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MAGNETIC FABRIC OF THE UPPER JURASSIC SEDIMENTS, KRÍŽNA UNIT, TATRA MTS., POLAND

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Abstract: The anisotropy of magnetic susceptibility (AMS) was studied in the Upper Jurassic radiolarian limestones of the Western Tatra Mts. in Poland. Analysis was carried out on the material from 34 hand samples at 5 localities within the Krížna Unit. Well defined compactional magnetic fabric with slight tectonic disturbance was found. These results confirmed the results of structural studies which revealed the brittle character of deformations in the studied area. Very weak magnetic lineation directed SSW-NNE was encountered. It is subparallel to dominant fold axes and cleavage direction in the area. The magnetic fabric of the Krížna sediments in the Western Tatra Mts. differs from that in the Belianske Tatry where a strong tectonic overprint was previously described.

Key words: Central Western Carpathians, Tatra Mts., Krížna Nappe, radiolarites, magnetic fabric.

Introduction

No study of magnetic fabric has ever been made in the Polish Inner Carpathians. Also in the neighbouring Slovak area very few such studies are known. Hrouda et al. (1988) and Hrouda & Kahan (1991) reported a deformational magnetic fabric from the crystalline and sedimentary rocks of the Branisko-Čierna Hora Mts. and Tatra Mts. On the other hand Kądziałko-Hofmokl et al. (1990) maintained that the sedimentary rocks of the Krížna Unit in the Malá Fatra Mts. revealed a 'primary' magnetic fabric with minimum axes of susceptibility ellipsoid perpendicular to the bedding plane and well defined lineation.

In this study the results from 5 sites, sampled in the Krížna Unit of the Polish Tatra Mts. are presented. The rocks sampled were the Upper Jurassic radiolarites and radiolarian limestones, which were already reported to be a suitable material for paleomagnetic studies (Kądziałko-Hofmokl & Kruczyk 1987; Grabowski 1995). The sedimentology and stratigraphy of these rocks were described by Lefeld (1974), while the tectonics was studied by Kotański (1965), Bac (1971) and Piotrowski (1978).

Geological setting and sampling sites

Tatra Mts. is the northernmost occurrence of the "core mountains" in the Central Western Carpathians (Fig. 1). It is a megaanticlinal horst of crystalline pre-Mesozoic rocks, covered by Mesozoic deposits ranging from Lower Triassic to Upper Cretaceous (Książkiewicz 1977) (Fig. 2). The Late Cretaceous orogenic movements caused the formation of nappe structures and now the Mesozoic rocks occur in several overthrusted units: the High-Tatric (cover) and Sub-Tatric (Krížna and Choč Nappes) units are distinguished. The High-Tatric units, which were subjected to only minor horizontal displacements, are divided into para-autochthonous unit, that is a roughly in situ sedimentary cover of the crystalline rocks, and several detached units. The Sub-Tatric nappes were transported from the south and they occur in the form of separate tectonic slices. Paleogene rocks overlay discordantly the Mesozoic and crystalline core. In the Neogene the uplift of the Tatra Massif, as well as other massifs in the Central Western Carpathians took place (Kováč et al. 1994) giving rise to the origin of "core mountains" surrounded by basins filled with Tertiary sediments.

Two Sub-Tatric nappes are distinguished: the lower — Krížna Nappe, and the higher Choč Nappe (Fig. 2). Upper Jurassic radiolarites and radiolarian limestones occur in the Krížna sequence only. They crop out in the Western part of the Tatra Massif in a distinct tectonic unit, called the Bobrowiec Unit (localities 1-4 in the Fig. 3), as well as in the minute tectonic slice — the Gładkie Upłaziańskie slice (locality 5 in the Fig. 3).

The tectonics of the Bobrowiec Unit was described by Bac (1971). The unit is a monocline dipping gently (30-40°) towards the NNE. It comprises the complete profile of sedimentary rocks from the Lower Triassic to Lower Cretaceous. Its maximum thickness reaches to 1000 m but is often smaller due to tectonic reduction. Brittle deformations prevail, while folds are developed only locally in the more competent rocks. The fold axes are mainly SW-NE, sometimes revealing even meridional N-S directions (Bac et al. 1981; Fig. 4). The W-E fold axes are subordinate and occur in the top part of the Bobrowiec Unit in the vicinity of the Choč thrust zone. The fault strikes are NW-SE in the western and NE-SW in the eastern part of the Bobrowiec Unit (Fig. 3). Fracture cleavage and joint system reveal mainly NE-SW direction in the entire unit, while the NW-SE direction is subordinate (Bac 1971).

Gładkie Upłaziańskie is the southernmost occurrence of the Krížna Unit in the Tatra Massif. The tectonic slice, comprising the sediments from the uppermost Middle Triassic up to Up-

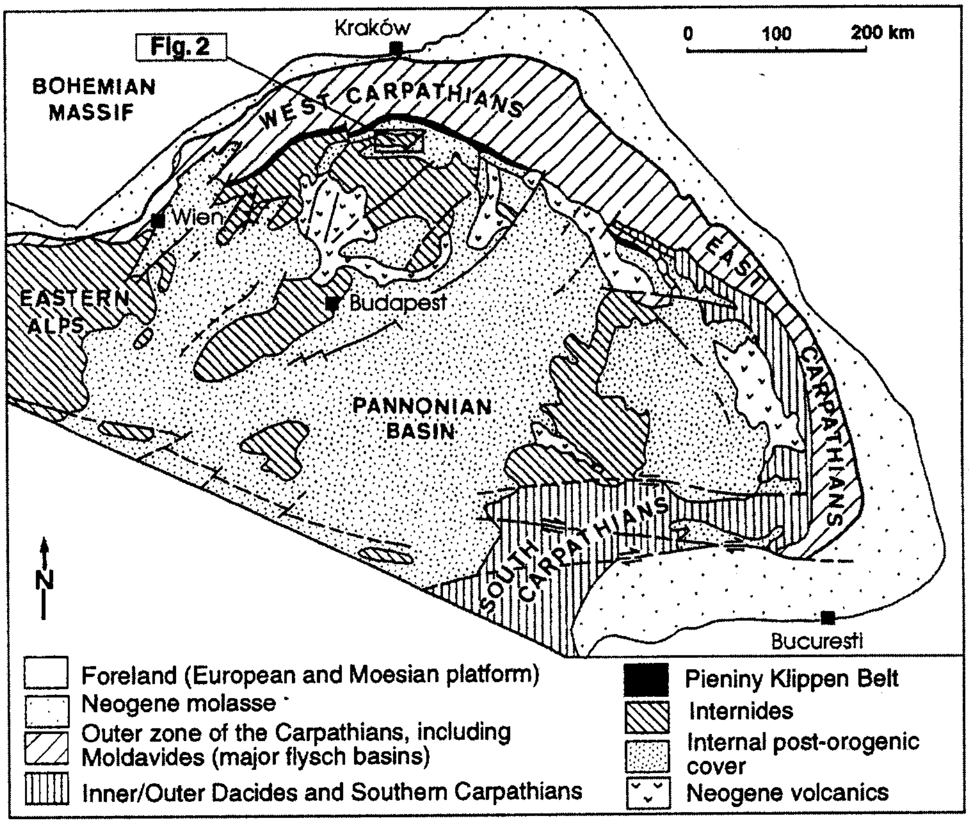


Fig. 1. Simplified tectonic map of the Carpathian arch (after Winkler & Ślączka 1994). Box indicates the area presented in Fig. 2.

per Jurassic-Lower Cretaceous is a remnant of a larger tectonic unit which underlay the Bobrowiec Unit (Kotański 1965). It lies at low angles on the levelled surface of the lower tectonic elements. The strata dip steeply (60-80°) towards the NNE. The fold axes distribution is bimodal with maxima 25° and 95°, while the joint system is the same as in the Bobrowiec Unit, NE-SW and NW-SE (Piotrowski 1978).

34 hand samples were taken from 4 localities in the Bobrowiec Unit and 1 locality at Gładkie Upłaziańskie (Fig. 3). Locality 2 was situated close to one of the faults.

Laboratory methods

The analysis of anisotropy of magnetic susceptibility (AMS) is now a widely used method for studying petrofabrics (see Hrouda 1982). It is a measure of internal deformation of the rock structure, reflected by the alignment of dia-, para- and ferromagnetic minerals. Geometrically the AMS is represented as a three-axis ellipsoid (K1 > K2 > K3), which for tectonically deformed rocks is co-axial with finite strain ellipsoid. The most weakly deformed sediments exhibit the axes of minimum susceptibility (K3) perpendicular to the bedding plane (compaction stage), while during progressive deformation the K3 axis is reoriented in a direction parallel to the tectonic shortening (Hrouda, op. cit.). It is a matter of primary importance to identify the mineralogical source of AMS. It may happen that different AMSs are carried by para- and ferromagnetic minerals in the same rock (recent case, see Aubourg et al. 1995). The most common technique applied is the study of anisotropy of low-field susceptibility and the method was used in this study. This method has a disadvantage because it is not capable of distinguishing between the para- and ferromagnetic anisotropies and another methods (for example anisotropy of high-field susceptibility and investigations of susceptibility in low temperatures, see Richter & van der Pluijm 1994) should be used. These techniques were not available to the author so the source of AMS was deduced mainly from the mineralogical composition of the studied rock.

Cylindrical specimens, 22 mm high and 20 mm in diameter, were drilled from the hand samples. Usually 2 to 3 specimens were obtained from each sample. AMS measurements and data analysis were performed in the paleomagnetic laboratory of the Polish Geological Institute in Warsaw. The AMS has been measured using a KLY-2 Kappabridge (Geofyzika, Brno) and computed using the Aniso program (Jelínek 1977). The following parameters which characterize the AMS were examined:

1 — degree of anisotropy P = K1/K3;

2 — parameters defining the shape of the anisotropy ellipsoid — lineation L = K1/K2 and foliation F = K2/K3 (the elipsoid is prolate if L > F and oblate if F > L);

3 — mean susceptibility K_m = (K1 + K2 + K3)/3 calculated for normalized volume 10 cm^3.

Magnetic minerals were determined using the thermomagnetic method (described in Kądziałko-Hofmokl & Kruczyk 1987) in the paleomagnetic laboratory of the Institute of Geophysics, Polish Academy of Sciences. Additional observations were made in thin sections in transmitted light and with X-ray analysis.

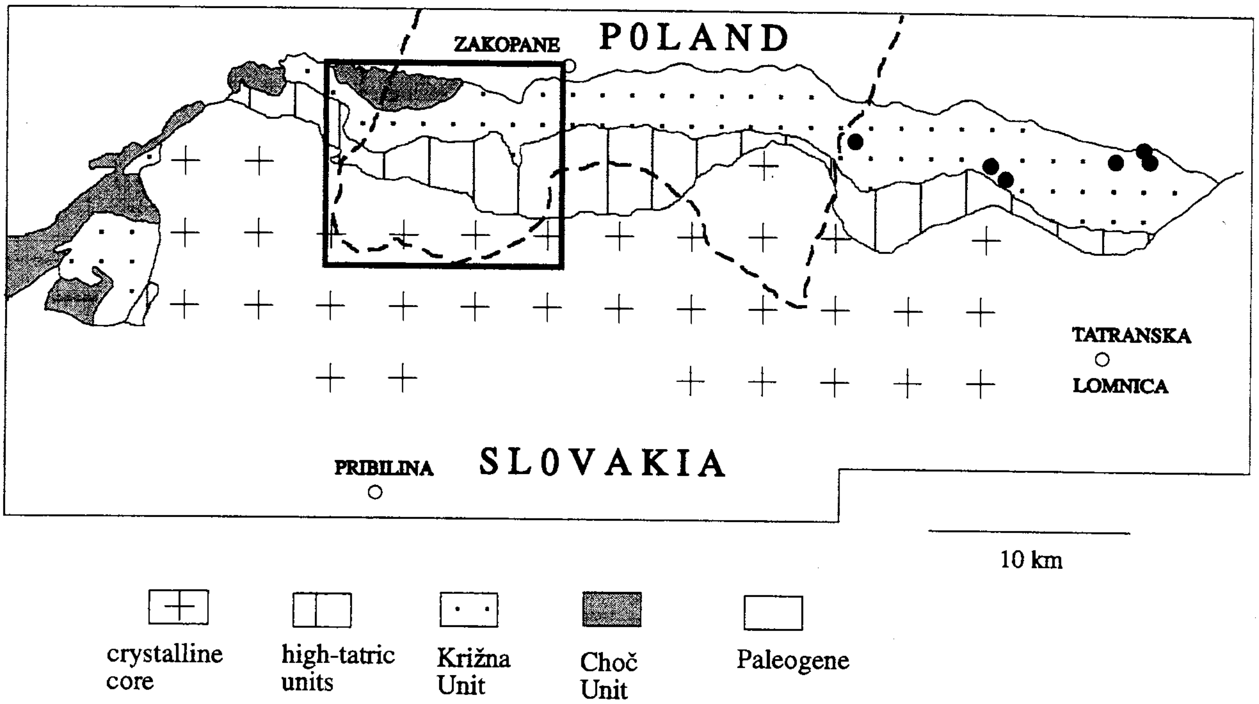


Fig. 2. Tectonic sketch map of the Tatra Mts. (modified, after Hrouda & Kahan 1991). Localities sampled in the Krížna Unit by Hrouda & Kahan (1991) are indicated by dots.

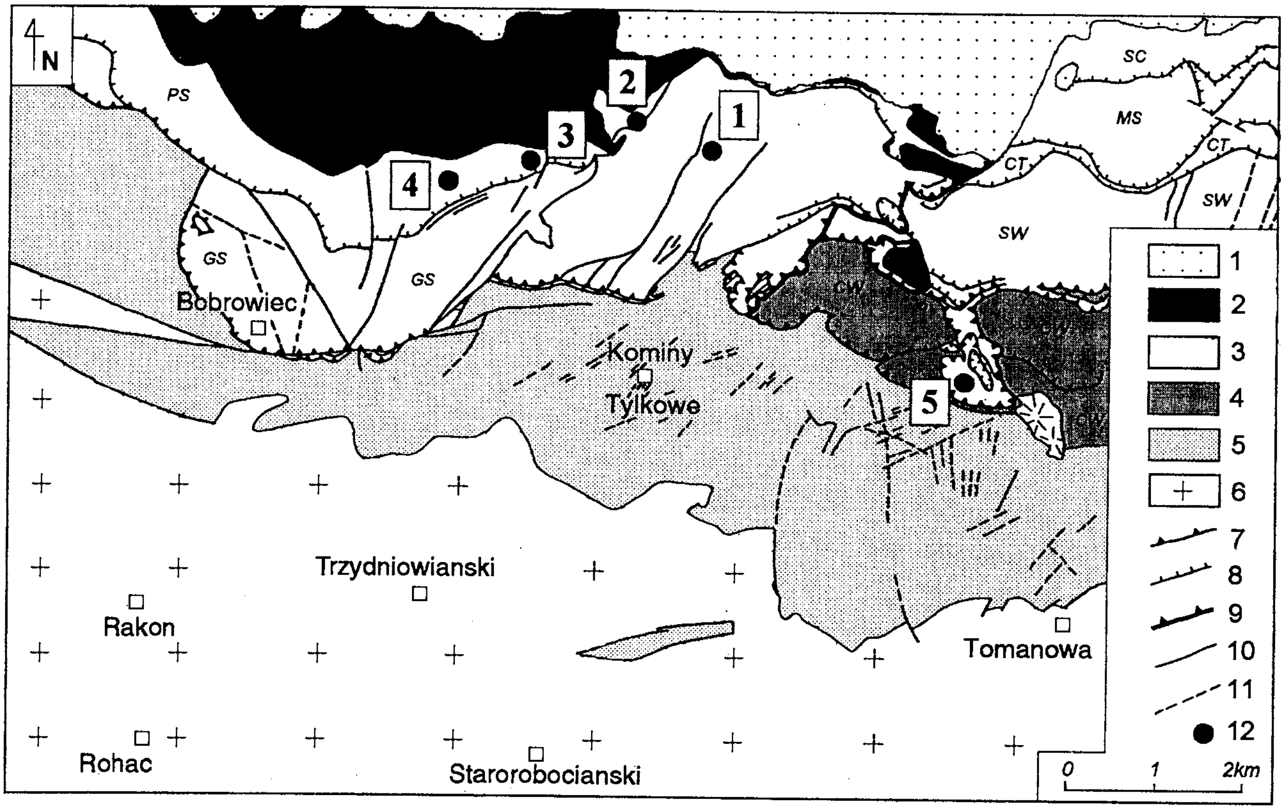


Fig. 3. Tectonic sketch of neighbouring areas of the Bobrowiec Unit (after Bac 1971, modified). **1.** Eocene, **2.** elements of the upper Sub-Tatric (Choč) nappe: FU — Furkaska Unit, KU — Koryciska Unit, **3.** elements of the lower Sub-Tatric (Krížna) nappe: Bobrowiec Unit: GS — Głębowiec slice, PS — Parządczak slice; Zakopane part of the Sub-Tatric zone: SW — Suchy Wierch Unit, CT — Czarna Turnia Unit, MS — Mała Świnica Unit, SC — Samkowa Czuba Unit, **4.** overthrusted High-Tatric units: CW — Czerwone Wierchy Unit, **5.** sedimentary autochthonous cover, **6.** crystalline rocks, **7.** main overthrusts, **8.** subordinary overthrusts, **9.** boundary of western and Zakopane parts of the Sub-Tatric zone, **10.** faults, **11.** faults recorded by photointerpretation, **12.** sampling places.

Results

Magnetic mineralogy

Thermomagnetic curves (Fig. 4a) reveal the presence of magnetite and hematite. The inflexion point on the first curve, about 550 °C, is close to the Curie temperature of magnetite (585 °C) while the persistence of the IRM at temperatures above 600 °C indicates the presence of hematite. That feature is not visible on the second heating curve, which reveals a "magnetite-like" shape. That indicates production of secondary magnetite during heating: the intensity of IRM after first heating is ten times greater than in the natural state (see Fig. 4a). The increase of susceptibility after demagnetization above 500 °C is also related to that process.

The results of alternating field demagnetization (Fig. 4b) support the occurrence of low and high coercivity minerals: more than a half of the NRM decays up to 20 mT but the rest persist up to 45 mT (maximum reliable demagnetization level).

A fine ferruginous substance is regarded as primary and is uniformly distributed in the rock matrix between bioclasts. Microscopic observations revealed the presence of paramagnetic minerals: ferroan calcite, which occurs in thin hydrothermal veins, and unidentified phyllosilicates in the matrix. Unfortunately the X-ray analysis failed to idenify any minerals other than calcite and silica. According to chemical analysis the radiolarites contain 2 % of Al_2O_3 (Lefeld 1974) what additionally supports the occurrence of phyllosilicates. Thus the low field susceptibility is most probably composite and originates from ferro- and paramagnetic minerals.

Magnetic fabric

The degree of anisotropy P is low and there is no clear correlation between that parameter and the mean susceptibility K_m (Fig. 5). That means that the matrix minerals (ferroan calcite, phyllosilicates) could influence the anisotropy of magnetic susceptility (Rochette 1987). That author postulated that

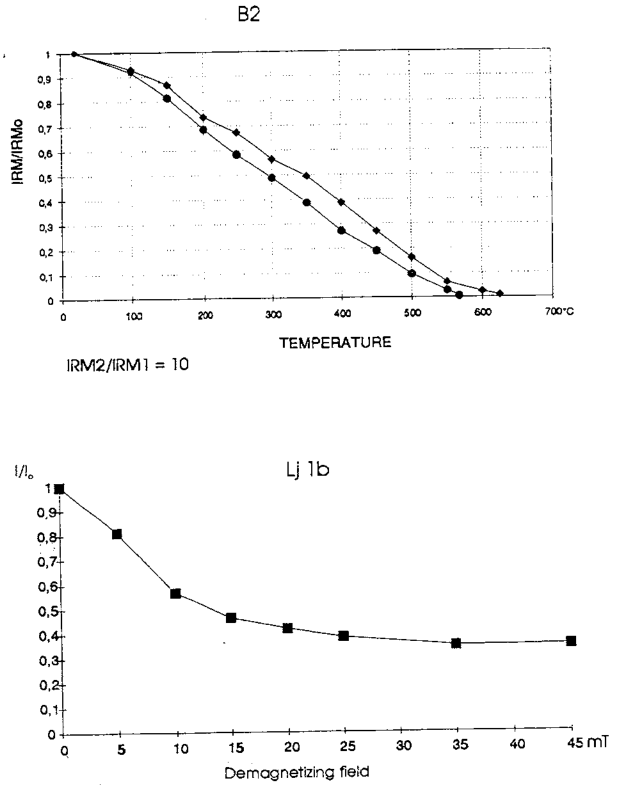


Fig. 4. (a) — Thermal demagnetization of the isothermal remanent magnetization (IRM), (thermomagnetic analysis), diamonds — first heating curve, dots — second heating curve. The IRM2/IRM1 ratio indicates the increase of the IRM intensity after the first heating. **(b)** — Alternating field demagnetization of the natural remanent magnetization (NRM).

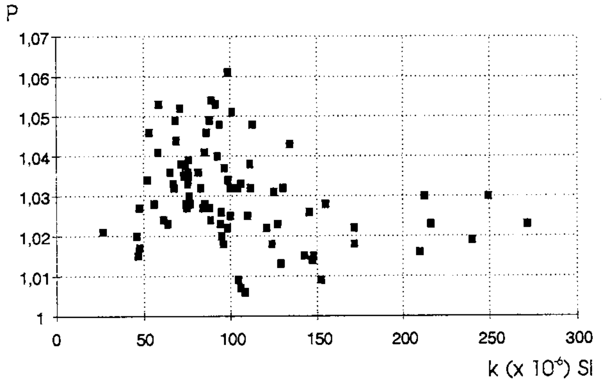


Fig. 5. Plot of the anisotropy degree P versus mean susceptibility k for all specimens.

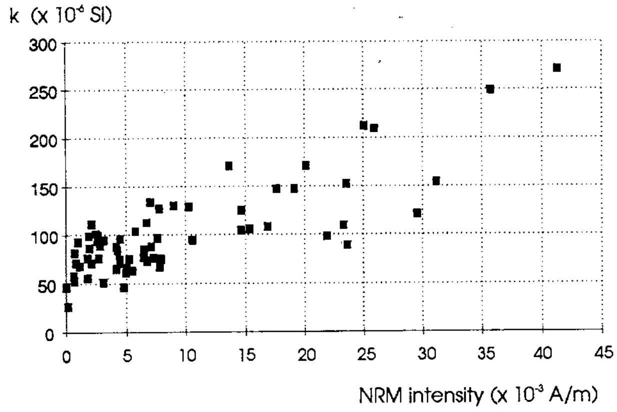


Fig. 6. Plot of the NRM intensity versus mean susceptibility k, normalized for volume 10 cm^3.

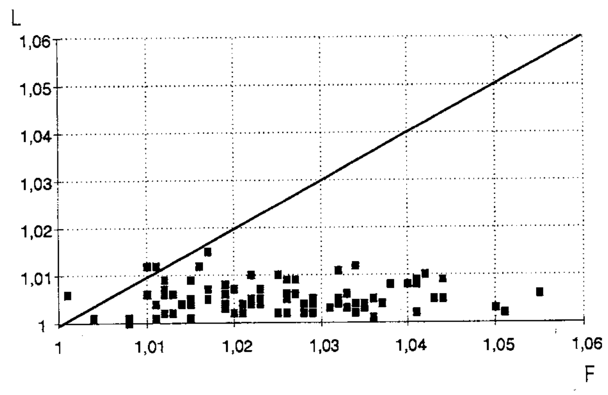
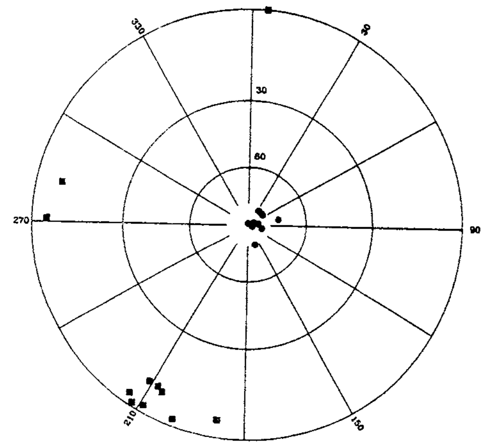
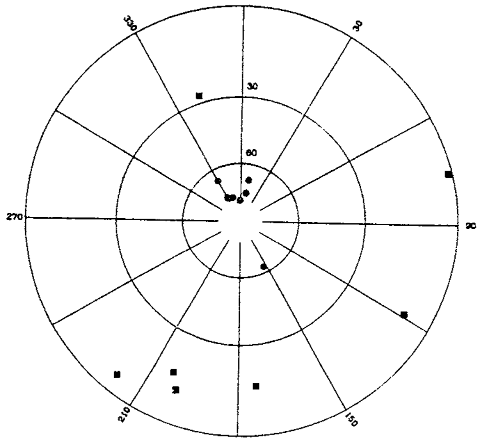


Fig. 7. Plot of AMS lineation parameter (L) versus foliation (F).

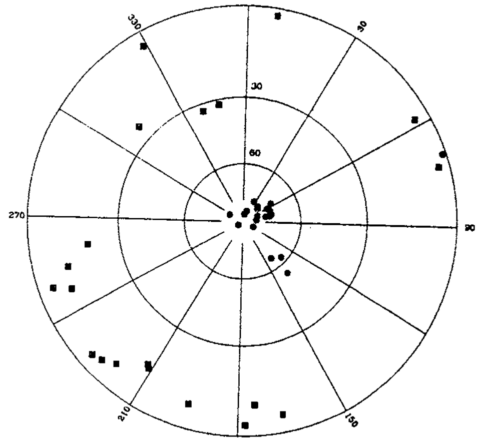
Loc.1



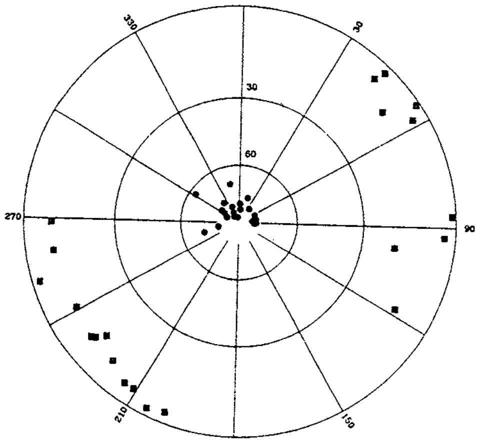
Loc.2



Loc.3



Loc.4



Loc. 5

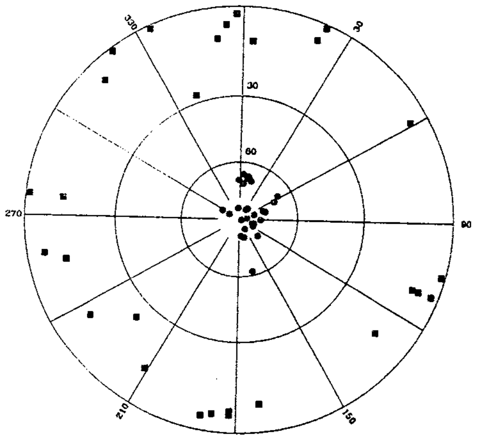


Fig. 8. Stereographic projection of minimum (dots) and maximum (squares) susceptibility axes from the investigated localities, after tectonic correction.

below $K_m = 300\times10^{-6}$ SI the anisotropy is carried mainly by the matrix. Observations gathered in the present study support that conclusion because K_m is between 47 and 271×10^{-6} SI. A correlation is observed between the intensity of the natural remanent magnetization (NRM) and K_m (Fig. 6) which suggests a contribution of NRM carriers to K_m. It is possible that bulk susceptibility arises mainly due to ferromagnetic minerals while anisotropy is mainly due to matrix, as it was recently stated by Aubourg et al. (1995) for some weakly deformed sediments from the Western Alps. Unfortunately the influence of matrix on bulk susceptibility cannot be estimated qualitatively here because the high field anisotropy of magnetic susceptibility was not measured.

In all localities the oblate magnetic fabric was observed (Fig. 7). The magnetic foliation is generally parallel to the bedding plane (Fig. 8). The foliation is very well defined. The half confidence angle of the K3 relatively to the K2 axis is low and in 75 % of specimens does not exceed 10° and only in 5 specimens (6 % of collection) is greater than 20°. Such pattern of foliation in the thrust sheets is commonly accepted as compactional fabric resulting from the pressure of the overlying rocks, when they still lay in the horizontal position (Kligfield et al. 1983). It is also a premise that the bedding in the studied tectonic units was approximately horizontal during the nappe deformation (Hrouda & Kahan 1991). The distribution of the K3 axes in the locality 3 and 5 is bimodal, which indicates some additional deformations of rock structure.

Weak magnetic lination was revealed in all localities (Fig. 8). The azimuths of lineation are variegated and only in the locality 1 the SSW directed maximum may be clearly identified. Such picture could indicate either that there is no regional direction of lineation, or that there exist several competing lineation systems. The second possibility is more likely. The plots of the K1 declination vs. the lineation parameter L and the half confidence angle of the K1 within the foliation plane (E12) reveal that lineations with declinations of 150-240° are more conspicuous than the W-E trending lineations (Fig. 9). In Tab. I mean lineation was calculated for all 5 localities, taking into account only the best defined lineations. The mean directions of lineations are grouped with the SSW azimuth.

The depositional origin of the K1 alignment is not probable. The sedimentary rocks studied here were deposited in a deep water environment, thus the activity of water currents should be an extraordinary phenomenon. Moreover detailed sedimentological studies of the formation (Lefeld 1974) did not reveal structures related to directional transport. Thus the SSW-NNE directed lineation should be of tectonic origin. Geological interpretation of magnetic lineation is not simple, especially when its mineralogical source is not known. It is generally assumed that the K1 axis is parallel to the X (stretching) axis of the finite strain ellipsoid. Therefore several possible explanations for origin of magnetic lineation in Sub-Tatric radiolarian limestones may be suggested:

1. It originated due to northward transport of the Krížna Nappe in the Late Cretaceous.

2. It originated during a WNW-ESE directed compressional episode.

3. It originated due to intersection of bedding plane and main cleavage plane NE-SW.

The idea of tectonic transport of the Krížna Nappe from the south is based on the paleogeographical and paleofacial considerations of Slovak geologists (see, Książkiewicz 1977) but it has still found no equivocal support in the orientation of mesostructures in the Sub-Tatric zone (Piotrowski 1978). The directions of fold axes in the Bobrowiec Unit and Gładkie Upłaziańskie slice may be evidence for a NW-SE compression but its geological cause is not known. The dominant cleavage plain NE-SW is parallel to the faults which may be of strike-slip character. More investigations in both the Sub-Tatric units and Tertiary cover are needed as well as studies of the mineralogical source of magnetic lineation to distinguish between these hypotheses.

The relatively simple magnetic fabric described here is very different from the one found by Hrouda & Kahan (1991) in the Krížna Nappe in the Slovak area. The directions of folia-

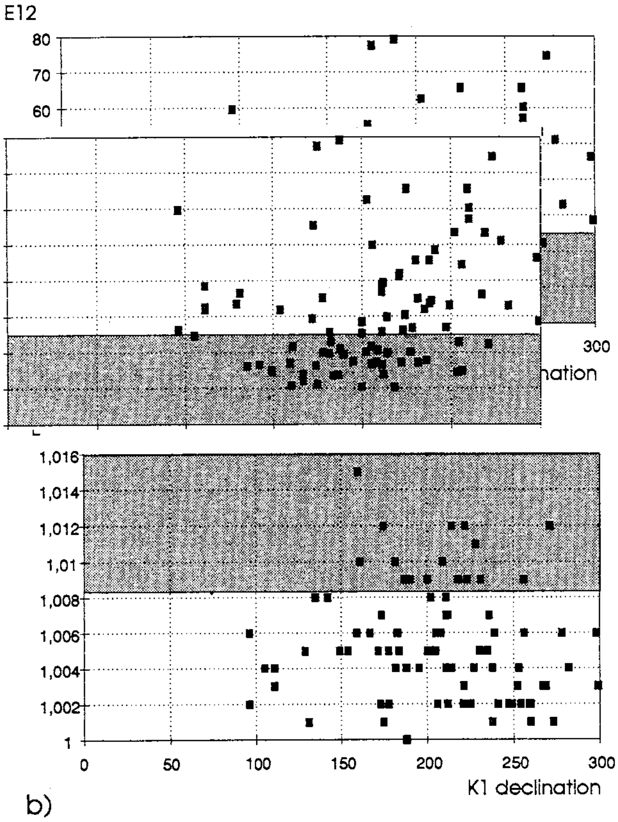


Fig. 9. Plots of the declination of K1 axis vs. the half-confidence angle E12 of K1 within the plane K1-K2 (a) and vs. the lineation parameter L (b).

Table I: Mean directions of minimum and maximum susceptibility axis in studied localities.

Loc.	K3				K1				
	D	I	α_{95}	n	D	I	α_{95}	N	remarks
1	79	84	4	11	201	4	10	6	E12<22°
2	350	74	6	6	199	12	35	3	E12<22°
3	57	82	3	16	188	1	23	8	E12<22°
4	338	84	4	21	220	1	10	8	E12<32°
5	82 7	84 69	4 2	20 8	352	4	18	8	E12<22°

Explanation: Loc. — number of locality (see Fig. 3), K3, K1 — minimum, maximum susceptibility axes, D — declination, I — inclination, α_{95} — 95% half confidence angle, n — number of specimens used for calculations, E12 — half-confidence angle of K1 within the K1-K2 plane.

tions and lineations were highly scattered there, tending to create a wide N-S girdle. These authors sampled the easternmost parts of the Sub-Tatric Krížna Unit in the Belianske Tatry and Široká Massif (Fig. 2), belonging to independent Havran, Bujačí Vrch and Skalki units. The rocks sampled were of different lithology and mineralogy (shales and sandstones) than those in the present study (radiolarian limestones) what should be born in mind while discussing the geological implications. A conclusion can be drawn that a great difference may exist in the style of deformation between the western (Bobrowiec Unit) and eastern part (Havran, Bujačí and Skalki units) of the Krížna Nappe in the Tatra Mts. The combination of simple and pure shears were dominant in the east (Hrouda & Kahan, op. cit) while compaction and slight stretching prevailed in the west.

Conclusions

1. The magnetic fabric of the Upper Jurassic radiolarites and radiolarian limestones in the Krížna Unit of the Western Tatra Mts. is predominantly compactional with slight tectonic influence. It is characteristic for weakly deformed sediments — the rigid style of deformation was also confirmed by structural studies.

2. Weak SSW-NNE directed magnetic lineation is observed, which is sub-parallel to fold axes and main cleavage direction.

3. In contrast to the compactional magnetic fabric in the Western Tatra Mts., the magnetic fabric in the Krížna units in the Belianske Tatry is of tectonic origin indicating a higher degree of internal deformation in the eastern part of the Tatra Massif.

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