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Magnetic fabric of sedimentary formations of the Strážovské vrchy Mts., sedimentological and tectonic implications

Magnetická vnitřní stavba sedimentárních formací Strážovských vrchů, sedimentologická a deformační interpretace

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Abstract: The magnetic fabric in the sedimentary rocks of the Cover Formation is deformational in origin. In sedimentary rocks of the Krížna nappe (sandstone, marlstone), it is partially sedimentary and partially depositional in origin. The magnetic lineations in rocks with sedimentary magnetic fabric agree with palaeocurrent directions determined by Jablonský (1978) using sedimentological methods.

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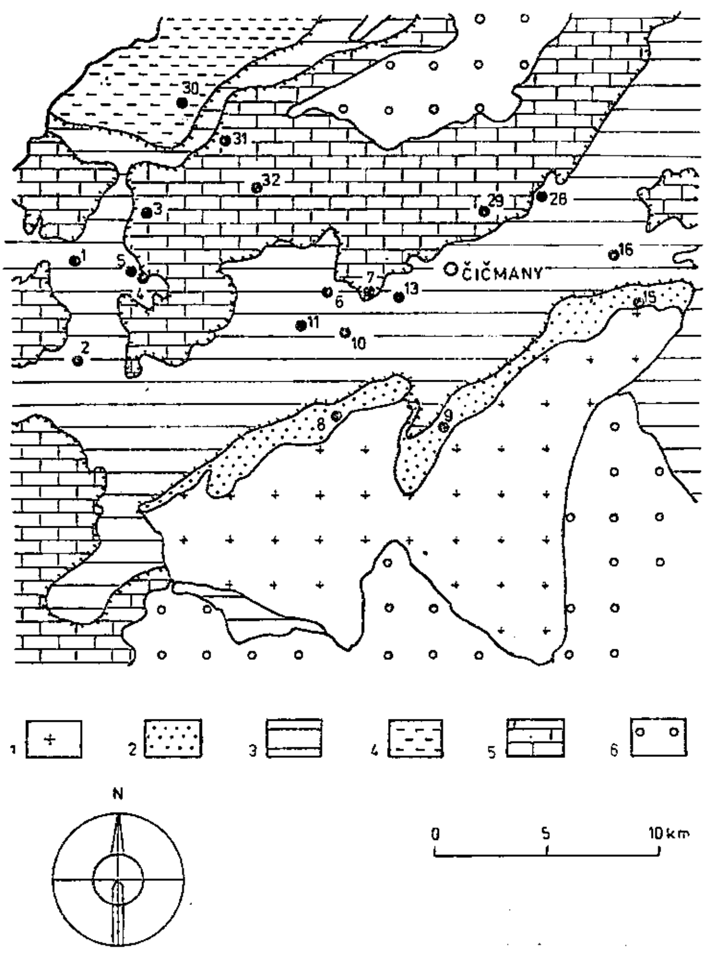
Introduction

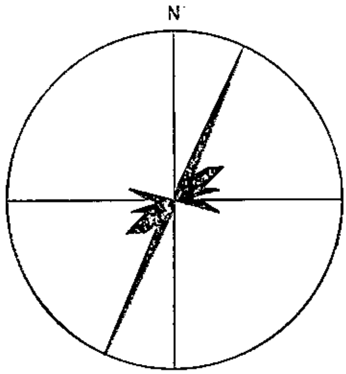
The Strážovské vrchy Mts. create one of the so-called core mountains of the Central West Carpathians (see Fig. 1). They are characterized, as any core mountains, by the crystalline core covered by sedimentary rocks of the Cover Formation and overthrust by the Subtatric nappes among which the Křížna nappe, the Choč nappe and Strážov nappe are the most important. Their geology has been comprehensively treated by Mahel (1985).

In the Strážovské vrchy Mts. the Krížna nappe crops out on a relatively large area, being represented by deep-sea sediments of the Zliechov series and in the uppermost part also by flysch sediments Albian in age. The palaeogeographical situation has been studied by sedimentological methods (Jablonský 1978) mostly on sandstone (see Fig. 2).

The purpose of the present paper is to extend this study using the method of magnetic anisotropy, which enables the preferred orientation of magnetic minerals in a rock to be determined. This method can be applied not only to the investigation of sandstone, but also marlstone and claystone. In addition, it is also able to detect very sensitively weak ductile deformation modifying the sedimentary fabric. We used this method, in combination with sedimentological methods, in the study of the sedimentary rocks of the Strážovské vrchy Mts. Though also the Cover Formation and the Choč nappe were investigated, the paper is essentially devoted to the Krížna nappe, because in this nappe sufficient number of suitable outcrops of marlstone and sandstone have been found, while in the Cover Formation and in the Choč nappe only non-magnetic quartzite and limestone may have been sampled.



1. Geological scheme of the Strážovské vrchy Mts. with the sampling sites plotted (closed circles with numbers) *1* – metamorphic and granitoid rocks, *2* – Cover Formation, *3* – Krížna nappe, *4* – Manín Unit, *5* – Choč and Strážov nappe, *6* – Palaeogene and Neogene. Simplified from M. Mahel' (1985)



2. Rose diagram of the orientations of the palaeocurrents in the Alb of the Križna nappe, determined by sedimentological methods. Compiled from the data of J. Jablonský (1978)

Measurement and processing techniques, data presentation

The magnetic anisotropy of oriented specimens was measured by the KLY-2 Kappabridge (Jelínek 1973, 1982) and computed using the ANISO 11 program (Jelínek 1977). In order to obtain a statistical evaluation of the magnetic anisotropy in individual localities, recourse was had to the RESEA and ANS 21 programs (Jelínek 1978), which enable a complete statistical evaluation of a group of specimens to be carried out. The RESEA program transforms the susceptibility tensors of specimens from the geographical coordinate system to the so-called paleogeographical system (defined by the magnetic north and the horizontal bedding plane). Then, the ANS 21 program computes the mean tensor in the latter coordinate system and its variance (for details see Jelínek 1978; Hrouda–Stráník 1985).

The results of measurements are summarized in Table 1 and Figs. 3–10. The first column of the table contains the locality number (corresponding to that in Fig. 1), the second the petrographical type of the rock investigated, the third the stratigraphical position of the locality investigated, the fourth the totals of the specimens measured in each locality (n) and the fifth the arithmetical means of the mean magnetic susceptibility $k_m = (k_1 + k_2 + k_3)/3$, where $k_1 \geq k_2 \geq k_3$ are the principal susceptibilities. The k_m values are given in the order of 10^{-6} (SI units are used). In the sixth to tenth columns there appear pairs of values of the magnetic lineation $L = k_1/k_2$, magnetic foliation $F = k_2/k_3$, magnetic anisotropy degree $P' = \exp\sqrt{\{2[(\eta_1 - \eta)^2 + (\eta_2 - \eta)^2 + (\eta_3 - \eta)^2]\}}$, shape factor $T = 2(\eta_2 - \eta_3)/(\eta_1 - \eta_3) - 1$ ($\eta_1 = \ln k_1$, $\eta_2 = \ln k_2$, $\eta_3 = \ln k_3$, $\eta = (\eta_1 + \eta_2 + \eta_3)/3$, and $q = (k_1 - k_2)/[(k_1 + k_2)/2 - k_3]$ parameter. The values given in the upper line are the arithmetical means of the values for individual specimens, while those given in the lower line represent the parameters derived from the mean tensor for a locality as a whole (calculated using the RESEA and ANS 21 programs). For the simplicity's sake the former parameters will henceforth be called the specimen parameters, while the latter the locality parameters. In the eleventh column there are the mean values of the angle (f) between the minimum susceptibility direction and the bedding pole. In the last column the abbreviation of the magnetic anisotropy pattern is given. It consists of two letters, one capital and one small. The capital letter characterizes the relation of the magnetic lineation to the magnetic foliation: P – the magnetic lineation is parallel to the dip line of magnetic foliation, T – the magnetic lineation is transverse to the dip of magnetic foliation, N – the magnetic foliation is parallel to the bedding or the magnetic foliation or lineation are largely scattered spatially so that the above relationship cannot be established. The small letter indicates the orientation of partial girdle in magnetic foliation poles with respect to the trend of magnetic lineation: p – the girdle is parallel, t – the girdle is transverse, o – the girdle is oblique to the trend of magnetic lineation.

Origin of magnetic fabric

In order to understand the magnetic fabric generation under different deposition regimes, many laboratory deposition experiments have been made by experimentalists of the British school (represented by Hamilton, Rees and their co-workers), simulating the natural deposition conditions as closely as possible (see, for example, Rees and Woodall 1975; Rees 1983). It has been shown that during grain by grain deposition (or from thin suspension) from still or running water onto a flat or sloping bottom the q parameter value is less than 0.5 and the magnetic foliation dips less than 15° from the bedding towards the origin of flow. The magnetic lineation is parallel to the direction of flow and to the dip of magnetic foliation. During deposition from very concentrated grain dispersion onto a sloping bottom the q value is higher, reaching 0.7, the magnetic foliation dips 25–30° towards the origin of flow, and the magnetic lineation is parallel to the flow (to the dip of the slope) and to the dip of magnetic foliation. During deposition from medium-concentrated suspension (ca 8 % in Rees' 1983, experiments) the q value is less than 0.3, the magnetic foliation dips less than 15° towards the origin of flow, and the magnetic lineation is perpendicular to the flow direction and to the dip of magnetic foliation. The transverse orientation of magnetic lineation, as shown by Rees' (1983) experiments, can originate also due to synsedimentary pure shear deformation, but the q value is high (0.5–1.0). In all experiments having produced the magnetic lineation parallel to the dip of magnetic foliation the magnetic foliation poles create an embryonic girdle which is parallel to the trend of magnetic lineation. On the other hand, during ductile deformation this girdle is perpendicular to the magnetic lineation. If all the properties mentioned are regarded as characteristic of sedimentary magnetic fabric, they can be used as criteria for distinguishing rocks with sedimentary magnetic fabrics from those with deformational fabrics.

Table 1

Magnetic anisotropy parameters of the sedimentary rocks of the Strážovské vrchy Mts.

Loc.	Rock	Strat.	n	k_m	L	F	P	T	q	f	Ch
	Cover Formation										
8	quartzite	T_1	5	15	1.012	1.014	1.027	0.11	0.61		T_t
					1.010	1.017	1.027	–	0.46		
9	sandstone limy	K_{2al}	13	107	1.011	1.013	1.025	−0.03	0.73		T_t
					1.009	1.013	1.022	0.15	0.51		
15	quartzite	T_1	10	30	1.014	1.016	1.030	−0.15	0.88		T_t
					1.007	1.002	1.009	−0.70	1.38		
	Křížna nappe										
1	sandstone	K_{2al}	10	113	1.011	1.031	1.043	0.45	0.33	14	P_p
2	sandstone	K_{2al}	11	154	1.007	1.019	1.026	0.44	0.38	38	T_t
					1.004	1.010	1.013	0.27	0.34		
3	sandstone	K_{2al}	12	221	1.002	1.012	1.014	0.70	0.17	12	T_t
					1.001	1.012	1.013	0.85	0.07		
4	sandstone	K_{2al}	8	168	1.007	1.013	1.020	0.08	0.41	21	P_t
					1.006	1.012	1.018	0.44	0.42		
5	silty sandstone	K_{2al}	8	195	1.003	1.023	1.027	0.75	0.14	2	N_t
					1.002	1.024	1.026	0.83	0.09		
6	limy sandstone	K_{2al}	16	115	1.008	1.032	1.043	0.53	0.30	5	N_p
					1.006	1.031	1.037	0.13	0.18		
10	marlstone	J	9	95	1.014	1.036	1.051	0.42	0.35	76	T_t
					1.011	1.035	1.047	0.16	0.28		
11	marlstone	J	11	78	1.006	1.024	1.030	0.58	0.24	7	P_p
					1.004	1.024	1.029	0.72	0.16		
13	marlstone	J	9	18	1.010	1.003	1.013	−0.41	1.15	–	–
					1.004	1.001	1.005	−0.67	1.41		
16	marlstone	J	11	196	1.013	1.036	1.049	0.35	0.43	40	T_p
					1.013	1.016	1.028	0.43	0.58		
30	sandstone	K_{al}	10	182	1.003	1.009	1.012	0.38	0.40	39	N_o
					1.001	1.004	1.005	0.28	0.26		
31	sandstone	K_n	12	113	1.011	1.030	1.041	0.41	0.38	14	P_p
					1.006	1.029	1.036	0.76	0.20		

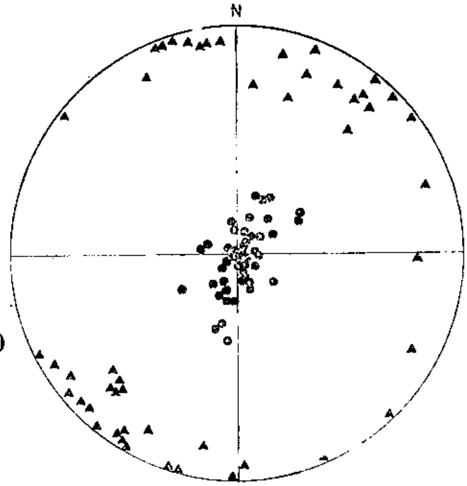
As clear from Table 1, in the Cover Formation the mean susceptibility of quartzite is very low, in sandstone it is an order of magnitude higher. (From locality No. 8 only specimens with $k_m > 10 \times 10^{-6}$ were used for interpretation, because less magnetic specimens display unreliable values of magnetic anisotropy parameters arising from the compensation effect of ferromagnetic and diamagnetic fractions — Hrouda 1986.) In all localities of the Cover Formation the specimen anisotropy degree is very low and the locality anisotropy degree is even lower. The magnetic fabric is planar in some specimens and linear in the others. The locality magnetic fabric is planar in localities Nos. 8 and 9 and linear in locality No. 15. The magnetic foliation makes a large angle with the bedding in all specimens in localities Nos. 8 and 15 and in many specimens in locality No. 9. The partial girdles in magnetic foliation poles are oriented in general transversely to magnetic lineation. From these observations we can conclude that the magnetic fabric of the sedimentary rocks investigated in the Cover Formation is undoubtedly deformational in origin.

In the Krížna nappe, as seen from Table 1, the specimen anisotropy degree of both sandstone and marlstone is low, while the locality degree is even lower. The specimen magnetic fabric and the locality magnetic fabric are mostly planar, only in locality No. 13 they are linear. In the majority of localities all three principal susceptibilities are well defined; only in localityNo. 13 they are widely scattered.

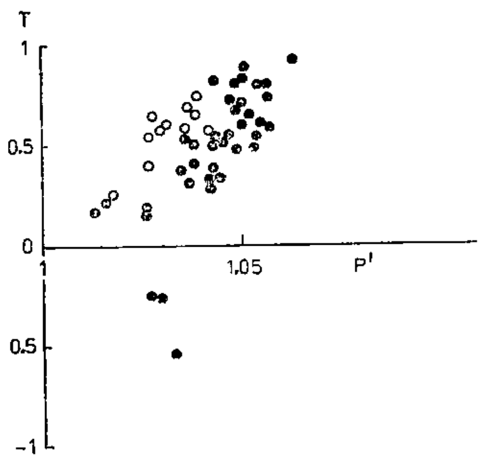
After applying the criteria for distinguishing the sedimentary from deformational magnetic fabrics following the observations described in the beginning of this chapter, the magnetic fabric can be classified as sedimentary in localities Nos. 1, 6, 11, 31 and deformational in localities Nos. 2, 3, 4, 5, 10, 13, 16, 30. From Table 1 it is clear that sandstone localities exhibit both types of the magnetic fabric, while the marlstone ones show mostly deformational fabrics.

We realize that we were perhaps too severe in regarding only those rocks which fit all the criteria described in the beginning of this chapter as displaying the sedimentary magnetic fabric. For example, the rocks exhibiting the magnetic lineation transverse to the dip of magnetic foliation may originate not only through deformation, but also through the deposition from medium-concentrated dispersion. However, as this kind of deposition takes place relatively rarely, in a bounded deposition regime corresponding to that in the A division of the Bouma flysch sequence (see Tiara and Scholle 1979; Rees 1983), it seems to us that we make smaller error if we include these rocks into those with deformational magnetic fabric than if they were regarded as depositional.

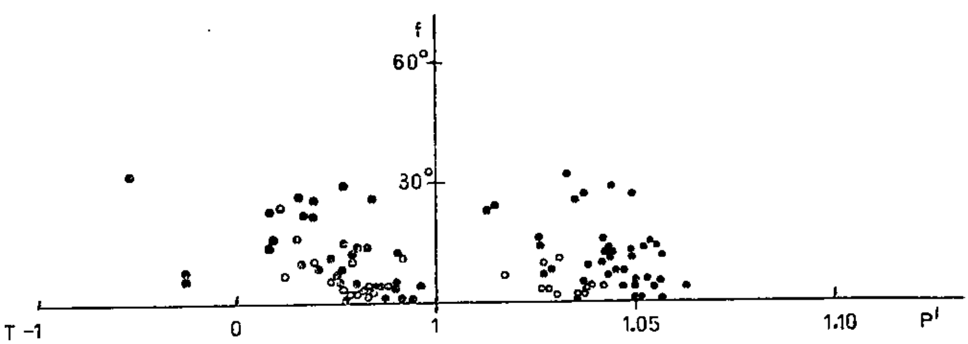
Fig. 3 shows the orientations of magnetic foliation and lineation in the palaeogeographical coordinate system, Fig. 4 the relation between P' and T parameters and Fig. 5 the relation between f and $P'(T)$ parameters for rocks with sedimentary fabric. It is clear from Fig. 3 that the magnetic foliation poles create an embryonic girdle parallel to the magnetic lineation, the T value increases with increasing P' (Fig. 4) and the T value decreases with decreasing f (Fig. 5). These



3. Orientations of magnetic lineation (*triangles*) and poles of magnetic foliation (*circles*) in the rocks with sedimentary magnetic fabric in the Krížna nappe in the palaeogeographic coordinate system. Equal-area projection on lower hemisphere



4. Magnetic anisotropy plot of sediments with sedimentary magnetic fabric in the Krížna nappe
Closed circles — sandstone, *open circles* — marlstone



5. The f vs $P'(T)$ plot of rocks with sedimentary magnetic fabric in the Křižna nappe

relationships convince us that the magnetic fabric in localities 1, 6, 11, 31 is really sedimentary in origin. The correlation between T and f parameters reflects variation in the strength of the flow (tangential shear along the bed).

Sedimentological implications

It is clear from Table 1 that in localities with sedimentary magnetic fabrics (in the Krížna nappe) f angle is less than 15° and mean q values less than 0.5. These values imply that the rocks in these localities were not deposited from concentrated grain dispersion. Except for locality No. 6 the magnetic lineations are parallel to the dip of magnetic foliation and q values are relatively high. This magnetic fabric corresponds to that generated during the deposition from thin suspension. The orientation mechanism of grains in such rocks is a rotation of grains in a sheared (flowing) fluid.

In the locality No. 6 the magnetic foliation is virtually parallel to the bedding and it is therefore impossible to deduce whether the magnetic lineation is parallel or transverse to the dip of magnetic foliation. The parallelism of the magnetic foliation to the bedding implies the idea that the deposition of limy sandstone in this locality was from thin suspension and that the orienting mechanism of grains was almost ideal shear flow.

The orientations of magnetic lineation and foliation in localities with sedimentary magnetic fabric are presented in a synoptic diagram in Fig. 3 in the palaeogeographical coordinate system. It can be seen in Fig. 3 that the magnetic lineations are mostly oriented NE–SW, but there are also some specimens oriented NNW–SSE to NW–SE. The magnetic foliation poles create an embryonic girdle oriented NE–SW, i.e. parallel to the magnetic lineation and, consequently, the magnetic lineations can be regarded as representing the directions of the near-bottom water currents. It can be concluded from the orientation of magnetic lineation that the near-bottom currents operating in the sedimentation basin of the Krížna nappe formations were mostly oriented NE–SW and subordinately also NNW–SSE. However, it is necessary to realize that these directions are related only to the today's configuration of the nappe. As the nappe may have rotated during its movement, the actual directions of the currents in respect to the ancient north may have been different. As the palaeogeographical situation in the time of deposition has not yet been clearly known, it can hardly be decided whether the directions indicated by magnetic anisotropy represent the directions of the transport of the clastic material into the basin or those transporting the clastic material along the basin.

Fig. 2 gives an approximate information of the orientations of the palaeocurrents determined by sedimentological methods.

Fig. 2 was compiled from the data contained in the Supplement 1 in the paper by Jablonský (1978). The palaeocurrent determinations are based on the measurement of flute casts, prod marks, groove casts, cross lamination, ripple marks. In Fig. 2 all the determinations are presented together. The maximum between 20 and 30° (200–210°) comes mostly from flute casts and prod marks, the other maxima come from the other fabric elements. It is clear from the comparison of Figs. 2 and 3 that the palaeocurrents determined magnetically are compatible with those determined non-magnetically. Only the NNW–SSE directions determined magnetically have no correspondence with the directions determined sedimentologically.

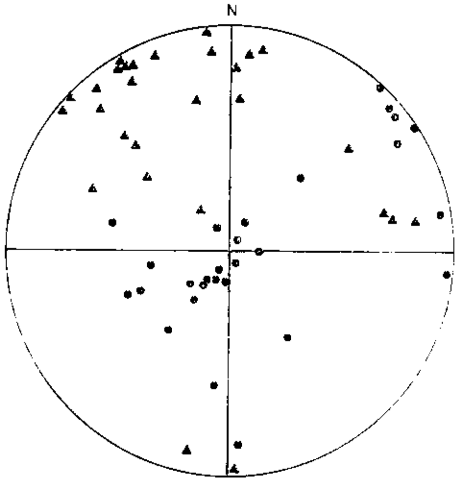
The investigation of the palaeocurrent directions confirms Jablonský's (1978) conclusion that the transport directions in the Krížna nappe basin were mostly NE–SW.

Tectonic implications

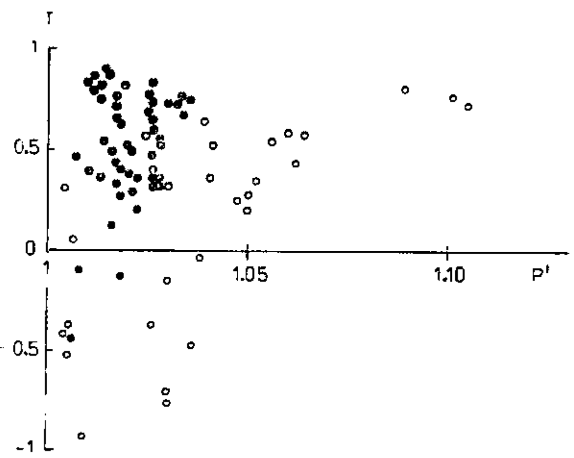
The magnetic fabrics in all three localities investigated in the Cover Formation have been classified as deformational in origin. In Fig. 6 showing the orientation of magnetic lineation, poles of magnetic foliation in the palaeogeographical coordinate system we can see that the magnetic foliation poles create an imperfect NE–SW girdle and the plunge of the magnetic lineations varies from virtually horizontal to virtually vertical, while the magnetic lineations trend mostly NNW–SSE. The magnetic anisotropy degree is relatively low and the specimen magnetic fabric ranges from clearly linear to clearly planar (see Table 1). The angle between the magnetic foliation and bedding ranges from virtually zero to almost 90°. From all these observations one can conclude that the deformational overprint of the sedimentary magnetic fabric has not been complete and that the magnetic fabric of individual specimens represent different stages of the superposition of the deformational magnetic fabric on the sedimentary one.

In localities with deformational magnetic fabric in the Krížna nappe the anisotropy degree P' in sandstone is lower than in the localities with sedimentary fabric and varies only slightly (Table 1). The shape parameter T varies widely, ranging from slightly linear to almost perfectly planar magnetic fabric, and, unlike to the localities with sedimentary magnetic fabric, there is obviously no correlation between the P' and T parameters (Fig. 7). In marlstone the anisotropy degree P' ranges from very low ($P' < 1.01$) to relatively high ($P' > 1.1$) and the T parameter ranges from -0.9 to $+0.8$; a positive, even though not too close, correlation exists between the P' and T parameters (Fig. 7). As it is clear from Fig. 8, there is apparently no correlation between the anisotropy degree P' and the magnetic foliation/bedding angle (f) in sandstone. As for the T and f parameters, the correlation does not seem to exist at first sight as well (see Fig. 8), but after a more detailed inspection we can see that for the lower values of T the higher values of f are characteristic and vice versa. In marlstone there are two groups of specimens, one displaying high f values (50–80°) and one showing low f values (less than 20°). In both groups the P' and T values vary largely and there is apparently no correlation between the f and P' or T parameters (see Fig. 8).

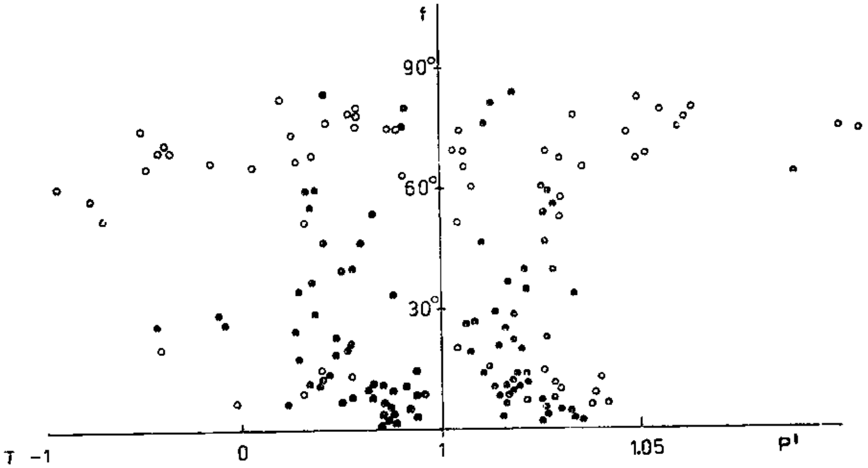
In sandstone both the poles of bedding and those of magnetic foliation create imperfect girdles oriented NW–SE and the magnetic lineation is mostly horizontal, but exhibits large azimuthal scatter (see Fig. 9). In marlstone the poles of bedding and those of magnetic foliation again create imperfect NW–SE oriented girdles. The magnetic lineation plunges gently to moderately and its scatter is smaller than sandstone; the predominating direction is NE–SW (Fig. 10).



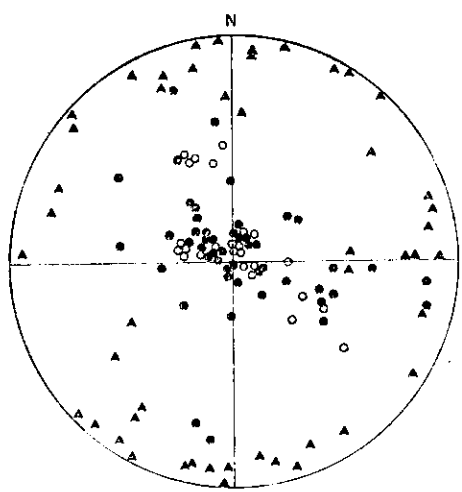
6. Orientations of magnetic lineation (*triangles*), poles of magnetic foliation (*closed circles*) and poles of bedding (*open circles*) in the Cover Formation in the palaeogeographical coordinate system. Equal-area projection on lower hemisphere



7. Magnetic anisotropy plot of rocks with deformational magnetic fabric in the Krížna nappe
Closed circles – sandstone, *open circles* – marlstone



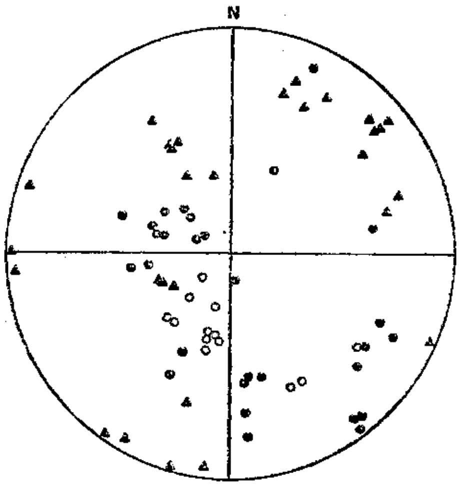
8. The *f* vs *P′*(*T*) plot of rocks with deformational magnetic fabric in the Krížna nappe
Closed circles —sandstone, *open circles* —marlstone



9. Orientations of magnetic lineation (*triangles*), poles of magnetic foliation (*closed circles*), and poles of bedding (*open circles*) in sandstone with deformational magnetic fabric in the Krížna nappe in geographical coordinate system. Equal-area projection on lower hemisphere

From the above observations we may deduce that the magnetic fabric in sandstone reflects a weak overprinting of the sedimentary fabric by the deformational fabric and that the deformation is represented by a combination of simple shear with the shortening parallel approximately to the bedding. During this deformation the sedimentary magnetic fabric was modified in such a way that the anisotropy degree of a rock and the planarity of the magnetic fabric were lowered. The magnetic foliation rotated from the bedding to various degree about the axis

NE–SW and the magnetic lineation may have remained in the original orientation if the deformational magnetic fabric was coaxial with the sedimentary magnetic fabric, while it may have been deflected strongly, if the superposition was non-coaxial.



10. Orientations of magnetic lineation (*triangles*), poles of magnetic foliation (*closed circles*), and poles of bedding (*open circles*) in marlstone with deformational magnetic fabric in the Krížna nappe. Equal-area projection on lower hemisphere. Geographic coordinate system

In marlstone, probably due to its higher ductility, the overprint of deformational fabric on the sedimentary one was in general stronger. In those specimens in which the overprint was relatively weak the anisotropy degree decreased, like in sandstone, but in those where the overprint was strong it increased. The increasing planarity of magnetic fabric with increasing anisotropy degree probably indicate that the overprint may have been very strong in some specimens. The orientation of the girdle of magnetic foliation poles being NW–SE and the orientation of the magnetic lineation NE–SW suggest that the deformation mentioned may have been represented by a combination of a simple shear and shortening parallel to the bedding (shortening in the direction NW–SE).

Conclusions

The magnetic fabric in the Cover Formation and in the Krížna nappe of the Strážovské vrchy Mts. has been investigated. From the investigation the following conclusions have been drawn:

1. The magnetic fabric in the Cover Formation is strongly influenced by ductile deformation. The influence is higher in quartzite than in sandstone.

2. The magnetic fabric in the Krížna nappe, both in sandstone and marlstone, is composite, i.e. partially sedimentary and partially deformational in origin.

3. In localities with predominantly sedimentary magnetic fabric the magnetic lineations are oriented in a compatible way with the orientation of palaeocurrents determined by sedimentological methods by Jablonský (1978). The palaeocurrent directions determined by both magnetic and sedimentologic methods are NE–SW.

4. The ductile deformation having affected the Krížna nappe rocks is represented by a combination of simple shear and pure shear. The pure shear is represented by a shortening in the NW–SE direction.

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Přeložil F. Hrouda

References

Hrouda, F. (1986): The effect of quartz on the magnetic anisotropy of quartzite. – Stud. geophys. geod., 30, *39–45*. Praha.

Hrouda, F.–Straník, Z. (1985): The magnetic fabric of the Ždánice thrust sheet of the Flysch Belt of the West Carpathians: sedimentological and tectonic implications. – Sedimentary Geol., 45, *125–145*. Amsterdam.

Jablonský, J. (1978): Príspevok k poznaniu albu zliechovskej série Strážovských vrchov. *In*: Paleogeografický vývoj Západných Karpát, *175–187*. – Geol. úst. D. Štúra. Bratislava.

Jelínek, V. (1973): Precision A. C. bridge set for measuring magnetic susceptibility of rocks and its anisotropy. – Stud. geophys. geod., 10, *58–78*. Praha.

– (1977): The statistical theory of measuring anisotropy of magnetic susceptibility of rocks and its application. – Geofyzika, s. p. Brno.

– (1978): Statistical processing of anisotropy of magnetic susceptibility measured on groups of specimens. – Stud. geophys. geod., 22, *50–62*. Praha.

– (1982): Kappabridge KLY-2. – Geofyzika. Brno (Leaflet).

Mahel', M. (1985): Geologická stavba Strážovských vrchov. – Geol. úst. D. Štúra. Bratislava.

Rees, A. I. (1983): Experiments of the production of transverse grain alignment in a sheared dispersion. – Sedimentology, 30, *437–448*. Amsterdam.

Rees, A. I.–Woodall, W. A. (1975): The magnetic fabric of sand and sandstones. – Earth planet. Sci. Lett., 25, *121–130*. Amsterdam.

Tiara, A.–Scholle, P. A. (1979): Deposition of resedimentated beds in the Pico Formation, Ventura Basin, California from magnetic fabric measurements. – Geol. Soc. Amer. Bull., 90, *952–962*. New York.