Paleomagnetic and magnetic fabric data from Lower Triassic redbeds of the Central Western Carpathians: new constraints on the paleogeographic and tectonic evolution of the Carpathian region

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Abstract: In the Central Western Carpathians (CWC), most published paleomagnetic results from Permo-Mesozoic rocks document extensive remagnetizations and come from thin-skinned thrust units that have undergone multistage deformation. We present results from lower Triassic redbeds from the autochthonous cover overlying the basement that carry a primary magnetization. Petromagnetic results indicate that the dominant ferromagnetic carrier is hematite, while magnetic susceptibility and its anisotropy are controlled by both ferromagnetic and paramagnetic minerals. Magnetic fabrics document weak deformation related to Late Cretaceous shortening. The directions of the high unblocking temperature remanence components pass both reversal and fold tests, attesting to their primary nature. Paleomagnetic inclinations are flatter than expected from reference datasets, suggesting small latitudinal separation between the CWC and stable Europe. Paleomagnetic declinations are mostly clustered within individual mountain massifs, implying their tectonic coherence. They show only minor differences between the massifs, indicating a lack of significant vertical-axis tectonic rotations within the studied central parts of the CWC. The paleomagnetic declinations are therefore representative of the whole of the CWC in terms of regional paleogeographic interpretations, and imply moderate counterclockwise rotations (*c.* 26°) of the region with respect to stable Europe since the Early Triassic.

Paleomagnetism is a useful method of studying mountain chains, as it provides valuable data on both the paleogeographic position of the large crustal units amalgamated as a result of orogenic processes, as well as the kinematics of smaller tectonic units such as thrust-sheets or fault-bounded blocks. However, the correct interpretation of paleomagnetic results requires an awareness of the complexity of multi-stage tectonic processes. Difficulties include distinguishing between local and regional paleomagnetic rotations, and determining the proper tectonic correction of paleomagnetic vectors in areas that have undergone several deformation phases (e.g. Appel *et al.* 2012; Pueyo *et al.* 2016; Calvín *et al.* 2017; Michalski *et al.* 2017; Mattei *et al.* 2019). Nonetheless several studies have successfully applied paleomagnetic and magnetic fabric data to oroclines in which the origin of a mountain belt curvature is interpreted (e.g. Lowrie & Hirt 1986; Lacquement *et al.* 2005; Weil *et al.* 2010; Meijers *et al.* 2017; Szaniawski *et al.* 2017; Pastor-Galán *et al.* 2018; Satolli *et al.* 2019).

A first objective of this study was to obtain a more thorough knowledge of the paleogeographic and tectonic evolution of the Western Carpathians by applying paleomagnetic methods. We focused on the Central Western Carpathians (CWC) unit, which forms the largest part of the Western Carpathians and constitutes a fragment of the Alcapa terrane (Fig. 1 and Section 1). We hoped to determine whether the CWC constitutes a coherent tectonic assemblage, or whether individual mountain massifs forming the

CWC experienced independent tectonic rotations. This question also bears an oroclinal bending aspect, as the mountain massifs form a curved arc following the regional trend of the mountain belt (Fig. 1). We also hoped to determine if the CWC was rotated relative to stable Europe, which is key to understanding the regional paleogeographic evolution of this part of central Europe.

Paleomagnetic studies of the CWC unit have been conducted over the last four decades, providing numerous results from rocks of different ages and tectonic positions (recently summarized by Márton *et al.* 2016). However, the regional interpretation of these results and the formulation of a consistent model of the paleogeographical evolution of the CWC pose a challenge. The main problem arises from the fact that most of the results obtained from Mesozoic rocks were derived from thin-skinned thrust-sheets (e.g. Kruczyk *et al.* 1992; Krs *et al.* 1996; Grabowski & Nemčok 1999; Grabowski 2005; Grabowski *et al.* 2009, 2010) and document variable tectonic rotations. However it is difficult to distinguish whether the paleomagnetic directions reflect regional rotations of the whole lithosphere or whether they result from local nappe-scale rotations. Only a handful of results come from the autochthonous Mesozoic cover of the CWC, but they pertain to only a relatively small area of the Tatra Mountains (Grabowski 1995, 1997; Szaniawski *et al.* 2012) or are based on a small number of sampling sites (Pruner *et al.* 1998). Moreover, Mesozoic limestones in the CWC record extensive remagnetization; most of the previous results
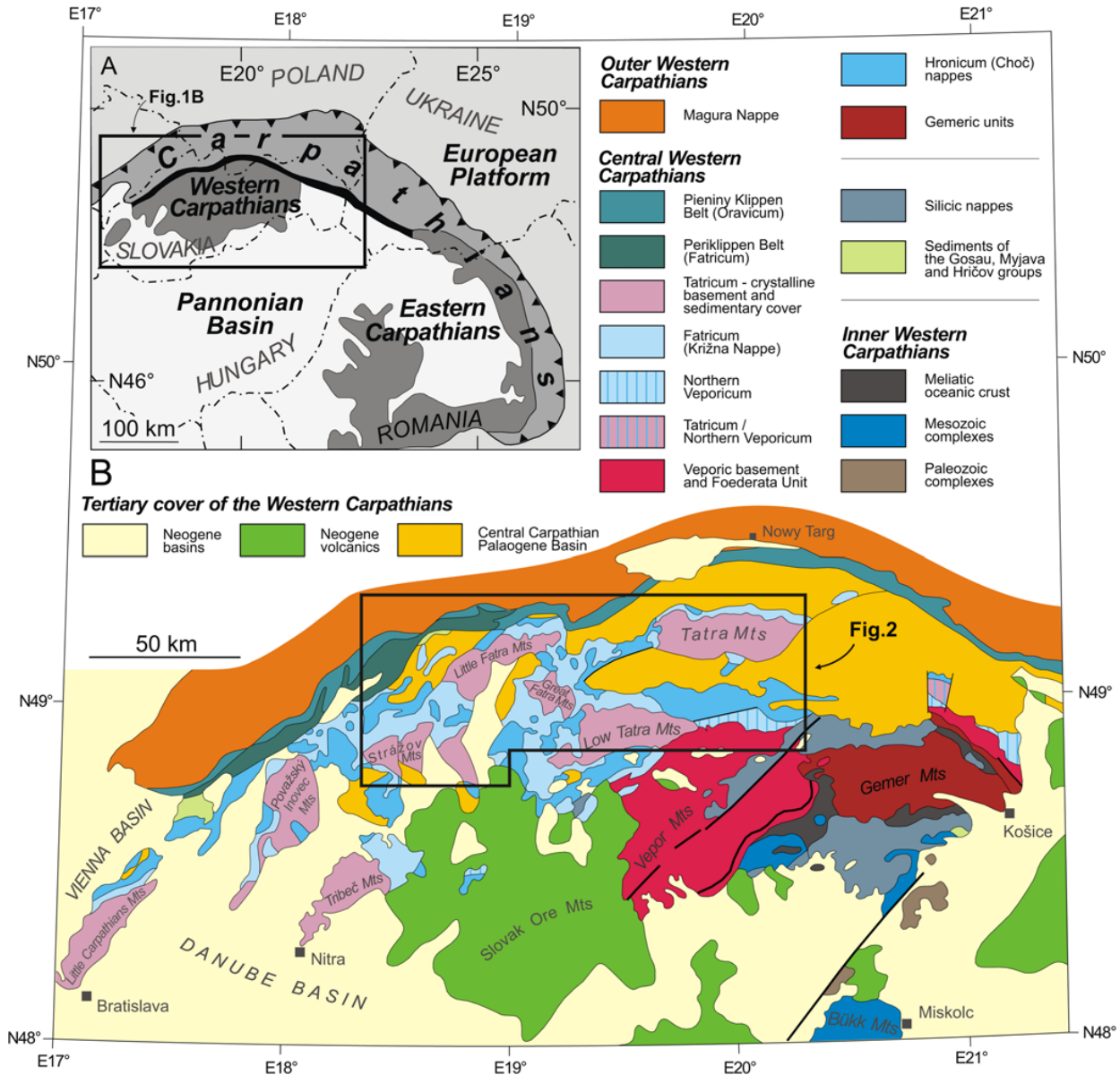
Fig. 1. Schematic tectonic map of the Western Carpathians with the location of the study area (compiled after Lexa *et al.* 2000; Plašienka 2003; Bezák *et al.* 2004).

document secondary magnetizations recorded in the intermediate stage of complex polyphase deformation histories (summarized by Márton *et al.* 2016), and are difficult to interpret in a regional framework.

This study is a continuation of our earlier work performed in the Tatra Mountains, a mountain massif of *c.* 800 km² forming part of the CWC. We have previously studied in this area Lower Triassic redbeds from the autochthon deposited directly on the crystalline basement (Szaniawski *et al.* 2012). Our previous results document a well-preserved primary remanent magnetization recorded by hematite. Moreover, the rocks studied previously in the Tatra Mountains autochthon display a relatively clear tectonic position: (i) they are situated only slightly above the nonconformity between the crystalline basement and the Mesozoic sedimentary cover, (ii) they underwent only minor deformation during Late Cretaceous shortening, being located in a footwall position relative to thin-skinned nappes, and (iii) the present-day bedding attitude of these rocks results predominantly from a single deformation

phase, i.e. the tilting of the whole Tatra Block related to the Neogene uplift (e.g. Rubinkiewicz & Ludwiniak 2005; Szaniawski *et al.* 2012).

Therefore, Triassic redbeds from the autochthonous cover constitute a good research target for a paleomagnetic study. The main limitation of our previous study arises from the fact that it was confined to a small area of the Tatra Mountains. In the current study we have scrutinized rocks of matching age, lithology and tectonic position from nearby mountain massifs representing separate tectonic blocks: the Low Tatra, Great Fatra and Strážov Mountains (Fig. 2). As a result, the area of our new study has covered a significant part of the CWC, enabling a wider interpretation. In addition to the analysis of the magnetic remanence, we have also studied in detail the anisotropy of the magnetic susceptibility (AMS), aiming to constrain the strain pattern which helps us to better understand the tectonic evolution of the area. Additionally, we have examined the magnetic mineralogy of the rocks to fully interpret the paleomagnetic and AMS results.
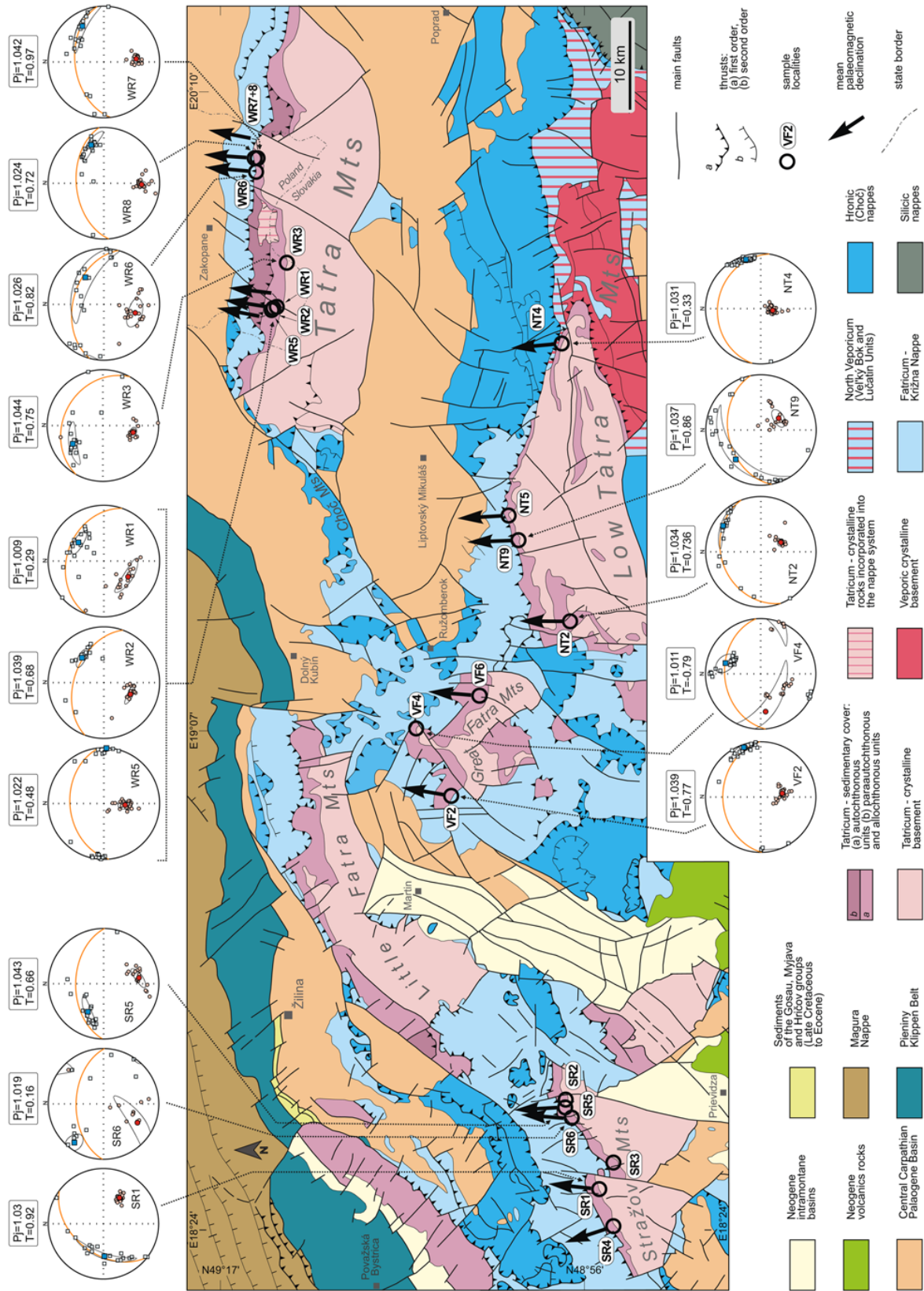
Fig. 2. Simplified geological map of the study area with marked location of sampling sites (compiled after Mahel' *et al.* 1982; Biely *et al.* 1992; Polák *et al.* 1997; Nemčok *et al.* 1994). Stereographic diagrams show AMS results (only for samples in which the susceptibility is higher than $30 \times 10{-}6$ SI volume); AMS principal axes are marked as red circles (Kmin) and blue squares (Kmax). Larger symbols representing site-mean principal axes are shown with their 95% confidence ellipses. Orange circles are mean bedding. T: shape parameter; Pj: corrected anisotropy degree (both parameters after Jelínek 1981).

Geological setting and sampling

The north-western part of the Carpathian orogenic belt is commonly divided into several tectonic units outlining a distinct structural pattern resulting from Mesozoic and Cenozoic orogenic processes. The northernmost external branch of the Western Carpathians forms the Outer Western Carpathians (OWC, Fig. 1), representing a typical foreland fold-and-thrust belt (e.g. Książkiewicz 1977; Roure *et al.* 1993; Matenco & Bertotti 2000; Oszczypko 2006). The OWC comprise uppermost Jurassic to lower Miocene sediments deposited onto the European Platform margin which were then thrusted toward the foreland in the Miocene (e.g. Pescatore & Ślączka 1984; Roca *et al.* 1995; Picha *et al.* 2006; Ślączka *et al.* 2006; Andreucci *et al.* 2013; Castelluccio *et al.* 2015, 2016). On their southern side, the OWC are bounded by an intensely deformed sedimentary mélange (Castelluccio *et al.* 2016) traditionally known as the Pieniny 'Klippen Belt' (although this unit includes no klippe, but rather blocks in matrix). Farther south are located the CWC (e.g. Andrusov 1965; Scheibner 1968; Birkenmajer 1986; Mahel' 1989; Golonka *et al.* 2015; Jurewicz 2018; Plašienka 2018*b*), which are the subject of this study (Fig. 1). The CWC are composed of various pre-Cenozoic rock units which were deformed and partially thrusted during the Cretaceous and then covered by a post-nappe Late Cretaceous to Paleogene sedimentary cover (Marschalko 1968; Mišík 1978, 1994; Wagreich & Marschalko 1995; Kázmér *et al.* 2003). On the southern side, the CWC are adjacent to the Inner Western Carpathians unit, which is bounded to the south by the Meliata Belt. This belt represents a suture zone, a relic of the Triassic–Jurassic Meliata ocean. The CWC together with the Inner Western Carpathians and the Meliata Belt are interpreted to form part of the Alcapa terrane, whose final amalgamation with the European Platform is dated to the Miocene (e.g. Němčok *et al.* 1998; Hrubcová & Środa 2015; Plašienka 2018*a*).

The studied mountain massifs (the Low Tatra, Great Fatra and Strážov Mountains), together with the previously analyzed Tatra Mountains, form part of the so-called Tatra–Fatra Belt (TFB) located in the outer portion of the CWC (Fig. 2). The TFB is formed by separate mountain massifs in which pre-Cenozoic rocks crop-out. The rocks in the massifs comprise Variscan crystalline basement with a mostly Mesozoic autochthonous sedimentary cover, overthrust by the thin-skinned Krížna and Choč nappes which were emplaced in the late Cretaceous. All these rocks are discordantly covered by Late Cretaceous–Early Paleogene syn-orogenic sediments (preserved only in limited locations) as well as widespread post-nappe deposits of the Central Carpathian Paleogene Basin which partially covers the areas between the raised massifs.

The mountain massifs forming the TFB have an elongated shape dozens of kilometres in length, with an elongation axis roughly parallel to the regional trend of the mountain belt. These massifs are actually horsts formed as a result of Neogene uplift processes (Kováč *et al.* 1994; Bac-Moszaszwili 1995; Anczkiewicz *et al.* 2005; Králiková *et al.* 2014). Such horsts are bounded to the S or SE by faults and tilted toward the foreland; e.g. the northward inclination of the Tatra Block is related to Neogene uplift and estimated to reach 40° (Sperner *et al.* 2002; Jurewicz 2005; Rubinkiewicz & Ludwiniak 2005; Szaniawski *et al.* 2012; Śmigielski *et al.* 2016). It should be noted at this point that according to geophysical observations and some geotectonic models (e.g. Tomek 1993; Roca *et al.* 1995; Ernst *et al.* 1997; Castelluccio *et al.* 2016) the crystalline basement of the TFB is also detached and underlain by a thrust fault, and therefore the TFB is itself interpreted as a basement nappe.

Samples for paleomagnetic studies have been collected from the Lower Triassic sandstones of the Lúžna Formation in the Low Tatra, Great Fatra and Strážov Mountains where these rocks lie usually directly on the Variscan crystalline basement (Permian sediments are known only from isolated outcrops). The Lúžna Formation is typically 30–100 m thick and includes basal conglomerates passing upwards into coarse- and medium-grained quartzose sandstones of light yellow colours, overlain by reddish fine-grained sandstones passing into red mudstones (Roniewicz 1966; Fejdiová 1980; Mišík & Jablonský 2000). Sampling has been carried out within the upper part of the profile, the preferred lithology of the sampled rocks ranging from gray-pink and red sandstones (sites NT2, NT5, NT9, VF2, SR1, SR4) to red mudstones (dominant in sites VF4, NT4). Usually, we collected 6–8 oriented hand samples at each site. It is worth noting that in the Tatra (previous study) and Low Tatra Mountains rocks of the appropriate lithology were relatively easy to find and sample, in contrast to the Great Fatra and the Strážov Mountains where white or lightly pinkish sandstone with gravels are dominant within the Lúžna Formation. Despite prolonged and intense field work, we have found only a few suitable outcrops (VF2, SR1, SR4) in the Great Fatra and the Strážov Mountains. Accordingly, in these latter areas we have decided to sample thin (5–20 cm) reddish intercalations of thick-bedded, yellowish quartzose sandstones and conglomerates. Within a single site, we collected samples from several such reddish layers (sites SR6, VF6). In addition we collected four samples from a single 20 cm red mudstone layer (site SR5) situated between massive quartzose sandstones. Samples were subsequently drilled in the laboratory to obtain standard oriented specimens. Despite our great efforts, we were not able to find rocks of appropriate lithology in the areas of the Považský Inovec and Tribeč Mountains to the SW (Fig. 1) where only thick-bedded, light-coloured sandstones and conglomerates occur.

Magnetic mineralogy and AMS characteristics

Our initial step in the recognition of ferromagnetic (*sensu lato*) minerals within our sample was the application of isothermal remanent magnetization acquisition (IRM) and back-field demag-netization (Hcr) tests. The IRMs were imparted using a Magnetic Measurements pulse magnetizer and the resulting remanence measurements made using a 2G enterprise 755 magnetometer housed in the Paleomagnetic Laboratory, Institute of Geophysics, Polish Academy of Sciences, Warsaw. The general form of the IRM curves was consistent for all studied sites. The initial (up to 1 T) increase in the magnetic remanence was relatively slow and the graph gradually flattened only in the fields of 1 to 3 T, i.e. in the coercivity range characteristic of hematite (Fig. 3a). After the application of higher fields (from 3 T up to 6 T), the magnetization remained almost unchanged or increased only slightly, most likely due to the presence of accessory goethite. The values of saturation magnetization were between 2 and 6 mA m^{-1} for red sandstones and mudstones but were up to an order of magnitude smaller in the case of gray-reddish sandstones from sites SR6 and VF2. Similarly to the IRM results, the back-field demagnetization tests also documented a relatively high coercivity as Hcr values ranged from 0.5 to 1 T.

Corresponding results were obtained using the method of thermal demagnetization of a three-component IRM (Lowrie 1990). The results confirmed a clear domination of the high-coercivity magnetic phase characterized by maximum unblocking tempera-tures (T_{ub}) of over 650°C, i.e. typical of hematite (Fig. 3b). The contribution of low- and medium-coercivity magnetic carriers was in most cases very low and showed up more distinctly only in single samples that did not display a clear correlation with their lithology (Fig. 3c). The observed maximum T_{ub} of this low- and medium-coercivity phase was mainly between 550 and 600°C, which is indicative of the presence of magnetite.

The thermal variations of susceptibility recorded in air documented relatively small thermochemical alterations as
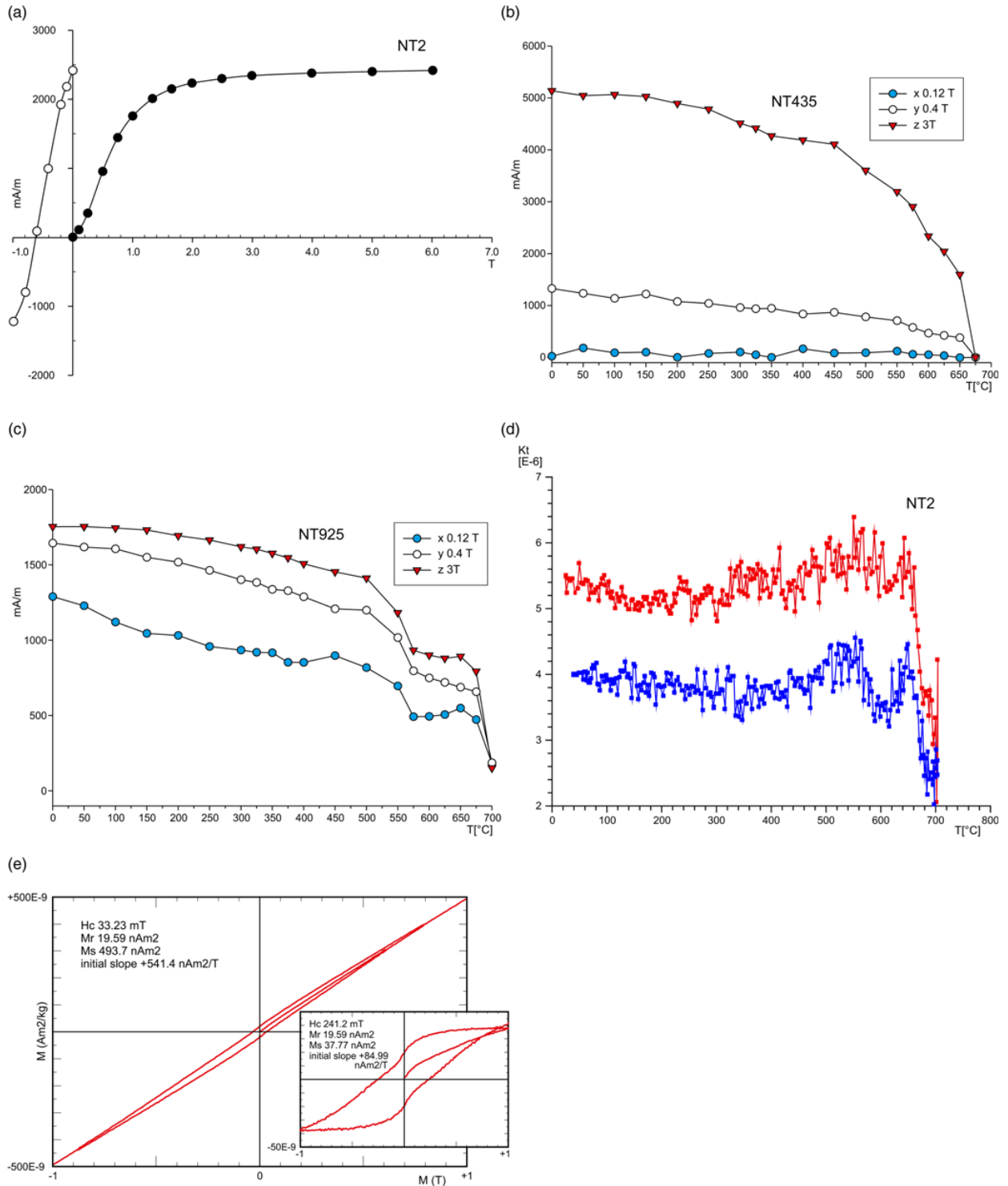
Fig. 3. Results of petromagnetic studies. (**a**) stepwise acquisition of IRM and its back field demagnetization; (**b** and **c**) thermal demagnetization of a composite three-axis IRM (Lowrie 1990); (**d**) susceptibly v. temperature curves; (**e**) hysteresis loops (small diagram shows results after paramagnetic slope correction).

thermomagnetic runs were almost fully reversible (Fig. 3d). These were measured using an AGICO CS-furnace attached to a KLY-3S susceptibility bridge. Up to temperatures of 600°C, the susceptibility signal was characterized by relatively minor changes. Initially (up to 450°C), the thermomagnetic curves were either flat or only slightly decreasing with a hyperbolic shape, the latter being characteristic of the presence of a paramagnetic phase, most likely a clay. The application of the Hrouda *et al.* (1997) method for distinguishing the ferromagnetic from paramagnetic susceptibility components (carried out in the temperature range 50–450°C) indicated that the ferro/para ratio was mostly above 70%. At higher temperatures (over 450°C), the susceptibility signal usually increased, a result we attributed to minor thermochemical alterations. Then, at temperatures above 600°C, the susceptibility
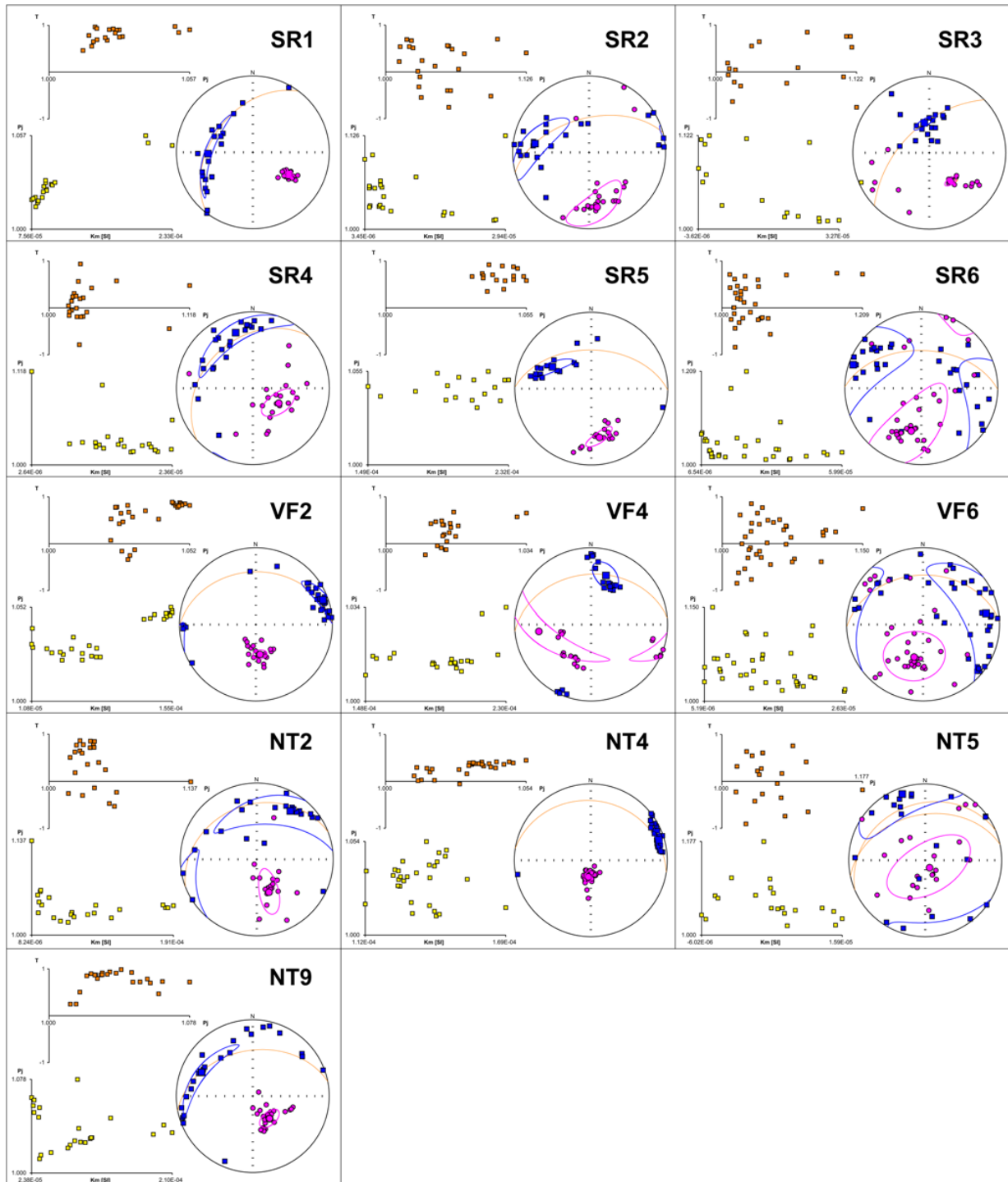
Fig. 4. AMS results. The diagrams display relationships of Km (susceptibility) v. Pj (corrected anisotropy degree), and of Pj v. T (shape parameter). Plots of AMS principal axes show Kmin (purple circles) and Kmax (blue squares). Larger symbols representing site-mean principal axes are shown with their 95% confidence ellipses. The orange circle is mean bedding.

decreased slowly with a significant drop of the signal above 650°C, which is indicative of hematite.

Petromagnetic studies were completed by an examination of hysteresis loops carried out with a Princeton Instruments Micro-Mag vibrating sample magnetometer (Fig. 3e). The results were coherent for all studied sites, showing effects of both paramagnetic and ferromagnetic minerals. After the correction for the paramagnetic phase, hysteresis loops were indicative of the presence of a high-coercivity ferromagnetic phase, matching the hematite identified previously using the thermal methods. Most of the loops also displayed a characteristic 'wasp-waisted' shape, indicating the co-occurrence of predominant high-coercivity minerals with smaller amounts of a low-coercivity ferromagnetic phase.

AMS studies, performed with an AGICO KLY-3S susceptibility bridge, revealed low to moderate values of magnetic susceptibility which showed some dependence on rock lithology (Fig. 4). The

highest susceptibility (mostly from 10^{-5} to up to 24×10^{-5} SI units) was observed in red mudstones and sandstones (sites NT4, SR1, SR5, VF4 and the majority of samples from sites NT2, NT9, SR6, VF2) while in gray-reddish sandstones the susceptibility values were noticeably lower, often reaching negative values (sites NT5, SR2, SR3, SR4, VF6). For sites with the lowest susceptibility, the AMS parameters were very different: the degree of anisotropy ranged from very small values to 1.2, AMS ellipsoids displayed variable shapes, and AMS axes were somewhat scattered. We attributed this to the effect of the overlapping of diamagnetic and para- and ferromagnetic sub-fabrics as well as a large observational error in cases where the susceptibility values were close to zero. Therefore, we decided to consider AMS parameters only for samples in which the susceptibility was higher than 30×10^{-6} SI units (Fig. 2).

In sites with higher susceptibility values ($>30 \times 10^{-6}$ SI units), the AMS characteristics were mostly similar. The anisotropy degree (P) (Chadima & Jelínek 2008) ranged from 1.01 to 1.04; the site-mean AMS ellipsoids were dominantly oblate, parallel to bedding and weakly to moderately developed. A magnetic lineation was expressed by a weak to quite good grouping of the maximum AMS

axes in particular sites. The results from SR6 differed in that the susceptibility values were very scattered, ranging from close to zero up to 600×10^{-6} SI units, while the AMS axes of individual samples were also scattered. Different and noteworthy results were observed in site VF4. Here, despite the fact that the susceptibility values were similar to the majority of other sites, the anisotropy degree was relatively low ($P = 1.01$) and the AMS ellipsoid was clearly prolate (Fig. 2). The maximum AMS axes were well clustered/grouped and lay in a bedding plane whereas the minimum axes formed a girdle perpendicular to the lineation.

Paleomagnetic results

Paleomagnetic studies were carried out in all the sites, except for site VF4 where the AMS results imply that these rocks have undergone a substantial tectonic strain that could potentially disturb the paleomagnetic record. As in the case of the AMS properties, the paleomagnetic results showed some variation related to the lithology. The highest natural remanent magnetization (NRM)
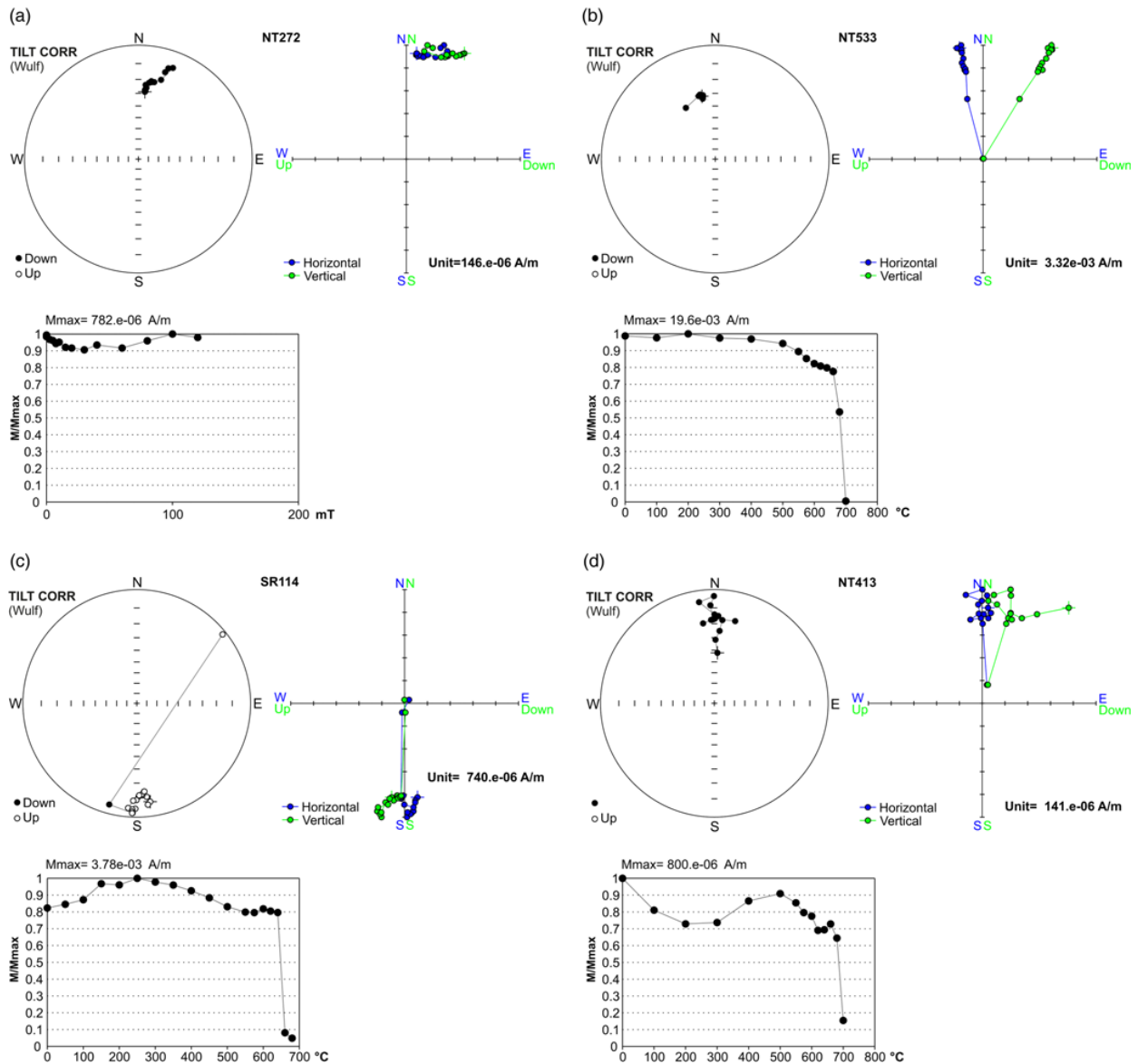

Fig. 5. AF (**a**) and thermal (**b**–**d**) demagnetization results of representative specimens; all diagrams after tectonic correction.

Table 1. *Paleomagnetic results*

Site	Dir/dip	N_1/n_1	N/R	D/I	Dc/Ic	k	α_{95}	K	A95	ΔDx	ΔIx
SR1	307/45	5/10	0/10	206.7/−33.2 (26.7/33.2)	186.1/−16.3 (6.1/16.3)	12.56	14.2	13.2	13.8	13.9	25.9
SR2	-	-	-	-	-	-	-				
SR3	-	-	-	-	-	-	-				
SR4	317/35	7/14	14/0	354.0/48.6	341.8/18.1	15.49	10.4	19.9	9.1	9.2	16.9
SR5	1/48	4/9	9/0	345.1/76.3	356.8/28.7	25.39	10.4	39.4	8.3	8.6	13.7
SR6	1/49	7/10	10/0	13.1/73.0	4.8/24.3	8.75	17.3	10.3	15.8	16.2	27.5
VF2	359/32	13/15	13/2	14.6/48.8	9.7/17.5	15.43	10.1	21.2	8.5	8.6	15.8
VF4	-	-	-	-	-	-	-				
VF6	358/36	8/13	12/1	10.6/61.4	4.6/25.8	9.23	14.4	9.1	14.5	15	25
NT2	339/29	6/16	16/0	14.2/57.3	0.4/31.5	25.19	7.5	26.5	7.3	7.6	11.6
NT4	9/23	10/13	13/0	349.8/46.9	354.7/24.8	26.26	8.2	39.1	6.7	6.9	11.7
NT5	337/27	9/12	12/0	5.3/50.4	356.6/25.5	26.24	8.6	39.7	7	7.2	12
NT9	349/40	5/14	14/0	6.3/61.1	357.9/21.9	13.21	11.4	15.2	10.5	10.7	18.9

Overall mean (14 sites) after tectonic correction: 4.4/22.6 k = 143 α_{95} = 3.3

(sites SR1, SR6, VF2, VF6, NT2, NT4, NT5, NT9 and WR1, WR2, WR5, WR6, WR7, WR8 from Szaniawski *et al.* 2012)

Dir/dip – tectonic orientation of strata (azimuth of dip, angle of dip), D/I – declination and inclination before tectonic correction, N1/n1– number of samples/specimens used in calculations, N/R - number of samples with normal/reversed polarity, Dc/Ic – declination and inclination after tectonic correction, k and α95 – standard Fisher statistical parameters for paleomagnetic directions, K, A95 – Fisher statistical parameters for virtual geomagnetic poles (after tectonic correction), ΔDx, ΔIx – errors for the declination and inclination respectively (after tectonic correction). The last four parameters are calculated based on the methods described by Butler (1992) and Deenen *et al.* (2011).

intensity (mostly between 0.5 and 3 mA m^{-1}) was typically observed in intensely red mudstones and sandstones. Slightly weaker magnetization was observed in rocks characterized by paler shades of red, while in the case of light gray sandstones the NRM intensity dropped to the noise level of the SQUID magnetometer. This general regularity, however, did not occur in each case: for example in light pink sandstones from NT5, magnetization was relatively high.

In specimens characterized by high and moderate magnetization, the structure of the NRM was usually relatively similar. NRM was to a larger degree immune to both alternating field demagnetization (up to 120 mT) and thermal demagnetization at low to moderate temperatures (Fig. 5a and b). Up to a temperature of 600°C, the magnetization intensity changed only to a small extent. At the same time, the orientation of the magnetization vector did not change significantly. The use of higher demagnetization temperatures resulted in a gradual decrease of the remanence and then its dramatic drop at temperatures of 640–700°C (with the maximum unblocking temperatures T_{ub} reaching up to 700°C). Zijderveld (1967) diagrams reveal that magnetization removed at these highest temperatures consists of only one component characterized by shallow to moderate inclinations (after a tectonic correction) and two polarities (Fig. 5b and c). These high-temperature (HT) components recorded by hematite were successfully determined by applying lines fitted to the demagnetization results above 660°C and anchored at the origin using least-squares fits (e.g. Remasoft; Chadima & Hrouda 2006).
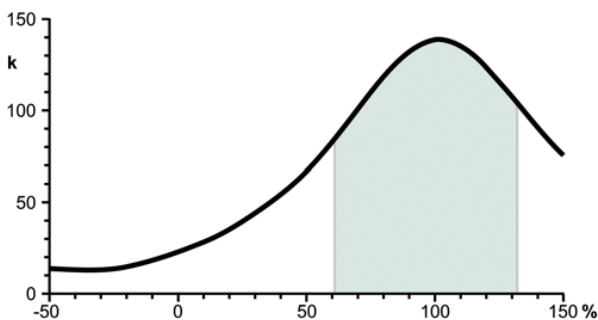
Fig. 6. Inclination-only fold test of site-mean results. Coloured area represents 95% level of confidence, k-Fisherian precision parameter.

Some of the specimens, especially those with a low NRM intensity, showed a somewhat greater proportion of NRM components characterized by a T_{ub} below 600°C. This magnetization displayed normal polarity and steep inclinations but its orientation was highly scattered for individual specimens and the equivalent segments of the Zijderveld plot were curved (Fig. 5d). This suggests that magnetic remanence eliminated at such low and intermediate temperatures has a multicomponent nature with overlapping T_{ub} spectra. It is also worth pointing out that some of the specimens, mainly red mudstones, underwent thermochemical alteration that appeared at temperatures above 550°C and made it difficult to separate the HT component.

After our initial recognition of the NRM structure, we focused our subsequent analytical efforts on the determination of the HT component. Its mean direction was successfully calculated in 10 sampling sites: seven of them represented normal polarity, two represented mixed polarity and one reversed polarity (Table 1). As site SR5 is represented only by four samples collected from a single 20 cm layer, its site-mean direction, although matching with the results obtained from other sites, was not taken into account in further calculations and interpretations. The magnetic properties of the HT component observed in these studies were compatible with those obtained in previous studies (Szaniawski *et al.* 2012) from the Tatra Mountains (see the discussion below) and therefore the whole dataset from the Tatra, Low Tatra, Great Fatra and Strážov Mountains was used in further statistical analyses.

We performed a fold test based on the site-mean directions from 15 sampling sites (sites SR1, SR4, SR6, VF2, VF6, NT2, NT4, NT5, NT9 from this study and sites WR1, WR2, WR5, WR6, WR7, WR8 from the Tatra Mountains). It should be noted that the performed test was not actually a fold test in the strict sense as that would have required the results to come from the opposite limbs of the folds. In our case, sampling sites were located within fault blocks of differentiated directions and angles of tilting. This, however, also had a value for the determination of timing between the remanence acquisition and the tectonic processes. Considering the fact that the sites were located within separate tectonic blocks, which may have been subjected to differential rotations, we decided to apply an inclination-only test using the procedure proposed by Watson & Enkin (1993) and Enkin & Watson (1996). We applied Enkin's (1994) software estimating 95% confidence limits using a parametric resampling procedure. The results of the test were
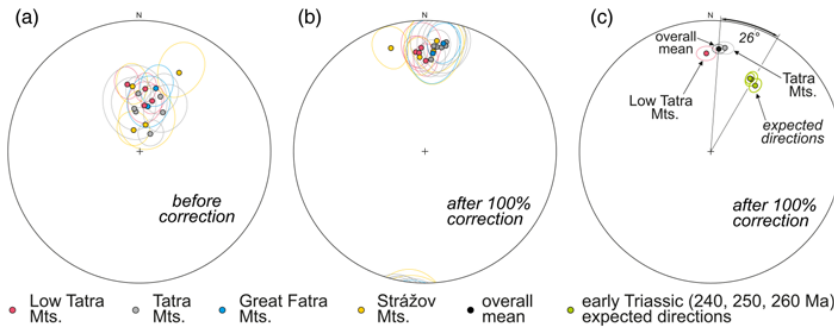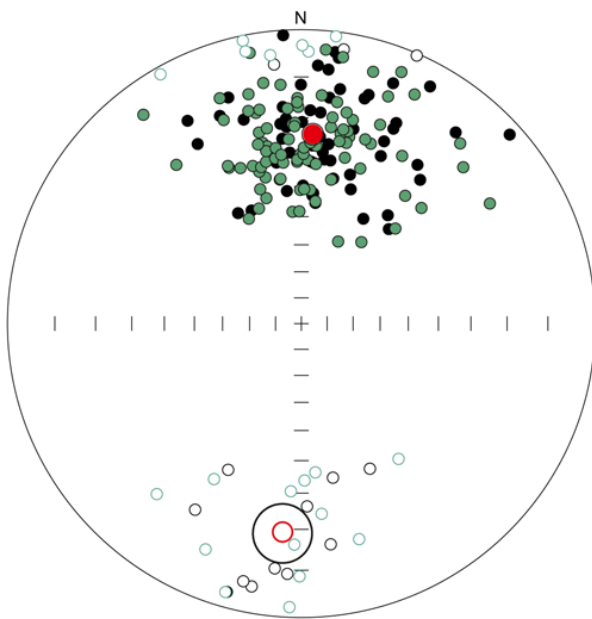
Fig. 7. Stereographic projections (equal area) showing sites mean directions (**a** and **b**) and the overall mean (14 sites, Table 1) together with mean of site-mean directions for the Low Tatra and Tatra Mountains combined with expected Early Triassic paleomagnetic directions for the region of study (**c**). Overall mean and mean of site-mean directions are shown with standard Fisher (α₉₅) circular cones while other directions with confidence ovals result from separate errors for declination and inclination (see Butler 1992 and Deenen et al. 2011; a platform Paleomagnetism.org of Koymans et al. (2016) was used to prepare the graphics).

positive with the optimum 101% degree of untilting and a 95% confidence limit in the range from 61% to 132% (Fig. 6).

If we consider possible block rotations to be an issue the application of a reversal test based on all specimens from different sites is problematic. Nevertheless, we decided to carry it out after rejecting data from site SR4 as the remaining site-mean directions were very well clustered (Fig. 7; see the discussion). We applied the reversal test procedure proposed by Mc Fadden & Mc Elhinny (1990) on all specimen directions from sites SR1, SR5, SR6, VF2, VF6, NT2, NT4, NT5, NT9 (this study) merged with data from the Tatras, sites WR1, WR2, WR5, WR6, WR7, WR8 (Szaniawski et al. 2012). The results of the test were positive as with 185 observations (Fig. 8) the angle between the two means γ_o was 5.3° and the angle at which the directions became significantly different γ_c was 8.2°.

Discussion

The petromagnetic properties of all rocks from the 11 studied sites, despite some obvious variations due to the lithology, are relatively homogenous and comparable with the results reported from other redbeds in the region. In the studied rocks, the ferromagnetic mineralogy is dominated by hematite with an accessory occurrence of magnetite and possibly some goethite. The hematite magnetic carrier records only one magnetization component displaying high unblocking temperatures and characterized by two polarities. These magnetic features are in line with those obtained previously in the Tatra Mountains (Szaniawski et al. 2012) in studies of the same redbeds from the Lúžna Formation sampled in an analogous tectonic setting. Hence, we have decided to interpret all these datasets jointly, now being able to combine data from four mountain massifs (the Tatra, Low Tatra, Great Fatra and Strážov Mountains) representative of a large portion of the CWC (Fig. 1).

First, we compiled all the AMS results. The petromagnetic results document that in red mudstones and sandstones the magnetic susceptibility is governed by ferromagnetic minerals with a significant participation of the paramagnetic phase, presumably phyllosilicates. Magnetic fabrics in the vast majority of sites are mostly planar with a distinct bedding-parallel magnetic foliation which we interpret as related to the mineral alignment associated with sedimentary processes and compaction.

In addition to a well-developed magnetic foliation, most of the sites also display a noticeable magnetic lineation. In most of the sites from the Tatra, Low Tatra and Great Fatra Mountains (Fig. 2, sites WR1, WR2, WR5, WR6, WR7 WR8, VF2, NT2, NT4), such lineations display an approximate NE–SW to E–W orientation, lie in the bedding plane, and are generally oblique to bedding strike. The orientation of the lineation is interpreted to be compatible with the regional bulk strain related to NW-directed emplacement of the Krížna nappe (Prokešová 1994; Kovač & Bendík 2002; Plašienka 2003; Pečeňa & Vojtko 2011; Prokešová et al. 2012) and is also similar to the strain pattern revealed by AMS from the Great Fatra Mountains (Krížna nappe and autochthonous cover, Gregorová et al. (2009)) and from the Tatra Mountains (basement, autochthonous cover and Krížna nappe, Hrouda & Kahan (1991), and the Krížna nappe, Grabowski (1996)). We interpret this lineation as tectonic in origin and related to Late Cretaceous deformation during which the studied rocks were affected by layer-parallel shortening associated with regional shortening and overthrusting of the Krížna and Choč nappes.

An interesting point to note is that, although the discussed NE–SW to E–W orientation of the lineation exists in the bedding plane, it is not parallel to the actual strike of the bedding. The fact that the lineation is somewhat oblique to the present horizontal plane results, in our opinion, from the multistage nature of the observed deformation. The present-day bedding attitude of the lower parts of the sedimentary cover in the Tatra Mountains and most likely also in the Great Fatra and Low Tatra Mountains results mainly from relatively young Neogene uplift which led to the

Fig. 8. A Stereographic projection showing direction of magnetization for all specimens from sites SR1, SR5, SR6, VF2, VF6, NT2, NT4, NT5, NT9 (green dots) combined with data from the Tatra Mountains after Szaniawski et al. (2012) (black dots). Mean directions (red dots) with 95% confidence cones are calculated separately for both polarities.

formation of elevated, foreland-tilted horst-blocks (e.g. Burchart 1972; Král' 1977; Grecula & Roth 1978; Piotrowski 1978; Bac-Moszaszwili *et al.* 1984; Kováč *et al.* 1994; Jurewicz 2000, 2005; Baumgart-Kotarba & Král' 2002; Sperner *et al.* 2002; Anczkiewicz *et al.* 2005; Rubinkiewicz & Ludwiniak 2005; Szaniawski *et al.* 2012; Králiková *et al.* 2014; Śmigielski *et al.* 2016). *Ipso facto,* the processes that led to the current bedding orientation postdate the lineation, and the rotational axis associated with the formation of the tilted fault blocks was oblique to the pre-existing lineation. This remark is in line with the outcomes of Hrouda *et al.* (2002) who postulate that the magnetic fabric of pre-Cenozoic rocks predates the Neogene brittle segmentation of the TFB in the elevated tectonic blocks.

The Neogene uplift mechanism of the tectonic blocks forming the TFB is the subject of a lively discussion: in the case of the Tatra Mountains, models assuming block faulting or alternatively a thick-skinned back thrust are proposed most frequently (e.g. Kotański 1961; Birkenmajer 1986, 2003; Mahel' 1986; Bac-Moszaszwili 1993; Sperner 1996; Hrušecký *et al.* 2002; Sperner *et al.* 2002; Kohút & Sherlock 2003; Petrík *et al.* 2003; Bielik *et al.* 2004; Jankowski 2015; Beidinger & Decker 2016; Castelluccio *et al.* 2016; Śmigielski *et al.* 2016; Ludwiniak *et al.* 2019). Our results seem to be more in line with the block faulting model as the thick-skinned thrusting process would likely have left its record in the magnetic fabric of the studied rocks. The NE–SW lineation is in most cases not associated with such a hypothetical thick-skinned thrusting as it is oblique both to the strike of the bedding and to the elongation of the Tatra and Low Tatra blocks.

More problematic is the interpretation of the lineation of the Strážov Mountains. It seems to be mainly NW–SE-oriented but the quantity of data is small (three sites only) and the grouping of the maximum AMS axes in site SR1 is poor. Furthermore, site SR5 represents a 20 cm layer of mudstone surrounded by massive quartzose sandstones, while the samples of site SR4 come from several mudstone–sandstone intercalations (15–40 cm thick) separated by massive quartzose sandstones. It differs from the sites in the Tatra, Great Fatra and Low Tatra Mountains where we sampled much thicker sequences of red sandstones and mudstones which did not lie in the immediate vicinity of massive quartzose sandstones. This suggests that the strain was possibly related to the localized simple shear occurring in thin mudstone/sandstone layers existing between the quartzose sandstones and associated with the general NW–SE regional shortening and thrusting in the Late Cretaceous, the latter documented in the Strážov Mountains by structural observations (Prokešová *et al.* 2012) and AMS results (Hrouda & Hanák 1990).

All the AMS results discussed above contrast with the magnetic fabric observed in site VF4 in the Great Fatra Mountains. Here, the AMS properties (susceptibility similar to that observed in other sites but a lower anisotropy degree and a prolate AMS ellipsoid) are indicative of an important strain that has significantly changed the primary magnetic fabric. We attribute this strain to local tectonic deformation. Despite our best efforts, we have been unable to recognize a more detailed local tectonic setting due to the poor exposure of rocks in this area.

The paleomagnetic direction of the hematite bearing the high-temperature remanence component has been successfully determined in nine sites (not including site SR5 with a low number of samples). This, together with the previous results from the Tatra Mountains (six sites), forms a comprehensive dataset representative of a greater part of the CWC unit. All the evidence indicates that the HT component represents a primary magnetization. It is recorded in hematite grains of a high T_{ub} representing a typical magnetic carrier of the primary magnetization in redbeds. Such a high-T_{ub} hematite is characterized by high resistance to thermal remagnetization (Pullaiah *et al.* 1975), so the remanence they carry has not been thermally overprinted as the maximal burial temperatures for the basement of the Tatra, Low Tatra, Great Fatra and Strážov Mountains are estimated at 120–160°C (Anczkiewicz *et al.* 2005; Danišík *et al.* 2011, 2012; Śmigielski *et al.* 2016). The HT remanence component shows both polarities passing a reversal test. The results of the inclination-only fold test are also positive, yet they refer mostly to the relatively young Neogene deformation responsible for most of the actual bedding attitude. The primary nature of the HT component is also supported by the fact that the site-mean directions are much better clustered than individual specimen directions (Figs 7 and 8), a feature we associate with the averaging of secular variation.

As already mentioned above, the site-mean directions are mostly well grouped, except for site SR4 in which the declination deviates by *c.* 20° counterclockwise. This site is located in the Strážov Mountains which are smaller and characterized by a greater tectonic segmentation into minor tectonic blocks compared to the Tatra, Low Tatra and Great Fatra Mountains (Fig. 2). Even though during our field work we made all efforts to avoid intensively tectonized regions, we consider the divergent result from site SR4 to be the effect of local tectonic deformations and we do not take it into account in our calculation of the mean of site-mean paleomagnetic directions.

The remainder of the site-mean directions are reasonably well clustered (Fig. 7b) and their diversity results mainly from the inclinations. The means of the site-mean directions calculated separately for the Tatra and Low Tatra Mountains (Fig. 7c; the Great Fatra and Strážov Mountains have not been included as the quantity of site-mean data is limited) are well clustered and their small dispersion results in this case more from the differences in declinations than in inclinations. This suggests that the calculation of the mean of site means provides a robust regional datum.

The differences in the mean directions for the Low Tatra and Tatra mountain massifs are small but statistically significant as their 95% confidence ellipsoids do not overlap (Fig. 7c). The clustering of the site-mean directions within individual mountain massifs is very good. The differences in direction resulting mainly from declination are commonly interpreted in paleomagnetic literature as an effect of vertical axis rotations. However, we suggest that in this case such a small diversity most likely has another reason. The rotation axis related to fault-block rotations associated with the Neogene uplift was not necessarily exactly horizontal. The particular mountain massifs forming an independent tectonic block are possibly cut by a system of second-order minor transverse or relay faults that may also have caused an additional tilting of rock layers (e.g. Walsh & Watterson 1991; Fossen & Rotevatn 2016). These processes are difficult to fully trace and their effects have not been completely restored by a simple tectonic correction based on the field-measured bedding orientation. As a result, the obtained prefolding inclinations are correct but declination values may be slightly biased. Accordingly, we have decided to calculate the overall mean direction based on site means from all four mountain massifs (Table 1).

The obtained site-mean inclination values yield a mean value of 22.6° after the application of a 100% tectonic correction (Table 1). Our results are based on rocks from the Early Triassic epoch lasting between 251.9 and 247.2 Ma (Cohen *et al.* 2013). We have compared such outcomes with reference data taken from the global apparent polar wander path (GAPWaP) for stable Europe in which results from sedimentary rocks are corrected for the inclination error (Table 11 in Torsvik *et al.* 2012). Reference paleolatitudes calculated for the current CWC position with respect to the European Platform from the given reference GAPWaP yield 22.3°N for 240 Ma, 20.6°N for 250 Ma and 20.5°N for 260 Ma. In order to compile the data, we have corrected our mean inclination result for the inclination error using the same simplified correction method as Torsvik *et al.* (2012) and assuming the same degree of inclination

error $f = 0.6$. As a result, we have obtained a value of 14.0° as the corrected mean inclination, which corresponds to a paleolatitude of 7.1°N. This outcome implies that in the Early Triassic the CWC were situated *c.* 14 degrees of latitude to the south of the place they would occupy if they were in their current mutual configuration with the European Platform. This result is in line with data from the Inner Carpathian unit (located south of the CWC and also forming part of the Alcapa). The results from Lower Triassic sediments provide a mean inclination of 24° (according to Márton *et al.* 1988, 2016) which we have corrected for inclination error (using $f = 0.6$) obtaining an inclination value of 15° and a paleolatitude of 8°. However, we believe that broader paleogeographic conclusions from the discussed data are impossible to draw at the moment as the inclination error correction procedure applied to the Carpathian results and sediments from the reference GAPWaP is oversimplified, which may result in a significant error, and thus further studies on this issue are needed.

The obtained mean directions, except for site SR4 (most probably due to local deformation), are relatively uniform across all the studied massifs and very similar to those obtained earlier in the Tatra Mountains (Fig. 7). The differences in the mean directions between the Tatra and Low Tatra Mountains, as discussed above, are actually minor considering the regional tectonic scale, and arose most probably relatively late in the course of the Neogene uplift. The studied mountain massifs are distributed over a wide area forming the middle part of the CWC. We therefore conclude that since the Early Triassic the central parts of the CWC unit were tectonically coherent with respect to each other. Moreover, a comparison of the obtained consistent directions of primary magnetization with the expected paleomagnetic direction for the studied region indicates a moderate counterclockwise rotation of *c.* 26° (Fig. 7c; expected directions and their confidence ellipses were calculated using the formulae given by Butler (1992), from the reference global apparent polar wander path of Torsvik *et al.* (2012)). This means that after the Triassic, the CWC unit has rotated as a coherent unit by 26° counterclockwise relative to the stable parts of the continent. At the same time, we do not rule out the possibility that marginal areas of the CWC may have been subjected to other local tectonic rotations. This may be true in particular of the western parts of the CWC (Malé Karpaty, Považský Inovec) where, for example, tectonic rotations associated with the so-called escape tectonics described by Sperner *et al.* (2002) are very likely.

Our results support previous paleomagnetic reports from the autochthonous Mesozoic cover of the CWC. Results from the Great and Malá Fatra derived from Jurassic and Cretaceous carbonates and interpreted as primary (Pruner *et al.* 1998) are indicative of moderate counterclockwise rotations. In turn, Jurassic–Lower Cretaceous limestones from the Tatra Mountains interpreted as remagnetized in the Late Cretaceous (Grabowski 1997; Márton *et al.* 2015) are very similar to reference declinations expected for the stable Europe. This suggests that the counterclockwise rotation recorded in both Triassic and Jurassic–Lower Cretaceous sediments from the autochthonous cover took place most probably during Late Cretaceous deformation. We propose that such a rotation of the CWC may reflect the early stages of collision between the Alcapa terrane and the irregularly shaped European foreland margin. Within this framework, the Bohemian massif would have acted as an indenter, similarly to the models proposed by Ratschbacher *et al.* (1991) and Sperner *et al.* (2002) for the Miocene. We treat this as a preliminary hypothesis, as the scale of Mesozoic latitudinal separation of the CWC and stable Europe is in our opinion not fully constrained, especially since available paleomagnetic data are not corrected for inclination error (see Castelluccio *et al.* 2016; Szaniawski *et al.* 2012, for a discussion).

Although the limited amount of available data does not allow one to formulate a definitive interpretation on the timing of CWC rotation

and its latitudinal position during the Mesozoic and the Cenozoic, it is worthwhile comparing our outcomes with the numerous paleomagnetic results reported on the Mesozoic sediments of the Krížna nappe (e.g. Kruczyk *et al.* 1992; Grabowski 1995, 2005; Grabowski *et al.* 2009, 2010). Most paleomagnetic directions from the Krížna nappe are interpreted as a secondary and remagnetized in the Late Cretaceous (see the discussion in Márton *et al.* 2015) and only two reports describe a primary magnetic record (Grabowski 2005; Grabowski *et al.* 2010). Declination results of both the primary and secondary components are very different, demonstrating both clockwise and counterclockwise rotations. However, counterclockwise rotations seem to prevail in the western parts of the CWC unit, reaching maximum values of *c.* 65° in the Malé Karpaty Mountains (Grabowski *et al.* 2010; Márton *et al.* 2015). We suggest that such dispersed declinations may have resulted from local rotations related to the emplacement of the Krížna Nappe or, more likely, they are an effect of multiple deformations of various kinematics (Late Cretaceous thrusting and Neogene rotational uplift), which have not been properly restored by a simple bedding correction based on the field-measured orientation of strata.

More problematic is the comparison of the paleomagnetic results from Mesozoic rocks of the CWC with those reported from postorogenic sediments of the Carpathian Paleogene Basin (Fig. 2). A compilation of available data leads to the conclusions that the reported paleomagnetic directions are in fact distinctly different, also within the areas (e.g. Liptov Basin) situated between the Mesozoic massifs examined in our studies (Márton *et al.* 1999; Túnyi & Köhler 2000; Túnyi *et al.* 2008). The second ambiguity is the fact that most of the described directions are rotated considerably counterclockwise, which has been interpreted as the result of a 60° counterclockwise rotation of both the CWC and OWC units in the period between 18.5 Ma and 14.5 Ma (Márton *et al.*, 2015). We are skeptical about this interpretation due to the absence of proper geological evidence for such a large and relatively young rotation (see Szaniawski *et al.* 2013 for a discussion). We also point out that sediments of the Carpathian Paleogene Basin, although poorly deformed, have undergone a multi-stage tectonic evolution which included, among others, a synsedimentary extension and further compression and deformation related to the Miocene uplift (e.g. Jurewicz 2005; Pešková *et al.* 2009; Głowacka 2010; Ludwiniak 2010, 2018; Vojtko *et al.* 2010; Kováč *et al.* 2018; Ludwiniak *et al.* 2019). None of these deformations have been restored by a tectonic correction based on a simple field-measured orientation of strata that may result in a declination bias. We point out that the inclination values of Paleogene sediments are steep (60°) (see e.g. Márton *et al.* 2015) and thus a potential error in declination related to the multi-stage deformation and tectonic correction is significant.

Conclusions

(1) Lower Triassic sandstones from Low Tatra, Great Fatra and Strážov Mountains record a primary magnetization carried by hematite, consistent with earlier results obtained from matching rocks sampled in the Tatra Mountains.

(2) Magnetic susceptibility is controlled by both ferromagnetic and paramagnetic minerals. Although magnetic fabrics are mainly sedimentary in origin, with bedding-parallel magnetic foliation, they show also a distinct tectonic overprint expressed by the magnetic lineation. We interpret this lineation as effect of Late Cretaceous deformation.

(3) The inclination of primary magnetization recorded by hematite suggests minor latitudinal separation between CWC and stable Europe in the Early Triassic. However this requires further confirmation using more specialized methods of inclination error correction.

R. Szaniawski *et al.*

(4) Paleomagnetic declinations are usually consistent within individual mountain massifs and show only slight differences among them. This implies a lack of large-scale differential vertical axis rotations of individual tectonic blocks forming the central part of the CWC.

(5) Paleomagnetic declinations indicate moderate (*c*, 26°) counterclockwise rotations of the CWC relative to the stable parts of the continent since the Early Triassic.

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