and structural data. *Geologica Carpathica*, **45**, 83–96.

Kováč, M., Marko, F. and Nemčok, M. 1990. Neogene history of intramontane basins in the western part of the Carpathians. *Rivista Italiana di Paleontologia e Stratigrafia*, **96**, 381–404.

Lewandowski, M., Nowożyński, K. and Werner, T. 1997. PDA – a package of FORTRAN programs for paleomagnetic data analysis (manuscript).

Lewchuk, M.T., Al.-Aasm, I.S., Symons, D.T.A. and Gillen, P. 2000. Late Laramide dolomite recrystallization of the Husky Rainbow "A" hydrocarbon Devonian reservoir, NW Alberta, Canada. Paleomagnetic and geochemical evidence. *Canadian Journal of Earth Sciences,* **37**, 17–29.

Lewchuk, M.T., Evans, M. and Elmore, R.D. 2003. Synfolding remagnetization and deformation: results from Paleozoic sedimentary rocks in West Virginia. *Geophysical Journal International*, **152**, 266–279.

Lowrie, W. 1990. Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties. *Geophysical Research Letters*, **17**, 159–162.

Lowrie, W. and Hirt, A.M. 1987. Anisotropy of magnetic susceptibility in the Scaglia Rossa pelagic limestone. *Earth and Planetary Science Letters*, **82**, 349–356.

McCabe, C. and Elmore, R.D. 1989. The occurrence and origin of late Paleozoic remagnetization in the sedimentary rocks of North America. *Reviews of Geophysics*, **27**, 471–494.

McCaig, A.M. and McClelland, E. 1992. Paleomagnetic techniques applied to thrust belts. In: McClay, K.R (Ed.), Thrust Tectonics, pp. 209–216. Chapman and Hall.

McFadden, P.L. 1990. A new fold test for paleomagnetic studies. *Geophysical Journal International*, **103**, 163–169.

Maheľ, M. 1985. Geologická stavba Strážovských vrchov (Geological structure of the Strážovske vrchy Mts), 221 pp. Geologický Ústav D. Štúra; Bratislava.

Michalík, J. 1995. Lower Cretaceous stratigraphy, facies, faunas and Tethyan/Boreal influences in the Western Carpathians. *Cretaceous Research*, **16**, 299–310.

Michalík, J. 2007. Sedimentary rock record and microfacies indicators of the latest Triassic to mid-Cretaceous tensional development of the Zliechov Basin (Central West Carpathians). *Geologica Carpathica*, **58**, 443–453.

Michalík, J., Lintnerová, O., Gaždzicki, A. and Soták, J. 2007. Record of environmental changes in the Triassic/Jurassic boundary interval in the Zliechov Basin, Western Carpathians. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **244**, 71–88.

Michalík, J., Vašíček, Z. and Borza, V. 1990. Aptychi, tintinnids and stratigraphy of the Jurassic – Cretaceous boundary beds in the Strážovce section, Central Western Carpathians, Western Slovakia). Knihovnička Zemniho plynu a nafty, 9a, 69–92.

Middleton, M. F. and Schmidt, P.W. 1982. Paleothermometry of the Sydney Basin. *Journal of Geophysical Research*, **87**, 5351–5359.

Oliva-Urcia, B., Pueyo, E.L. and Larrasoana, J.C. 2008. Magnetic reorientation induced by pressure solution: a potential mechanism for orogenic scale remagnetizations. *Earth and Planetary Science Letters*, **265**, 525–534.

Opdyke, N.D. and Channell, J.E.T. 1996. Magnetic stratigraphy, 346 pp. Academic Press; San Diego.

Plašienka, D. 1995. Passive and active margin history of the northern tatricum (Western Carpathians, Slovakia). *Geologische Rundschau*, **84**, 748–760.

Plašienka, D. 1996. Mid-Cretaceous (120-80 Ma) orogenic processes in the Central Western Carpathians: brief review and interpretation of data. *Slovak Geological Magazine*, **3-4/96**, 319–324.

Plašienka, D., Grecul, P., Putiš, M., Kováč, M. and Hovorka, D. 1997. Evolution and structure of the Western Carpathians: an overview. In: Grecul, P., Hovorka, D. and Putiš M. (Eds), Geological evolution of the Western Carpathians. Mineralia Slovaca – Monograph, Bratislava, pp. 1–24.

Plašienka, D. and Prokešova, R. 1996. Towards an evolutionary model of the Krížna cover nappe (Western Carpathians, Slovakia). *Slovak Geological Magazine*, **3-4/96**, 279–286.

Plašienka, D. and Soták, J. 1996. Rauhwackized carbonate breccias in the West Carpathian nappe edifice: introductory remarks and preliminary results *Slovak Geological Magazine*, **3-4/96**, 287–291.

Polák, M., Ondrejičková, A. and Wieczorek, J. 1998. Lithobiostratigraphy of the Ždiar Formation of the Križna nappe (Tatry Mts.). *Slovak Geological Magazine*, **4**, 35–52.

Pueyo, E.L., Mauritsch, H.J., Gawlick, H-J., Scholger, R. and Frisch, W. 2007. New evidence for block and thrust sheet rotations in the central northern Calcareous Alps deduced from two pervasive remagnetization events. *Tectonics*, **26**, TC5011, doi: 10.1029/2006/TC001965.

Pueyo, E. L., Pocoví, A., Parés, J.M., Millán, H. and Larrasoaña, J.C. 2003. Thrust ramp geometry and spurious rotations of paleomagnetic vectors. *Studia Geophysica & Geodaetica*, **47**, 331–358.

Pullaiah, G., Irving, E., Buchan, K.L. and Dunlop, D.J. 1975. Magnetisation changes caused by burial and uplift. *Earth and Planetary Science Letters*, **28**, 133–143.

Skiba, M. and Michalik, M. 1999. Origin of non-carbonate components in Triassic carbonate rocks from the Križna unit in the Tatra Mts. *Mineralogical Society of Poland - Special Papers*, **14**, 122–123.

Spötl, C., Kunk, M. J., Ramseyer, K. and Longstaffe, F.J. 1998. Authigenic potassium feldspar: a tracer for the timing of palaeofluid flow in carbonate rocks, Northern Calcareous Alps, Austria. In: Parnell, J. (Ed.), Dating and Duration of Fluid Flow and Fluid-Rock Interaction. *Geological Society*, *London*, *Special Publications*, **144**, 107–128.

Stamatakos, J. and Kodama, K.P. 1991. Flexural flow folding and the paleomagnetic fold test: an example of strain reorientation of remanence in the Mauch Chunk formation. *Tectonics*, **10**, 807–819.

Suk, D., Peacor, D. R. and Van der Voo, R. 1990. Replacement of pyrite framboids by magnetite in limestone and implications for paleomagnetism. *Nature*, **345**, 611–613.

Suk, D., Van der Voo, R. and Peacor, D.R. 1993. Origin of magnetite responsible for remagnetization of Early Palaeozoic limestones of New York state. *Journal of Geophysical Research*, **98**, 419–434.

Tarling, D.H. and Hrouda, F. 1993. The Magnetic Anisotropy of Rocks, 217 pp. Chapman and Hall; London.

Van Velzen, A. 1992. Magnetic minerals in Pliocene and Pleistocene marine marls from Southern Italy. Rock magnetic properties and alteration during thermal demagnetisation. *Geologica Ultraiectina*, **122**, 154 pp.

Vašíček, Z., Michalík, J. and Reháková, D. 1994. Early Cretaceous stratigraphy, paleogeography and life in Western Carpathians. *Beringeria*, **10**, 3–168.

Villalaìn, J.J., Fernández – González, G., Casas, A. M. and

Gil-Ilmaz, A. 2003. Evidence for Cretaceous remagnetization in the Cameros Basin (North Spain): implications for basin geometry. *Tectonophysics*, **377**, 101–117.

Villalaìn, J.J., Osete, M.L., Vegas, R., Garcia – Duenas, A. and Heller, F. 1996. The Neogene remagnetization in the western Betics: a brief comment on the reliability of palaeomagnetic directions. In: Morris, A. and Tarling, D.H. (Eds), Palaeomagnetism and Tectonics of the Mediterranean Region, *Geological Society*, *London*, *Special Publications*, **105**, 33–41.

Weil, A.B. and Van der Voo, R. 2002. Insights into the mechanism for orogen-related carbonate remagnetization from growth of authigenic Fe-oxide: A scanning electron microscopy and rock magnetic study of Devonian carbonates from northern Spain *Journal of Geophysical Research*, **107**, B4, DOI 10.1029/2001JB000200.

Xu, W.R., Van der Voo, R. and Peacor, D.R. 1998. Electron microscopic and rock magnetic study of remagnetized Leadville carbonates, central Colorado, *Tectonophysics*, **296**, 333–362.

Zwing, A., Matzka, J., Bachtadse, V. and Soffel, H.C. 2005. Rock magnetic properties of remagnetized Palaeozoic clastic and carbonate rocks from the NE Rheinish massif, Germany. *Geophysical Journal International*, **160**, 477–486.

Manuscript submitted: 25th July 2008
Revised version accepted: 15th May 2009