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The magnetic fabric relationship between sedimentary and basement nappes in the High Tatra Mountains, N. Slovakia

FRANTIŠEK HROUDA

Geofyzika, n.p., P.O. Box 62, 612 46 Brno, Czechoslovakia

and

ŠTEFAN KAHAN

Department of Geology, Comenius University, Mlynská dolina B2, 800 00 Bratislava, Czechoslovakia

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Abstract—In the High Tatra Mountains (N. Slovakia), the magnetic fabrics are deformational in origin in sedimentary rocks of the Krížna nappe, in sedimentary rocks covering the underlying crystalline complex, and in granitoids and metamorphic rocks of this complex. The patterns of the principal susceptibilities are similar in all these units; their most important feature is a girdle in magnetic foliation poles oriented NNW–SSE to N–S. In sedimentary formations the magnetic fabric pattern is compatible with that predicted by mathematical modelling to develop during a complex deformation comprising lateral shortening and simple shear, which is characteristic of nappe deformation. Consequently, the magnetic fabric in the High Tatra Mountains probably resulted from deformation associated with the formation and movement of the nappes, during which not only the sedimentary strata, but also the crystalline complex, were thrust over the North European platform.

INTRODUCTION

THE Central West Carpathians of Czechoslovakia, unlike the Alps and other mountain chains, do not create a continuous mountain range but rather, they crop out within the mostly unfolded Intracarpathian Palaeogene and Neogene rocks as so-called core mountains. Among them, the High Tatra Mountains (see Fig. 1a) are of significance, because their nappe structure was revealed as early as 1903 (Lugeon 1903) and they served as the structural model for the whole Central West Carpathians (Uhlig 1898, Lugeon 1903, Matějka & Andrusov 1931, Andrusov 1968, Andrusov *et al.* 1973, Mahel' 1986). Since then, it has been accepted more or less universally that two upper Mesozoic sedimentary sequences create groups of nappes, among which the lower Krížna nappe and the upper Choč nappe are the most voluminous and important. The lowermost Mesozoic sedimentary sequence, underlying these nappes and overlying the crystalline complex, is called the Cover Formation; this, together with the crystalline complex was originally regarded as autochthonous. However, recently, both the crystalline complex and its sedimentary cover have been interpreted as allochthonous, and to have been thrust, like the Krížna and Choč nappes, over the North European Platform (Fig. 1b) (Leško *et al.* 1980, Leško & Ibrmajer 1983, Mahel' 1986). In addition, a recent seismic reflection survey has revealed a detailed thrust sheet structure throughout the whole High Tatra Mountains (Tomek personal communication 1987).

The magnetic anisotropy can easily be measured both in crystalline and sedimenary rocks, offering thus an excellent basis for the investigation of the fabric relationship between nappe and cover sedimentary rocks, granitoids and metamorphics of the crystalline complex. The purpose of the present paper is to study this relationship and to discuss the geological processes that may have given rise to the magnetic fabric observed.

GEOLOGICAL SETTING

Due to their prominent position the High Tatra Mountains have been the most intensely investigated core mountains in the Central West Carpathians. These investigations are reviewed by Kamenický (1968) and Mahel' (1968, 1986) to whose works the reader is referred for more detailed information. The following summary is based on these reviews and on the papers by Gorek (1958, 1959) and Kahan (1969).

The outcrop of the High Tatra Mountains is largely built up of the crystalline complex creating the central and southern areas. Only in the northern part do the sedimentary formations occur, creating the Cover Formation, Krížna nappe and Choč nappe (see Fig. 1a).

The crystalline complex can be divided into four units distinguished geologically and petrographically; (a) crystalline schists and synkinematic granite-gneisses; (b) migmatites; (c) granitoids; and (d) para-gneisses and hybrid rocks.

The metamorphic rocks of the crystalline complex originated during progressive regional metamorphism of the staurolite–sillimanite–kyanite zone and the sillimanite zone; the pressure–temperature conditions, as determined on the basis of thermobarometry and petro-

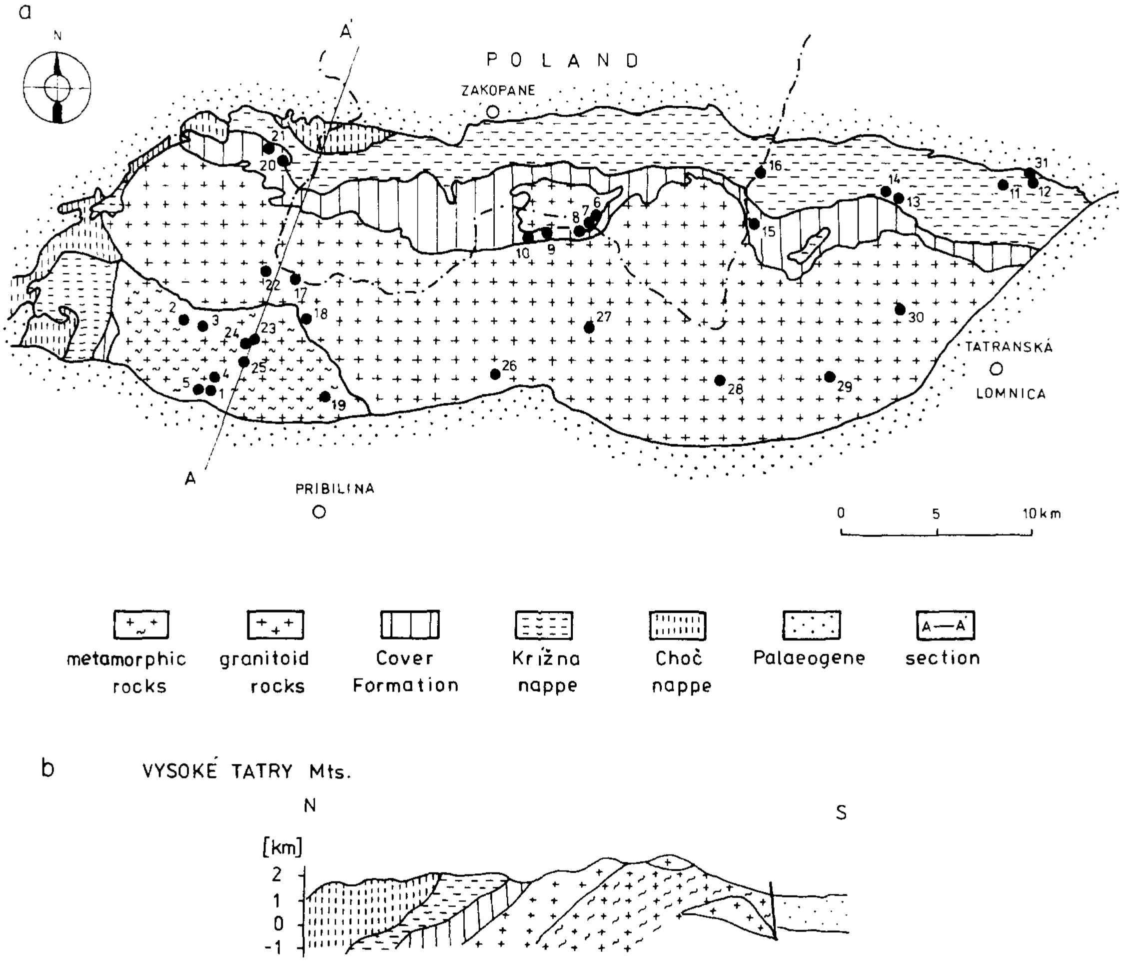

Fig. 1. (a) Geological map of the High Tatra Mountains, N. Slovakia, showing the sampling sites (numbered spots). Compiled from Sokolowski's map (in Mahel' 1968). (b) Geological section through the High Tatra Mountains (along the line A–A' in (a)). Adapted from Leško & Ibrmajer (1983). Legend as in (a).

genesis, corresponded to the temperature range of 530–700°C and to the pressure range of 400–700 MPa (4–7 kbar) (Janák *et al.* 1988). The absolute age dating suggests a Variscan age for both the metamorphic and granitoid rocks: biotite gneiss 264 Ma (Kantor 1959); injected biotite gneiss 300 Ma (Sedleckyi *et al.* 1965); biotite oligoclase granite 226 Ma (Kantor 1959); biotite granite 340–360 Ma (Sedleckyi *et al.* 1965). However, some rocks may be older (amphibolite xenolith in granite 425 Ma, Sedleckyi *et al.* 1965) and some may be younger (greenschist originated through retrogressive metamorphism of amphibolite 165 Ma, Sedleckyi *et al.* 1965).

The crystalline complex makes up a huge complicated domal structure, produced by multiphase deformation. The oldest phases are Variscan or even pre-Variscan and the most common metamorphic schistosity is considered to be of this age. The poles to this schistosity create an irregular girdle elongated in the N–S direction (see Fig. 2a) and the axes of the small-scale folds in this schistosity create also an irregular girdle containing several partial submaxima (Fig. 2b). The younger phase was probably an Alpine deformation giving rise to fracture cleavage and mylonite zones and also resulting in the reorientation of the folds into the direction NE–SW. As the intensity of this reorientation was variable, the girdle pattern in the small-scale fold axes was created. The poles to the fracture cleavage show an irregular pattern resembling an imperfect N–S oriented girdle (Fig. 2c). The similar patterns in the metamorphic schistosity and fracture cleavage (cf. Figs. 2a & c) suggest that the orientation of the latter was probably pre-determined not only by the configuration of the stress field, but also by the existence of the metamorphic schistosity as a plane of mechanical weakness.

The sedimentary rocks of the Cover Formation range from Lower Triassic to Middle Cretaceous in age, being represented by quartzite, sandstone, shale and various types of carbonates, including both dolomites and limestones.

The Krížna nappe, like the Cover Formation, consists of the sedimentary rocks ranging from Lower Triassic to Middle Cretaceous in age and being represented by various shales, sandstones, marly shales and carbonate rocks.

The Choč nappe is mostly represented by a thick sequence of dolomites and limestones Triassic in age.

The Cover Formation locally shows a monoclinal structure of a fairly steep dip (60–70°N), with local folds of rocks of different competence (e.g. shales with limestones), and areas of small recumbent folds with north vergence. The youngest beds are frequently overridden by slices of older formations or even by granite slices.

The Krížna nappe, on the Czechoslovak territory, is built up of two partial nappes. The folds are mostly N-dipping and the nappes consist of several digitations shown as false folds overturned outwards, with the frontal part plunging to the north.

The Choč nappe builds up only a small part of the High Tatra Mountains structure. Its strata show mostly a monoclinal dip to the north but with local folds.

SAMPLING AND DATA PRESENTATION

In the crystalline complex, the most common rock types were sampled. In sedimentary formations the sampling was confined to non-carbonate rocks, because carbonates are too weakly magnetic. For this reason, the Choč nappe has been avoided since its rocks are represented almost exclusively by carbonates.

Oriented block specimens were taken in the natural outcrops and road cuts where fresh rocks were available. From each locality five specimens were taken and from each of them two cylinder specimens were drilled. Prior to the specimen removal from the exposure, the orientations of mesoscopic fabric elements (schistosity, bedding, lineation) were measured.

The magnetic anisotropy was measured by the KLY-2 Kappabridge (Jelínek 1973, 1980) and computed by the ANISO 11 program (Jelínek 1977). The data were evaluated statistically using the ANS 21 program (Jelínek 1978). The magnetic fabric is represented by the following parameters: mean susceptibility (k_m), magnetic lineation (L), magnetic foliation (F), corrected anisotropy degree (P') and shape parameter (T). They are defined as follows

$$k_m = (k_1 + k_2 + k_3)/3, \quad L = k_1/k_2, \quad F = k_2/k_3,$$

$$P' = \exp \sqrt{\{2[(\eta_1 - \eta)^2 + (\eta_2 - \eta)^2 + (\eta_3 - \eta)^2]\}},$$

$$T = 2(\eta_2 - \eta_3)/(\eta_1 - \eta_3) - 1,$$

where $k_1 \geqslant k_2 \geqslant k_3$ are the principal susceptibilities and

$$\eta_1 = \ln k_1, \quad \eta_2 = \ln k_2, \quad \eta_3 = \ln k_3,$$

$$\eta = (\eta_1 + \eta_2 + \eta_3)/3.$$

Whereas the k_m, L and F parameters are simple and commonly used, the P' and T parameters are more complex and need some explanation. They were introduced by Jelínek (1981) to represent separately the anisotropy degree (P') and the shape of the susceptibility ellipsoid (T). The higher value of the P' parameter the higher the anisotropy. Thus $0 \leqslant T \leqslant 1$ indicates a planar magnetic fabric, while $-1 \leqslant T \leqslant 0$ indicates a linear fabric.

The P' and T parameters are particularly useful in graphical representation of the magnetic anisotropy data (the P'–T diagram), because they inform directly on the anisotropy degree and the shape of the susceptibility ellipsoid. This is a great advantage over the modified Flinn diagram (F–L plot) which does not represent directly the anisotropy degree. This problem is discussed in detail by Borradaile (1988) who compares the two diagrams.

The values of the above parameters are presented in Tables 1–4; the upper line for each locality is the arithmetical mean of the individual specimen values, and the lower line represents the values derived from the locality mean tensor (determined through averaging out the individual components of the specimen tensors and calculated by the ANS 21 program). In the text, the parameters derived from individual specimens are referred to as the *specimen parameters*, while those derived from the mean locality tensor are referred to as the *locality parameters*.

The orientations of magnetic foliation poles and magnetic lineations are presented in Figs. 2–5 for individual rock types or geological units, in equal-area projections on the lower hemisphere. Mostly they are presented in the geographical co-ordinate system, but also in the so-called palaeogeographical co-ordinate system (defined by horizontal bedding and north).

MAGNETIC MINERALOGY

The mean susceptibility of the rocks investigated is mostly low (see Tables 1–4). Consequently, in the metamorphic and granitoid rocks containing micas and hornblende the susceptibility may be due not only to the ferromagnetic minerals, but also to paramagnetic silicates. Let us investigate this problem in more detail.

The ferromagnetic minerals can be most easily identified through the investigation of the dependence of the acquisition isothermal remanent magnetization (AIRM) on the magnetizing field. This was investigated in selected specimens and the results are presented in Fig. 6(a). It can be seen in the figure that the AIRM saturates very rapidly, before the field of 200 mT. This probably indicates the presence of magnetite. However, in some sedimentary rocks the saturation is slow, probably indicating hematite.

The proportions of ferrimagnetic vs paramagnetic minerals cannot be obtained from the AIRM curves, and there is no method at our disposal that would be able to measure this proportion directly. For this reason, we shall try to estimate the contributions of the ferrimagnetic and paramagnetic minerals to the total susceptibility only roughly, based on the knowledge of the ferrimagnetic and paramagnetic minerals present, of the content of the paramagnetic minerals (in our rocks represented by about 10% of biotite, Kamenický 1968), and of the susceptibility of individual minerals.

The contribution of the individual minerals to the rock susceptibility can be estimated from Fig. 6(b) showing the susceptibilities of the fractions of individual minerals according to their contents in a rock. It follows from the figure that in rocks with susceptibility above 1×10^{-3} the main contribution is from magnetite, while in those with the susceptibility less than 5×10^{-4} the main contribution is from paramagnetic silicates (if their amounts are about 10% as in our rocks, Kamenický 1968).

Using the method of Henry & Daly (1983) the ferromagnetic component anisotropy was evaluated. This method is based on the assumption that the paramagnetic susceptibility is more or less constant in a locality, while the ferromagnetic susceptibility varies according to the ferromagnetic mineral content in a rock. From the slopes of the straight lines of principal susceptibilities vs mean susceptibility the ferromagnetic anisotropic component can be estimated. The results obtained have shown that in the rocks of the High Tatra Mountains the principal directions of ferromagnetic component are very similar to those of the whole rock.

MAGNETIC FABRIC IN METAMORPHIC ROCKS

The results of the magnetic anisotropy investigations are summarized in Table 1 and Fig. 2. It can be seen in the table that the mean specimen anisotropy degree varies strongly, ranging from 1.12 to 1.61, and the locality anisotropy degree is either slightly or considerably lower. In some localities the specimen magnetic fabric is planar, in others it ranges from planar to linear. The magnetic foliation is near the metamorphic schistosity and the poles to both create relatively wide and asymmetric maxima changing into imperfect girdles oriented N–S (see Fig. 2d). The magnetic lineation is predominantly subhorizontal, but exceptionally it plunges more steeply than 20° (see Fig. 2e). It creates an imperfect girdle in the horizontal plane, trending on average E–W.

From the comparison of Fig. 2(a) with (d) it follows that the magnetic foliation poles are near the main maximum of the schistosity poles. As the schistosity is doubtless a product of the Variscan regional metamorphism, it is very likely that the virtual parallelism of the magnetic foliation to the metamorphic schistosity is a Variscan feature of the magnetic fabric.

The magnetic lineation pattern fits only partially the overall pattern in axes of small folds in schistosity (cf. Figs. 2b & e). This can be accounted for as the effect of the Alpine deformation on the magnetic fabric during which the magnetic lineation was partially to entirely reoriented having obtained the imperfect girdle pattern.

Table 1. Parameters of magnetic anisotropy in metamorphic rocks*

Location No.	k_m (10^{-6})	L	F	P'	T
VT 1	456	1.021	1.091	1.122	0.64
		1.030	1.064	1.098	0.36
VT 3	228	1.071	1.097	1.178	0.14
		1.068	1.082	1.156	0.09
VT 4	566	1.078	1.443	1.614	0.70
		1.034	1.413	1.522	0.82
VT 5	1521	1.100	1.114	1.233	0.26
		1.047	1.115	1.172	0.41
VT 18	168	1.080	1.182	1.293	0.49
		1.070	1.177	1.267	0.23
VT 19	200	1.037	1.096	1.143	0.38
		1.025	1.060	1.089	0.41
VT 25	305	1.065	1.053	1.123	−0.11
		1.003	1.047	1.057	0.86

*The upper line for each locality shows arithmetic means of individual specimen values (specimen parameters), and the lower line shows the locality mean tensor; see text for explanation.

MAGNETIC FABRIC IN GRANITOID ROCKS

The results are summarized in Table 2 and Fig. 3. As can be seen in Table 2, the mean specimen anisotropy degree is relatively low, ranging from 1.05 to 1.18. The locality anisotropy degree is mostly much lower, indicating a relatively wide dispersion of principal susceptibilities of individual specimens. Both the specimen magnetic fabric and the locality magnetic fabric are mostly planar, even though linear magnetic fabrics are present as well.

In the main granitoid body the magnetic foliation poles create a wide and well developed girdle oriented N–S (see Fig. 3a). The magnetic lineation plunges gently to moderately and creates an imperfect girdle (see Fig. 3b).

In the granitoid rocks with intrusive magnetic fabric the magnetic foliation usually conforms to the shape of the granitic body and the magnetic lineation parallels the flow fabric elements (see Hrouda 1982). However, in the High Tatra Mountains the magnetic fabric is more or less homogeneous and the magnetic foliation does not conform the granitic body shape. Instead, the magnetic foliation poles create a girdle pattern perpendicular to the longer dimension of the granitic body and to the magnetic lineation. In addition, both the magnetic foliation and magnetic lineation patterns resemble those in the metamorphic rocks where the magnetic fabric is doubtless deformational in origin. From this one can conclude that the magnetic fabric in the granitoid rocks of the High Tatra Mountains is more probably deformational rather than intrusive in origin.

MAGNETIC FABRIC IN SEDIMENTARY ROCKS OF THE COVER FORMATION

The results are summarized in Table 3 and Fig. 4. The table shows that the specimen anisotropy degree is variable and lithology dependent. The locality anisotropy degree is lower, in some localities substantially. In shale the specimen magnetic fabric is planar and both the magnetic foliation and lineation are well developed on the locality scale. In the other rock types it is variable.

The overall pattern in the bedding poles for the localities investigated is represented by a girdle oriented NNW–SSE (see Fig. 4a). The magnetic foliation poles tend also to create a girdle oriented NNW–SSE to N–S (see Fig. 4a). The magnetic lineations are mostly horizontal or gently plunging, but in a portion of specimens

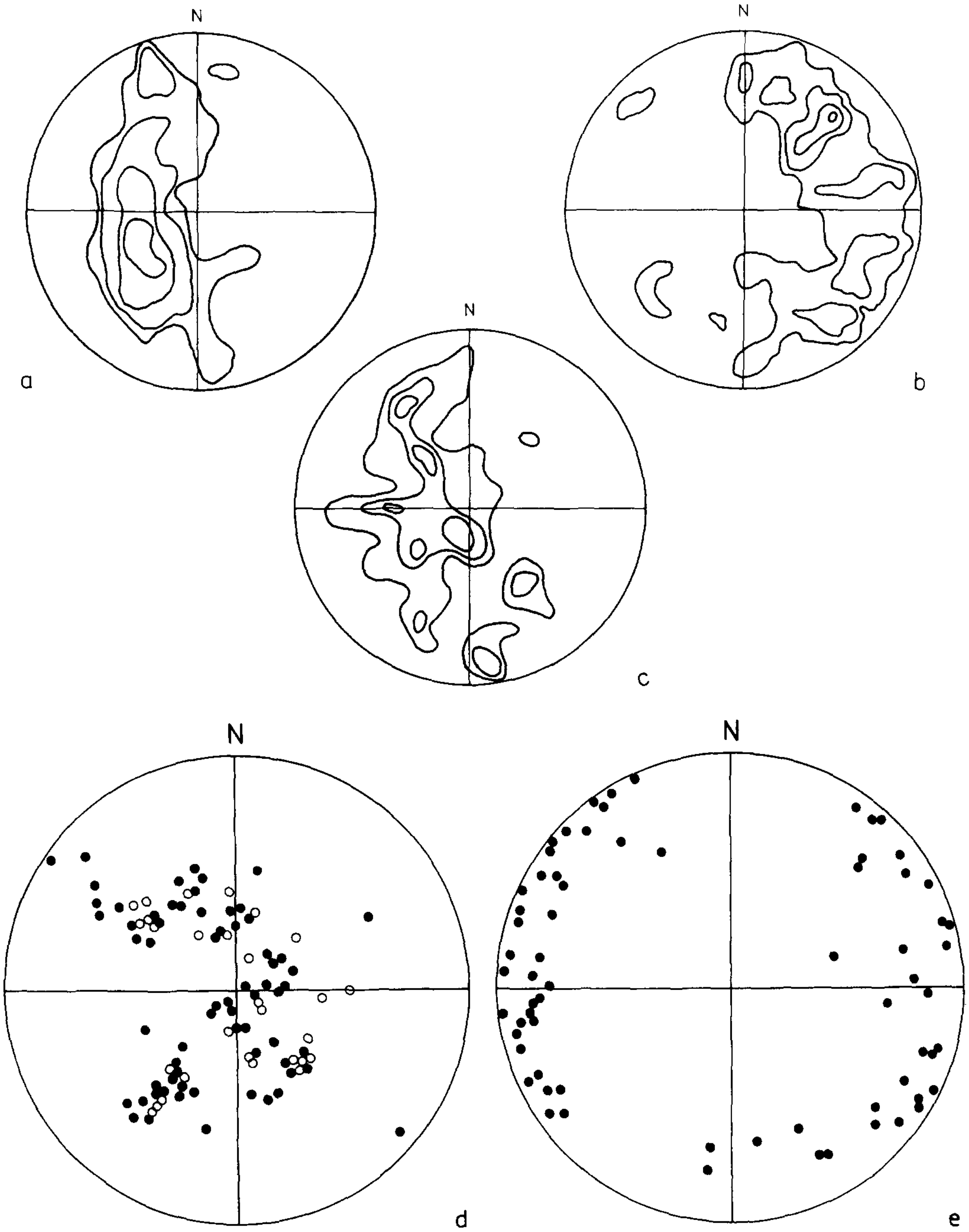

Fig. 2. Orientations of the mesoscopic fabric and the magnetic fabric elements in the metamorphic rocks of the High Tatra Mountains. (a) Contour diagram of the metamorphic schistosity poles in metamorphic rocks. Contours: 7, 5, 2 and 1% (325 poles). Compiled from data of Kahan (1969). (b) Contour diagram of the axes of small folds in metamorphic schistosity. Contours: 7, 5, 3 and 1% (205 axes). After Kahan (1969). (c) Contour diagram of the fracture cleavage poles in metamorphic rocks. Contours: 6, 4 and 2% (54 poles). Compiled from Kahan (1969). (d) Diagram to show the orientations of magnetic foliation poles (full circles) and of metamorphic schistosity poles (open circles) in individual specimens. (e) Diagram to show the orientations of magnetic lineation in individual specimens. Geographic co-ordinate system. Equal-area projection on lower hemisphere.

they plunge moderately to steeply; they create a wide girdle oriented E–W (see Fig. 4b).

In the palaeogeographic co-ordinate system the magnetic foliation poles create an imperfect N–S girdle (Fig. 4c); the magnetic lineation is mostly roughly horizontal and perpendicular to the above girdle, and only in four specimens it is moderately to steeply plunging and parallel to the girdle (Fig. 4d).

The problem of how to distinguish the sedimentary magnetic fabric from the deformational magnetic fabric has been solved through the investigation of the magnetic fabric of sediments artificially deposited in laboratories (e.g. Hamilton & Rees 1970), through mathematical modelling (Hrouda & Hrušková 1990) and through the investigation of rocks showing gradual transitions from undeformed sediments to strongly deformed rocks (e.g. Graham 1966, Hrouda 1979). The criteria for distinguishing these two magnetic fabric types are based mostly on the anisotropy degree (P'), shape of the susceptibility ellipsoid (T) and the angle between magnetic foliation and bedding (f). For sediments with purely depositional magnetic fabric it holds that

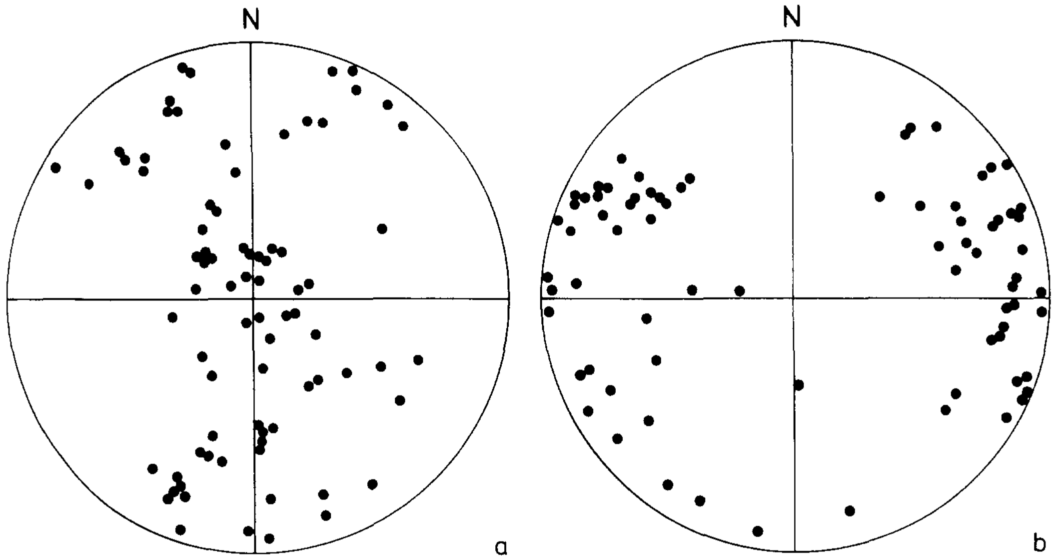

Fig. 3. (a) Orientations of magnetic foliation poles in the main granitoid body. (b) Orientations of magnetic lineation in the main granitoid body. Geographic co-ordinate system. Equal-area projection on lower hemisphere.

Table 2. Parameters of magnetic anisotropy in granitoid rocks*

Location No.	k_m (10^{-6})	L	F	P'	T
VT 2	101	1.036	1.025	1.063	−0.19
		1.012	1.018	1.031	0.22
VT 6	934	1.029	1.099	1.139	0.56
		1.020	1.064	1.089	0.53
VT 17	85	1.019	1.038	1.061	0.36
		1.020	1.026	1.047	0.14
VT 22	123	1.014	1.048	1.066	0.55
		1.016	1.014	1.030	−0.07
VT 23	172	1.015	1.116	1.147	0.74
		1.021	1.093	1.123	0.62
VT 24	208	1.022	1.136	1.175	0.71
		1.011	1.113	1.139	0.82
VT 26	121	1.021	1.035	1.058	0.25
		1.025	1.010	1.036	−0.45
VT 27	121	1.018	1.034	1.053	0.31
		1.014	1.014	1.028	0.01
VT 28	142	1.044	1.064	1.104	−0.10
		1.037	1.018	1.056	−0.34
VT 29	2930	1.060	1.093	1.173	0.10
		1.048	1.062	1.103	0.04
VT 30	885	1.027	1.068	1.089	0.30
		1.014	1.082	1.070	0.58

*The upper line for each locality shows arithmetic means of individual specimen values (specimen parameters), and the lower line shows the locality mean tensor; see text for explanation.

$$P' < 1.05, \quad T > 0, \quad f < 15°.$$

The reliability of the first two criteria is not accepted universally, but the criterion of the approximate parallelism of the magnetic foliation to the bedding is regarded as reliable.

Good additional criteria for solving this problem may be the parallelism of the magnetic lineation to near-bottom current indicators in depositional magnetic fabrics (for review see Hamilton & Rees 1970, Hrouda 1982) or the parallelism of the magnetic lineation to intersection lineation of bedding and cleavage in deformational magnetic fabrics (Borradaile & Tarling 1981, 1984, Hrouda 1982). However, the use of these criteria is limited by the presence of the current indicators and/or cleavage, and in the High Tatra Mountains sedimentary rocks neither of the above fabric elements is present.

The relatively high anisotropy degree in shale, the variable T values in quartzite and, above all, the existence of the magnetic foliation pole girdle in the palaeogeographic co-ordinate system (i.e. commonly a large f angle) and the magnetic lineation mostly perpendicular to the girdle suggest that the magnetic fabric is at least partially deformational in origin.

MAGNETIC FABRIC IN SEDIMENTARY ROCKS OF THE KRÍŽNA NAPPE

The results are summarized in Table 4 and Fig. 5. The specimen anisotropy degree is relatively low and the locality anisotropy degree is even lower. The specimen magnetic fabric is variable, and the locality magnetic fabric is mostly planar.

It can be seen in Fig. 5 that the bedding poles display a unimodal distribution. However, in contrast the magnetic foliation poles create a wide girdle oriented NW–SE (Fig. 5a). The magnetic lineations are scattered relatively widely (Fig. 5b).

In the palaeogeographic system the magnetic foliation poles are very scattered, mostly tending to create a wide N–S girdle (Fig. 5c). The magnetic lineation is also scattered, being sometimes even perpendicular to the bedding (Fig. 5d).

From the girdle pattern in the magnetic foliation poles, and from the orientation of magnetic lineation which is even perpendicular to bedding in many specimens, it can be concluded that the magnetic fabric is very probably deformational in origin.

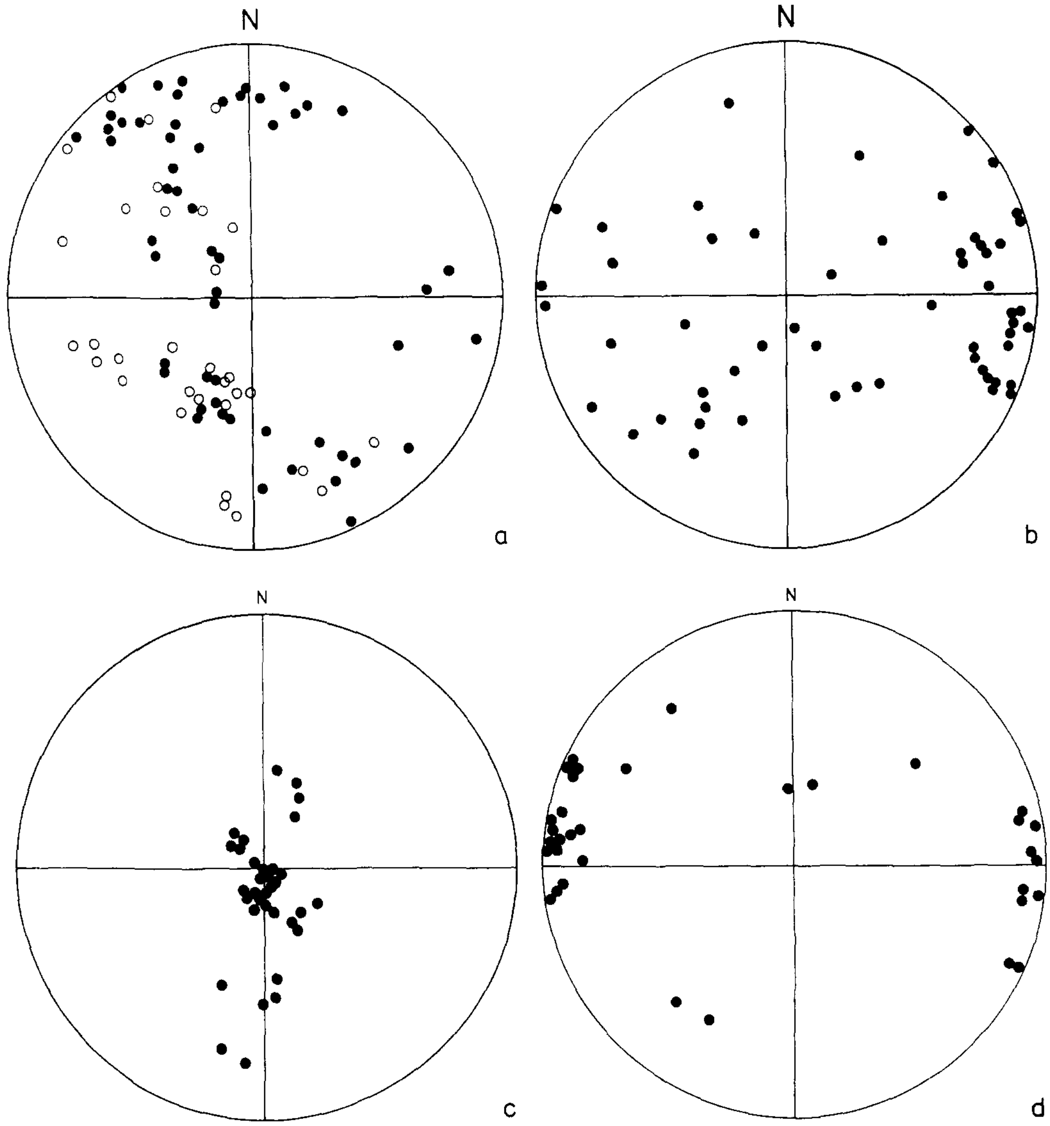

Fig. 4. (a) Orientations of magnetic foliation poles (full circles) and of bedding poles (open circles) in the Cover Formation. (b) Orientations of magnetic lineation in the Cover Formation. Geographic co-ordinate system. Equal-area projection on lower hemisphere. (c) Orientations of magnetic foliation poles in the Cover Formation. (d) Orientations of magnetic lineation in the Cover Formation. Palaeogeographic co-ordinate system. Equal-area projection on lower hemisphere.

TECTONIC INTERPRETATION

It has been shown in the preceding section that the magnetic fabric in the Krížna nappe is deformational in origin. The wide girdle pattern in the magnetic foliation poles contrasts with the unimodal pattern in bedding poles (Fig. 5a) as well as the large scatter in the magnetic lineations in space (Fig. 5b), indicating that the deformation process forming the magnetic fabric was rather complex.

The magnetic fabric in sedimentary nappes deformed by a combination of pure and simple shears (typical deformation of nappes, see Coward & Kim 1981, Sanderson 1982) was investigated theoretically on mathematical models (Hrouda 1985, 1990, Hrouda & Hrušková 1990) and empirically on some nappes of the Alps (Lamarche & Rochette 1987a, b). These studies showed that in rocks in which the bedding remains more or less horizontal during nappe deformation the magnetic foliation remains near the bedding and the magnetic lineation reorientates towards the direction of maximum stretch (transport direction), if the deformation is represented by a combination of lateral lengthening (spreading) and simple shear. If the nappe deformation is represented by a combination of simple shear and lateral shortening, the magnetic foliation can deviate even very strongly from the bedding and its poles tend to create a girdle parallel to the shortening direction (direction of the nappe transport) and the magnetic lineation gradually reorientates from the sedimentary directions towards the direction perpendicular to the girdle direction. Only if the simple shear is very strong can the magnetic lineation become parallel to the direction of the girdle in magnetic foliation poles. This is schematically illustrated in Fig. 7(a) showing the double plot of the magnetic anisotropy degree (P') and the shape parameter (T) against the angle between magnetic foliation and thrust plane (f'); each curve represents a sequence of plots for a constant pure shear parallel to the transport direction (α) and variable simple shears

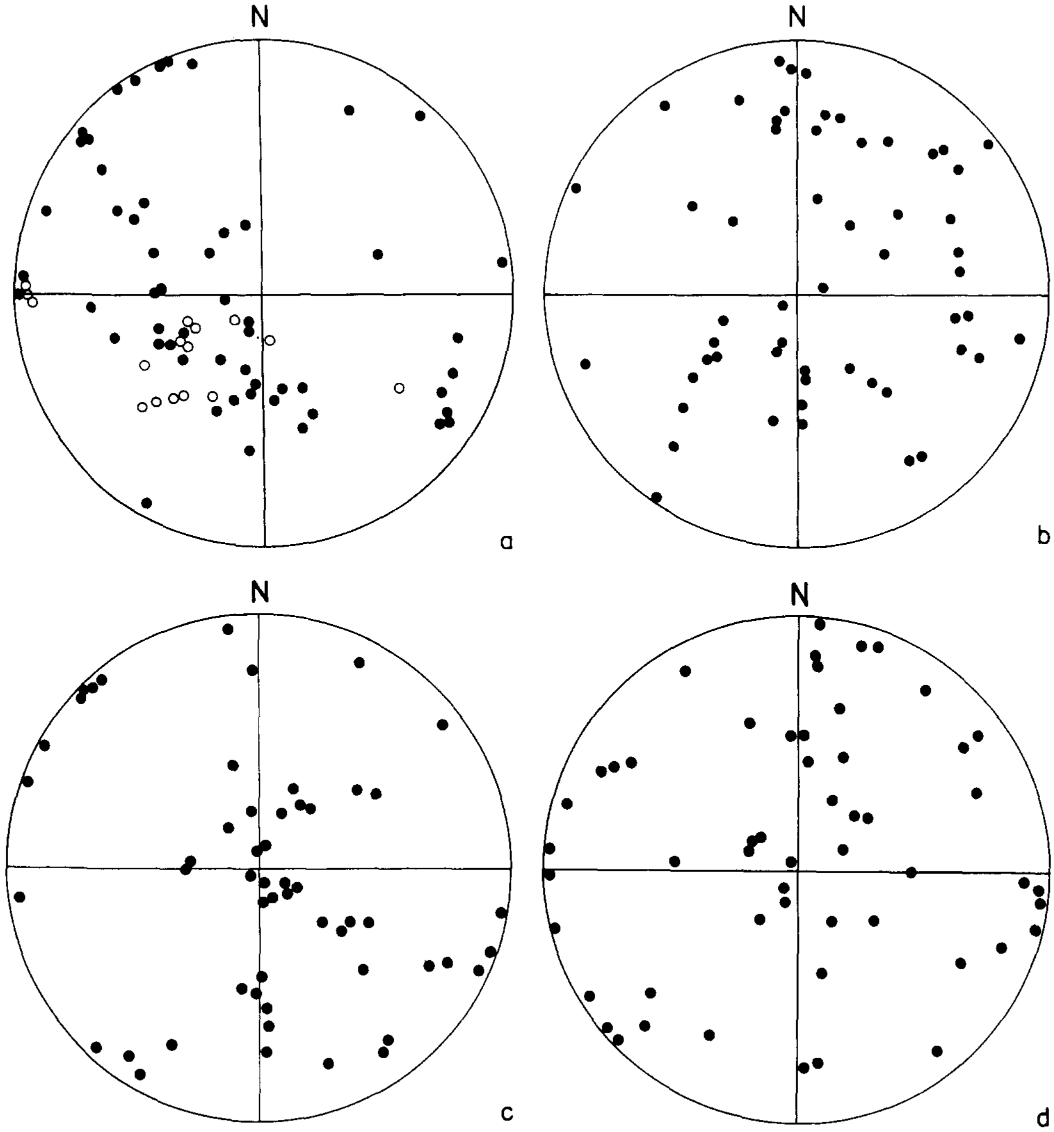

Fig. 5. (a) Orientations of magnetic foliation poles (full circles) and of bedding poles (open circles) in the Krížna nappe. (b) Orientations of magnetic lineation in the Krížna nappe. Geographic co-ordinate system. Equal-area projection on lower hemisphere. (c) Orientations of magnetic foliation poles in the Krížna nappe. (d) Orientations of magnetic lineation in the Krížna nappe. Palaeogeographic co-ordinate system. Equal-area projection on lower hemisphere.

Table 3. Parameters of magnetic anisotropy in sedimentary rocks of the Cover Formation*

Location No.	k_m (10^{-6})	L	F	P'	T	Rock†
VT 7	213	1.017	1.067	1.090	0.59	sh
		1.015	1.060	1.081	0.60	
VT 15	256	1.010	1.043	1.057	0.58	sh
		1.010	1.042	1.055	0.62	
VT 9	52	1.008	1.015	1.024	0.20	q
VT 20	16	1.009	1.016	1.025	0.07	q
VT 8	96	1.010	1.038	1.052	0.58	ls
		1.005	1.038	1.047	0.77	
VT 21	40	1.016	1.023	1.040	0.16	l
		1.005	1.026	1.034	0.70	

*The upper line for each locality shows arithmetic means of individual specimen values (specimen parameters), and the lower line shows the locality mean tensor; see text for explanation.

†sh—shale, q—quartzite, ls—limey sandstone, l—limestone.

Table 4. Parameters of magnetic anisotropy in sedimentary rocks of the Krížna nappe*

Location No.	k_m (10^{-6})	L	F	P'	T	Rock†
VT 11	103	1.004	1.009	1.013	−0.23	sh
		1.002	1.007	1.010	0.43	
VT 12	233	1.004	1.016	1.021	0.57	sh
		1.003	1.015	1.019	0.68	
VT 13	125	1.009	1.016	1.027	0.11	s
		1.006	1.016	1.023	0.47	
VT 16	106	1.024	1.010	1.035	−0.42	sh
		1.016	1.004	1.021	−0.60	
VT 14	21	1.012	1.014	1.028	0.09	s
		1.009	1.009	1.018	0.00	
VT 31	83	1.004	1.012	1.017	0.41	sh
		1.000	1.011	1.012	0.95	

*The upper line for each locality shows arithmetic means of individual specimen values (specimen parameters), and the lower line shows the locality mean tensor; see text for explanation.

†sh—shale, s—sandstone.

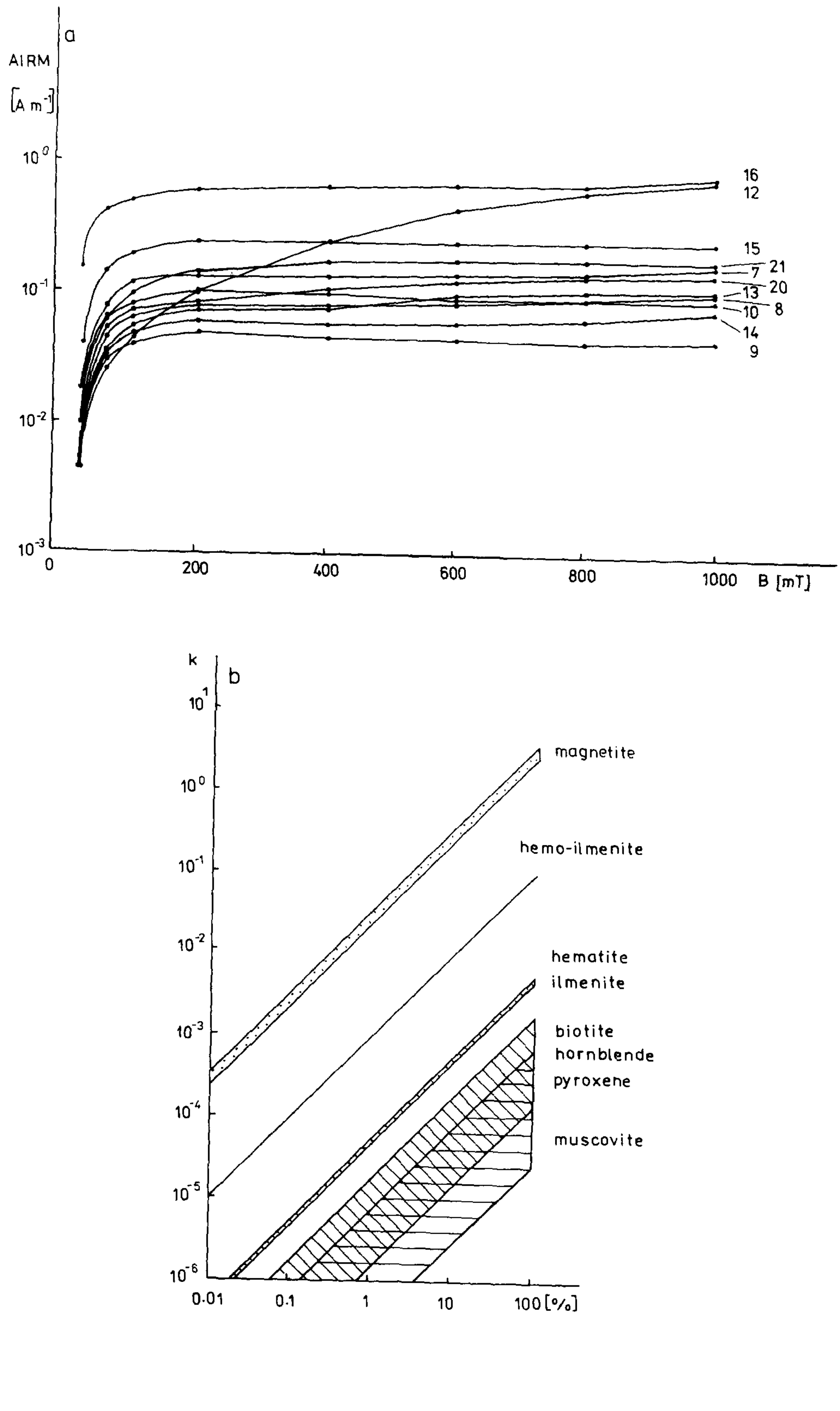

Fig. 6. (a) Diagram to show the dependence of the acquisition isothermal remanent magnetization (AIRM) on the magnetizing field (B) for pilot specimens from individual localities. (Numbers on the curves denote the locality numbers as presented in Fig. 1a.) (b) Model diagram of the contribution of some minerals to the rock susceptibility. Compiled using the data by Bleil & Petersen (1982), Borradaile *et al.* (1987), Kropáček & Krs (1971) and Zapletal (1986).

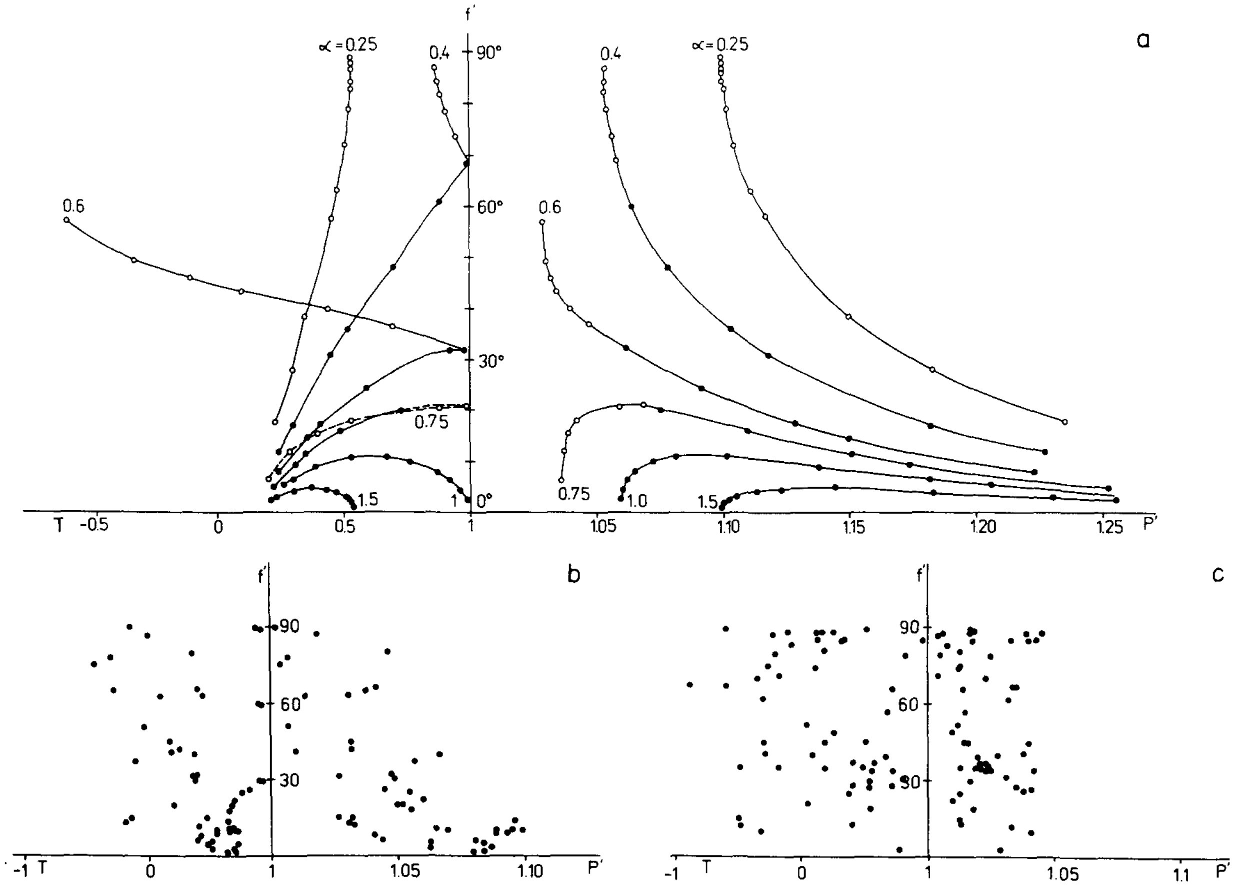

Fig. 7. (a) Double plot of P' vs f' and T vs f' to show model variation of magnetic anisotropy according to a model of strain in nappes. The pre-deformational parameters are: $P' = 1.053$, $T = 0.6$, magnetic lineation parallel to the transport direction. Further information in the text. (b) Double magnetic anisotropy plot for the sedimentary rocks of the Krížna nappe. (c) Double magnetic anisotropy plot for the sedimentary rocks of the Cover Formation.

ranging from $\gamma = 0.25$ to $\gamma = 30$. The plots also inform schematically of the orientation of magnetic lineation; full circles indicate its approximate parallelism to the transport direction, while open circles indicate its approximate perpendicularity to this direction.

Figure 7(b) shows a similar plot for the Krížna nappe specimens. It can be seen in this figure that the plots, mainly in the P' vs f' diagram, resemble much more the lateral shortening curves than the lateral lengthening curves. From this it can be deduced that the magnetic fabric in the Krížna nappe probably originated through the deformation represented by a combination of simple and pure shears. In addition, as the girdle in the magnetic foliation poles is oriented approximately parallel to the direction of the Krížna nappe transport as estimated from geological data (see Andrusov 1968, Mahel' 1986), it can be deduced that this deformation was associated with the creation and motion of the nappe. The main thrusting of the Mesozoic strata took place during the Upper Cretaceous, although subordinate post-Palaeogene back thrusting may also have operated (cf. Mahel' 1968, 1986).

It has also been shown in the preceding sections that the magnetic fabric in the sedimentary rocks of the Cover Formation is deformational in origin, or at least partially. In addition, the patterns in magnetic foliation poles and in magnetic lineations for the Cover Formation are similar to those for the Krížna nappe, and the double anisotropy plots are similar too, and compatible with the magnetic fabric pattern predicted by the modelling above (combined simple shear and shortening; Figs. 7a & c). Considering that part of the Cover Formation is known to be detached and thrust (for review see Mahel' 1968, 1986) and that an imbricate structure was revealed by reflection seismology throughout the whole High Tatra Mountains (Tomek personal communication 1987), it can be concluded that the Cover Formation is also a nappe (or a part of a larger nappe) and its magnetic fabric originated during the deformation processes associated with the creation and motion of this nappe. However, the similarity between the fabrics of the Krížna nappe and of the Cover Formation is not perfect. In the Cover Formation, the magnetic lineations making large angles with the bedding are mostly lacking, and the bedding poles tend to create an imperfect girdle. This probably indicates that the lateral shortening component was stronger and the simple shear component was in turn weaker than in the Krížna nappe.

In granitoid rocks, the magnetic fabric is also deformational in origin and in the main granitoid body the orientations in magnetic foliation poles and in magnetic lineations resemble those in the Krížna nappe and in the Cover Formation (cf. Figs. 3–5). Consequently, it is very likely that the magnetic fabric in the granitoid rocks was created as for the sedimentary rocks: i.e. by a combination of simple shear and lateral shortening, associated with the creation and motion of the nappes. Since the granitoid rocks are Variscan, whereas the sedimentary rocks of the Krížna nappe and Cover Formation are Lower Triassic to Middle Cretaceous in age, it must be concluded that the deformational magnetic fabric in the granitoid rocks is probably young, Alpine in age. This conclusion is in good agreement with the view that the granitoids are post-tectonic with respect to the Variscan tectonics (Kamenický 1968).

The magnetic anisotropy of metamorphic rocks is relatively strong and closely related to the metamorphic schistosity (Fig. 2) which is doubtless coeval with the main progressive regional metamorphism, i.e. Variscan in age. On the other hand, the patterns in principal susceptibilities in these rocks resemble those in the sedimentary and granitoids rocks (cf. Fig. 2 with Figs. 3–5), whose magnetic fabric was formed during Alpine thrusting-related deformations. It is obvious that these Alpine deformations also affected the metamorphic rocks giving rise to complex magnetic fabrics reflecting both the Variscan and Alpine deformation. The Variscan feature is the parallelism of the magnetic foliation to the metamorphic schistosity and the Alpine phenomenon is probably the deviation of the magnetic lineation from the perpendicular to the girdle in the schistosity poles.

The degree of anisotropy in metamorphic rocks is strongly variable. This may be accounted for by assuming that the Variscan metamorphic schistosity was folded before the Alpine deformation and this Alpine deformation amplified the Variscan magnetic fabric in the places where it was approximately coaxial to the Variscan magnetic fabric and weakened it in the places where it was oriented non-coaxially. The magnetic lineation was mostly deviated from the Variscan NNE–SSW directions towards the Alpine E–W directions.

CONCLUSIONS

The investigation of the magnetic fabric in metamorphic, granitoid and sedimentary rocks in the High Tatra Mountains (N. Slovakia) has drawn the following conclusions.

(1) In all the rock types investigated, i.e. in metamorphic, granitoid and sedimentary rocks, the magnetic fabrics are deformational in origin and show similar patterns both in magnetic foliation poles and in magnetic lineations.

(2) In the metamorphic rocks, the magnetic fabric is a complex fabric reflecting the Variscan and the Alpine ductile deformations. The former deformations gave rise to the magnetic foliation parallel to the metamorphic schistosity, while the latter deviated the magnetic lineation from perpendicular to the girdle in the schistosity poles.

(3) In granitoid rocks, the deformational magnetic fabric originated through the Alpine deformations associated with the creation and motion of nappes in this area. The granitoids are Variscan in age and post-tectonic in relation to the Variscan tectonism. The Alpine deformations overprinted and locally obliterated the Variscan intrusive magnetic fabric.

(4) In sedimentary rocks of the Cover Formation and the Krížna nappe the magnetic fabric was probably created during combined pure shear (lateral shortening) and simple shear deformations associated with the creation and motion of the nappes.

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