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MAGNETIC SUSCEPTIBILITY ANISOTROPY MEASUREMENTS ON MIOCENE IGNIMBRITES FROM BÜKKALJA, HUNGARY

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The results of susceptibility anisotropy measurements of Miocene ignimbrite samples from 4 localities in Bükkalja, Northeastern Hungary, are presented. It is concluded that the magnetic fabric of the rocks was affected by Miocene or younger stress fields. Using the intermediate susceptibility axes two compression directions can be identified: 11°–191° for Bogács (upper ignimbrite level) and 135°–315° for Sály (lower ignimbrite level) and these are in good agreement with compression directions derived from microtectonic measurements.

Keywords: magnetic susceptibility, anisotropy, Miocene, ignimbrite, Hungary, Bükk Mountains

1. Introduction

The anisotropy of low-field magnetic susceptibility can provide information about the magnetic fabric of rocks. The principal susceptibility directions are related to the geological structural elements and the stress field, e.g. the schistosity plane and bedding plane, respectively, the compression axes, etc. Several authors have used anisotropy data in geological structural analysis [e.g. HROUDA, 1979, 1982; RATHORE 1985; HIRT et al. 1988; ROCHETTE 1988].

In the Bükk Mountains the existing fault zones as well as the distribution of the Miocene volcanism indicate a rather complicated stress pattern. The ignimbrites of the Bükkalja that we measured also show clear magnetic anisotropy which we attempt to interpret here in structural geological terms.

2. Geology and sampling

There was a large-scale and recurring volcanic activity in NE Hungary during the Miocene age. Rhyolitic and dacitic tuffs were forced up during eruptions which covered the whole Bükkalja area and even the Bükk Mountains. Ignimbrites formed two levels in the rhyolite tuff:
a) the lower level resembles rhyolitic lavas and contains many dark grey perlitic or pitchstone inclusions of fluidal texture;
b) the upper level is of dacitic composition. The rock is hard, dark grey, brown or red, vitrophyric-porphyric, contains pitchstone and often has a fluidal texture [BALOGH and RÓNAI 1965].

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Stratigraphical dating of the Bükkalja ignimbrites is problematic. Balogh and Rónai [1965] claim that the two types of ignimbrites are of different age: a) is considered as lower Helvetian (Ottnangian) and b) as Tortonian (Badenian).

Radiometric dates range from about 60 to 12 Ma [Hámor et al. 1979].

78 independently oriented samples were drilled from 4 localities (Bogács: upper ignimbrite level; Kács, Sály and Kisgyőr: lower ignimbrite level) both for palaeomagnetic and anisotropy measurements *(Fig. 1)*. The samples were collected from several sampling points at Bogács (4 points), Sály (2), Kisgyőr (4) and from one point at Kács. Either the visible fabric and colour of the rocks at these points was different, or the sampling points represent different blocks of rock. One to four standard size specimens were cut from each sample.

The macroscopic texture of the ignimbrites showed well developed foliation at all localities. This foliation plane is subhorizontal, the dip ranges from 0 to 20 degrees.

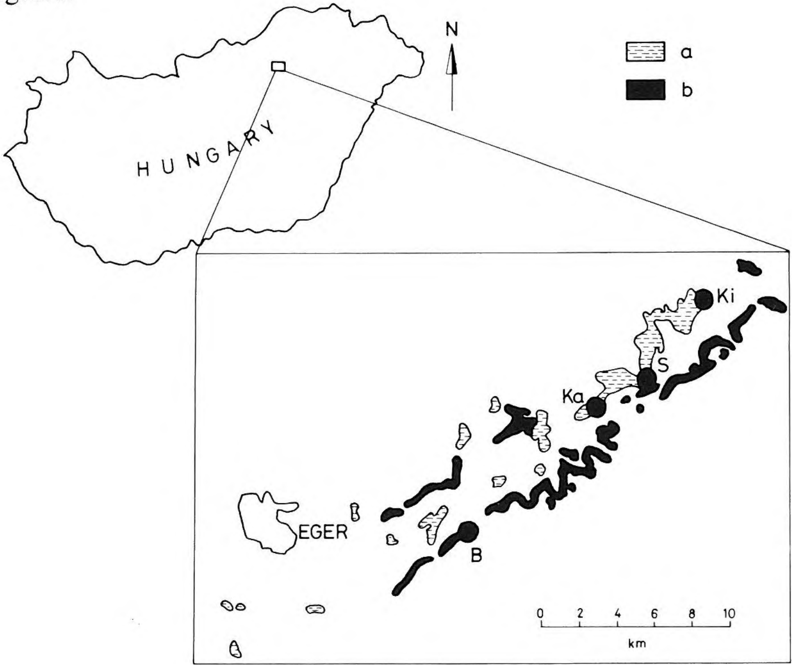


Fig. 1. Ignimbrit outcrops in the Bükkalja region, from Balogh and Rónai [1965]. a: lower ignimbrite level; b: upper ignimbrite level. Dots—sampling localities: B — Bogács, Ka — Kács, S — Sály, Ki — Kisgyőr

1. ábra. Ignimbrit feltárások a Bükkalján Balogh és Rónai [1965] után. a: alsó ignimbrit szint; b: felső ignimbrit szint. Pontok — mintavételi helyek: B — Bogács, Ka — Kács, S — Sály, Ki — Kisgyőr

Рис. 1. Игнимбритовые обнажения в Бюккалья по Балогу и Ронаи [1965]. а: нижний игнимбритовый горизонт; б: верхний игнимбритовый горизонт. Точки — места взятия проб: B — Богач, Ka — Кач, S — Шай, Ki — Кишдъер.

3. Susceptibility anisotropy and data evaluation

The magnetic susceptibility is a general property of rocks. In a weak magnetic field, H, there is a linear relationship between H and the induced magnetization, J, as follows:

$$J = \mu_0 \mathbf{k} H$$

where $\mu_0 = 4 \times 10^{-7}$ A/m and **k** is a symmetric tensor of second rank, called the 'susceptibility tensor' [Hrouda 1982]. Tensor **k** can be represented by a triaxial ellipsoid (susceptibility ellipsoid) of which the directions and length of the principal axes define the directions and the magnitudes of the so called principal susceptibilities (κ_{max}, κ_{inter}, κ_{min}), respectively.

The following anisotropy parameters have been found useful [Hrouda 1982]:
anisotropy degree:

$$P = \frac{\kappa_{\mathrm{max}}}{\kappa_{\mathrm{min}}},$$

magnetic lineation:

$$L = \frac{\kappa_{\mathrm{max}}}{\kappa_{\mathrm{inter}}},$$

magnetic foliation:

$$F = \frac{\kappa_{\mathrm{inter}}}{\kappa_{\mathrm{min}}},$$

ellipsoid form:

$$E = \frac{F}{L} = \frac{\kappa_{\mathrm{inter}}^2}{\kappa_{\mathrm{max}}\kappa_{\mathrm{min}}},$$

and
mean susceptibility:

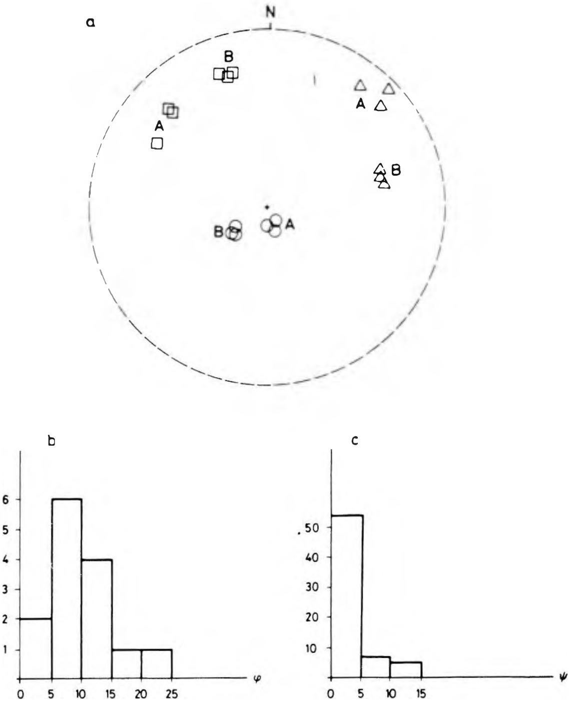
$$\bar{\kappa} = \frac{\kappa_{\mathrm{max}} + \kappa_{\mathrm{inter}} + \kappa_{\mathrm{min}}}{3}.$$

It is these parameters through which the magnetic anisotropy data can be related to the geological structure.

The directional susceptibility of the specimens was measured on a low-field susceptibility bridge (Kappabridge KLY-2) which is capable of measuring susceptibilities up to 2×10^{-1} SI with a precision of 5×10^{-8} (or 0.1%).

15 directional susceptibilities are measured [Jelínek 1977] and the elements of matrix **k**, its eigenvalues and eigenvectors determined by a computer program written for on-line measurements with an IBM PC/XT. A least square approach is used for estimating the standard error of the measurement, the error angles of the principal directions, etc. An F-test is performed to decide whether the anisotropy of the specimen is significant. The principal directions are plotted on a stereographic projection for each site or locality to monitor the grouping of the principal directions in the geographic and/or tectonic system.

In the course of the measurements it turned out that the principal directions and the respective anisotropy parameters of the sister specimens differ considerably. To determine the origin of these differences the measurements were repeated three times and it was found that the three measurements of the *A* sister differ significantly from those of the *B* sister, i.e. the principal directions within the sister are closer than the ones between sisters *(Fig. 2)*. The same is apparent in the variability of the anisotropy parameters *(Table I)*. It can be concluded that these features are caused by the different magnetic fabric of the sisters (e.g. inhomogeneous distribution of ferromagnetic minerals) and not by measuring errors. To eliminate the effect of heterogeneity, the anisotropy tensors of the sisters were averaged for each sample and the averaged tensors served as input for a statistics program. The latter was written for the evaluation of the anisotropy data on a group of specimens representing a geological body making use of Jelínek's statistical approach [JELÍNEK 1978]. The mean anisotropy tensor and its parameters were determined for each sampling point and locality. A T^2-statistics was used for characterizing the significance of the anisotropy at the 0.05 probability level.



Measurements	Mean susc. (10^{-6} SI)			*P*			*L*			*F*		
Sister	1	2	3	1	2	3	1	2	3	1	2	3
A	171	169	170	1.030	1.030	1.029	1.006	1.007	1.006	1.024	1.022	1.022
B	156	155	155	1.055	1.052	1.055	1.021	1.020	1.020	1.033	1.032	1.034

Table I. Mean susceptibility and anisotropy parameters of three repeated measurements of two sister specimens (*A* and *B*, see Fig. 2 for corresponding principal directions). $\bar{\kappa}$: mean susceptibility; *P*: anisotropy degree; *L*: magnetic lineation, *F*: magnetic foliation

I. táblázat. Egy minta két példányán végzett háromszori mérés átlag szuszceptibilitásai és anizotrópia paraméterei (*A* és *B* mintapéldányok, a megfelelő főirányokat lásd a 2. ábrán). $\bar{\kappa}$: átlag szuszceptibilitás; *P*: anizotrópia fok; *L*: mágneses lineáció, *F*: mágneses foliáció

Таблица I. Параметры анизотропии и средние чувствительности троекратного измерения, выполненного на двух образцах пробы. (*A* и *B* – образцы, соответствующие главные направления см. на рис. 2). $\bar{\kappa}$: средняя восприимчивость; *P*: степень анизотропии; *L*: магнитная линейность; *F*: магнитная фолиация.

Fig. 2. Repeatability of anisotropy measurements (cf. Table I)
a) Principal directions from three repeated measurements of sisters *A* and *B* of sample No. 4938. Stereographic projection, lower hemisphere. Squares: maximum, triangles: intermediate, circles: minimum susceptibility directions
b) Frequency distribution of angular distance (φ) between the minimum directions of sisters
c) Frequency distribution of angular distance (ψ) between the minimum directions of repeated measurements of one specimen

2. ábra. Anizotrópia mérések ismételhetősége (ld. I. táblázat)
a) A 4938 sz. minta *A* és *B* példányain végzett háromszori mérés főirányai. Sztereografikus vetület, alsó félgömb. Négyzetek: maximum, háromszögek: közepes, körök: minimum szuszceptibilitás irányok
b) Mintapéldányok minimum irányai közötti szögtávolság (φ) gyakorisági eloszlása
c) Egy mintapéldány ismételt méréseinek minimum irányai közötti szögtávolság (ψ) gyakorisági eloszlása

Рис. 2. Повторяемость измерений анизотропии (см. таблицу I).
a) Главные направления троекратного измерения, проведенного на образцах *A* и *B* пробы N 4938. Стереографическая проекция, нижняя полусфера. Направления максимальной (квадраты), средней (треугольники), минимальной (круги) восприимчивости.
b) Частотное распределения углового расстояния (φ) между минимальными направленийми.
c) Частотное распределение углового расстояния (ψ) между минимальными направлениями повторных измерений на одном образце пробы.

4. Results

The mean susceptibilities have lower values for the lower ignimbrite level (Kács, Sály, Kisgyőr: $1.5-4\times10^{-4}$ SI) than for the upper level (Bogács: $2-6\times10^{-3}$ SI). The anisotropy degree is rather low: 1.02–1.07 for the lower level and 1.01–1.03 for the upper level. The natural remanent magnetization (NRM) intensities vary between 2×10^{-2} and 3×10^{-1} A/m for the lower level while the upper level shows a variation in intensity between 10^{-1} and 10^{0} A/m.

Fig. 3 shows the variation of the anisotropy degree with the mean susceptibility (a), respectively the NRM intensity (b) for each sampling point. At Bogács a weak correlation is suggested while for the other three localities there is no correlation either between the anisotropy degree and the mean susceptibility or between the anisotropy degree and the NRM intensity.

Fig. 4 shows the NRM intensity versus mean susceptibility for each specimen of the lower ignimbrite level. As the mean susceptibility is below 10^{-3} SI units, it can be assumed that the susceptibility anisotropy is dominated by the paramagnetic minerals present [Rochette 1988]. The trend of the NRM intensity versus mean susceptibility leads to an estimation of the paramagnetic susceptibility to be about 10^{-4} SI units.

Despite the low anisotropy degrees found, the principal directions, especially the minimum directions, form well defined groups. The latter are near vertical and the magnetic foliation plane (defined by the maximum and intermediate directions) is subhorizontal, i.e. very close to the macroscopic foliation observed in the field.

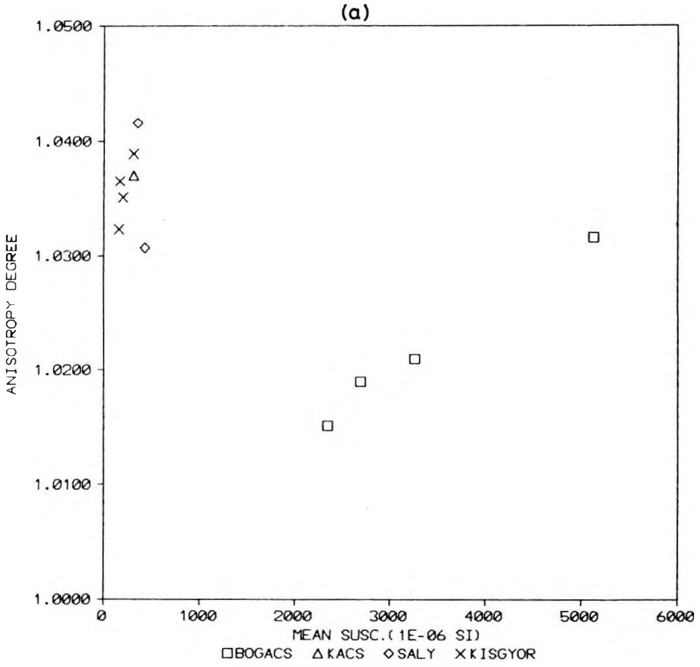
Fig. 5 shows two typical patterns of the distribution of the principal directions. At Bogács (Fig. 5a) all the three directions cluster while at Kács (Fig. 5b) only the minimum directions group and the maximum and intermediate directions show no preferred orientation in the foliation plane. From the other two localities, the principal directions resemble the first pattern at Sály and the second one at Kisgyőr.

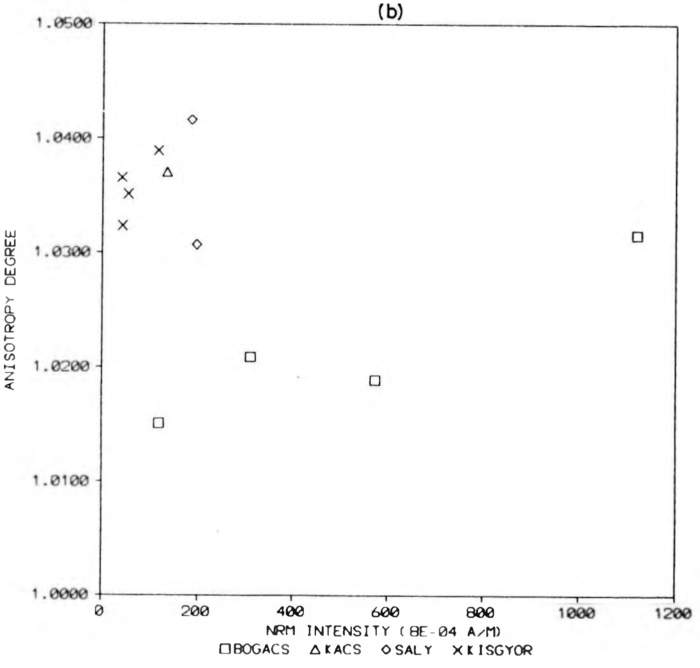
Fig. 6 is an $L-F$ (lineation vs foliation) diagram for the studied localities from which it is clear that the foliation is dominant over lineation for all localities. However, the foliation/lineation ratio (ellipsoid shape) is lower for Bogács and Sály than for the other two localities.

Fig. 3. Anisotropy distribution of sampling point means
a) versus mean susceptibility
b) versus NRM intensity

3. ábra. Mintavételi pontok átlagértékeinek anizotrópia fok eloszlása
a) az átlag szuszceptibilitás függvényében
b) a természetes remanens mágnesezettség (NRM) függvényében

Рис. 3. Распределение степени анизотропии средних значений по точкам отбора проб.
a) в зависимости от средней восприимчивости
b) в зависимости от естественной остаточной намагниченности (NRM).


(a)
1.0500
1.0400
1.0300
1.0200
1.0100
1.0000
ANISOTROPY DEGREE
0
1000
2000
3000
4000
5000
6000
MEAN SUSC.(1E-06 SI)
□BOGACS △KACS ◇SALY ×KISGYOR


(b)
1.0500
1.0400
1.0300
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1.0100
1.0000
ANISOTROPY DEGREE
0
200
400
600
800
1000
1200
NRM INTENSITY (8E-04 A/M)
□BOGACS △KACS ◇SALY ×KISGYOR

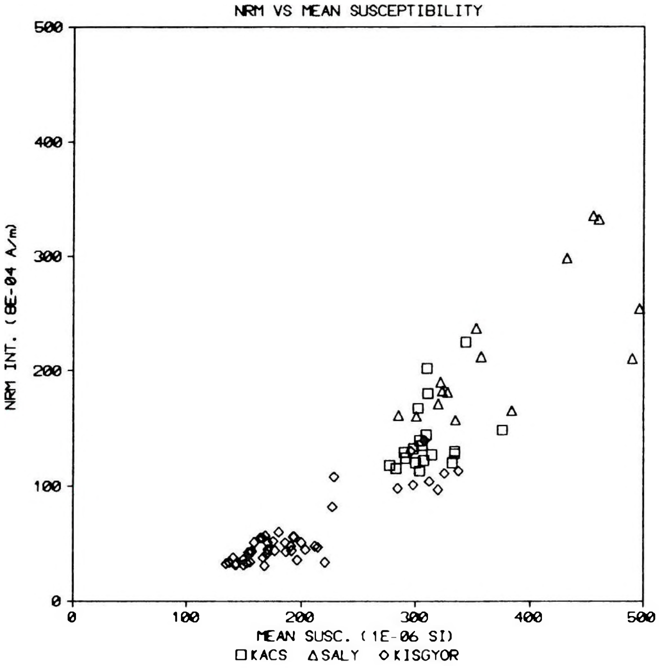

Fig. 4. NRM intensity vs mean susceptibility for the susceptibility range $< 10^{-3}$ SI units (specimen values)

4. ábra. NRM intenzitás az átlag szuszceptibilitás függvényében a $< 10^{-3}$ SI egység szuszceptibilitás tartományra (mintapéldányok értékei)

Рис. 4. Интенсивность естественной остсточной намагниченности (NRM) в зависимости от средней восприимчивости для области $< 10^{-3}$ SI (значения по образцам).

Table II summarizes the anisotropy results of the studied localities giving the anisotropy parameters and the principal directions, in polar coordinates (azimuth/inclination), of the mean anisotropy tensor for each locality with the confidence angles between the pairs of the principal directions. The lower E12 confidence angles for Bogács and Sály show that the clustering of the intermediate and maximum principal directions (Fig. 5a) is statistically significant.

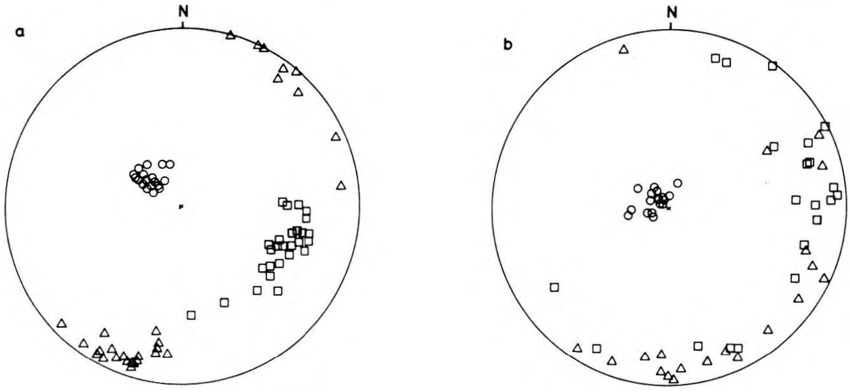

Fig. 5. Principal directions of specimens from a sampling point of Bogács (a) and Kács (b). Stereographic projection, lower hemisphere. Squares: maximum, triangles: intermediate, circles: minimum susceptibility directions

5. ábra. Bogács (a) és Kács (b) egy mintavételi pontjáról származó mintapéldányok főirányai. Sztereografikus vetület, alsó félgömb. Négyzetek: maximum, háromszögek: közepes, körök: minimum szuszceptibilitás irányok

Рис. 5. Главные направления образцов, взятых с участков Богач (a) и Кач (b). Стратиграфическая проекция, нижняя полусфера. Направления максимальной (квадраты), средней (треугольники), минимальной (круги) восприимчивости.

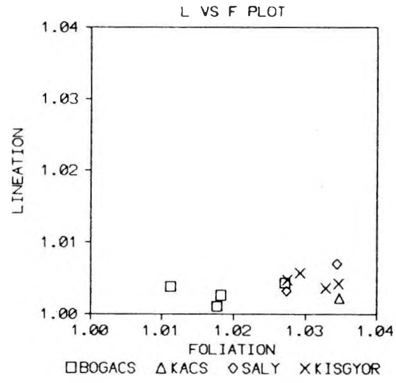

Fig. 6. Lineation vs foliation plot for sampling point means

6. ábra. Lineáció–foliáció diagram mintavételi pontok átlagértékeire

Рис. 6. Диаграмма линейность–фолиация средних значений по точкам отбора проб.

Locality	Spec./Sample	Mean susc. (10^{-6}SI)	P	L	F	E	Principal directions (D/I)			Confidence angles		
							MAX	INTER	MIN	E12	E23	E31
Bogács	63/30	3637	1.0225	1.0022	1.0202	1.0180	98.9/19.0	191.0/5.8	297.3/70.1	30.7	2.6	4.6
Kács	21/15	310	1.0371	1.0023	1.0348	1.0324	75.4/8.3	166.1/4.2	282.6/80.7	47.9	1.1	4.4
Sály	15/8	389	1.0359	1.0050	1.0308	1.0257	45.2/0.1	135.2/1.7	312.5/88.3	26.0	1.3	7.3
Kisgyőr	46/25	201	1.0336	1.0023	1.0313	1.0289	311.5/12.0	42.0/2.2	142.3/77.8	46.3	2.4	3.2

Table II. Anisotropy results for the localities studied. N/N_0: number of specimens/samples; $\bar{\kappa}$: mean susceptibility; P: anisotropy degree; L: magnetic lineation; F: magnetic foliation; E: ellipsoid shape. κ_{max}, κ_{inter}, κ_{min}: principal directions in polar coordinates (azimuth/inclination). E12, E23 and E31 are confidence angles between two principal directions (1—maximum, 2—intermediate, 3—minimum)

II. táblázat. Anizotrópia eredmények a vizsgált mintavételi helyekre. N/N_0: példányok/minták száma; $\bar{\kappa}$: átlag szuszceptibilitás; P: anizotrópia fok, L: mágneses lineáció; F: mágneses foliáció; E: ellipszoid alak. κ_{max}, κ_{inter}, κ_{min}: főirányok polárkoordinátákban (azimut/inklináció). E12, E23, és E31 két főirány közti konfidenciaszögek (1—maximum, 2—közepes, 3—minimum)

Таблица II. Результаты анизотропии по участкам отбора проб. N/N_0: количество образцов/проб; $\bar{\kappa}$: средняя восприимчивость; P: степень анизотропии; L: магнитная линейность; F: магнитная фолиация; E: эллипсоидальная форма; κ_{max}, κ_{inter}, κ_{min}: главные направления в полярных координатах (азимут/склонение). E12, E23, и E31 – доверительные углы по двум главным направлениям (1—максимум, 2—среднее значение, 3—минимум).

5. Discussion and conclusion

Palaeomagnetic and rock magnetic experiments of the samples, which will be reported elsewhere, show that the main carriers of the remanence are minerals of the magnetite type. In this case the susceptibility anisotropy is controlled by the shape anisotropy and the preferred orientation of the longer axes of the grains [Hrouda 1982].

The high mean susceptibility values as well as the existing correlation between the anisotropy degree and the mean susceptibility and between the anisotropy degree and the NRM intensity for the upper ignimbrite level, show that the susceptibility anisotropy at Bogács must be caused predominantly by ferromagnetic minerals. However, for the localities of the lower level there is no significant correlation between these parameters, but the NRM intensity increases with the mean susceptibility. This supports the hypothesis that the paramagnetic contribution plays a dominant role in the anisotropy of the lower level.

Both the magnetic and the macroscopic foliation is subhorizontal, with the minimum susceptibility axes being very close to the normal of the visible foliation plane as with sediments deposited in a low energy environment. However, the clustering of the maximum and intermediate axes in the foliation plane shows that the anisotropy of the ignimbrites was most probably affected by some additional orientation mechanism. The clustering has statistically significant confidence parameters for two localities, i.e. for Bogács from the upper ignimbrite level and for Sály from the lower level. At the other two localities of the lower level, i.e. at Kács and Kisgyőr, the paramagnetic contribution is higher than at Sály, as can be seen from the lower values of the mean susceptibility (Table II). The planar orientation of the paramagnetic minerals overprints the linear orientation of the ferromagnetic grains: the mean susceptibility ellipsoids are more flattened.

The linear-planar anisotropy pattern of both ignimbrite levels is similar to that of the sediments affected by weak horizontal stress [Graham 1966]. In such cases the compression directions can be related to the direction of the intermediate axes. *Fig. 7* shows the minimum and intermediate directions of the

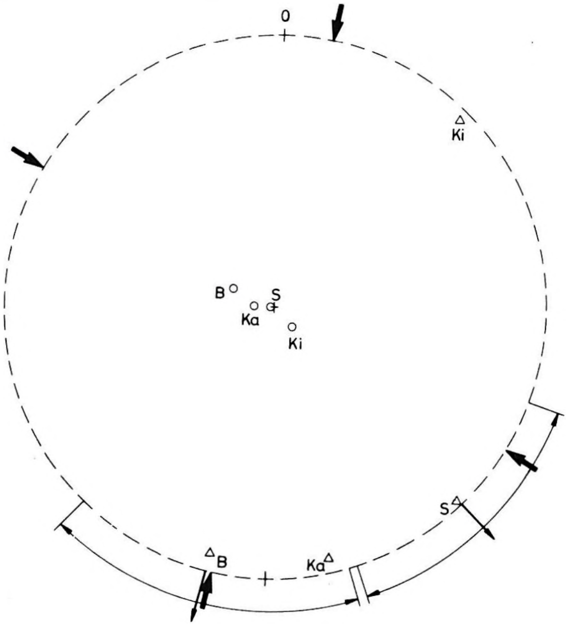

Fig. 7. Principal directions for the localities studied and their correlation with microtectonic results. Stereographic projection, lower hemisphere. Circles: minimum, triangles: intermediate directions; thin arrows: azimuthal direction of intermediate susceptibilities; arcs: confidence angles of respective intermediate directions; heavy arrows: compression directions from microtectonic measurements

7. ábra. A vizsgált mintavételi helyekre vonatkozó főirányok és korrelációjuk a mikrotektonikai eredményekkel. Sztereografikus vetület, alsó félgömb. Körök: minimum, háromszögek: közepes irányok; vékony nyilak: közepes szuszceptibilitások azimutális irányai; ívek: a megfelelő közepes irányok konfidencia szögei; vastag nyilak: mikrotektonikai mérésekből származó nyomásirányok

Рис. 7. Главные направления по участкам отбора проб и их корреляция с результатами микротектоники. Стратиграфическая проекция, нижняя полусфера. Минимальные (круги), средние (треугольники) направления; тонкие стрелки: азимутальные направления средних восприимчивостей; дуги: доверительные углы соответствующих средних направлений; утолщенные стрелки: направления сжатий, определенные микротектоническими измерениями.

mean anisotropy tensor for the studied localities. For Bogács and Sály the horizontal projections of the confidence angles of the intermediate directions (E12, arcs) are also indicated. As these do not overlap, two horizontal compression directions can be identified, i.e. 11°–191° for Bogács (upper ignimbrite level) and 135°–315° for Sály (lower ignimbrite level).

Microtectonic measurements in different Miocene rocks of the Bükkalja area [Bergerat and Csontos 1988; Tari 1988] have indicated compression directions of 10°–190° and 120°–300° at Sály and Kisgyőr, and of 10°–190° at Bogács (Fig. 7, heavy arrows), and it can be concluded that the anisotropy derived compression data are in good agreement with these.

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MÁGNESES SZUSZCEPTIBILITÁS ANIZOTRÓPIA MÉRÉSEK BÜKKALJAI MIOCÉN IGNIMBRITEKEN

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A tanulmány a Bükkalja 4 mintavételi helyéről származó miocén ignimbrit mintákon végzett szuszceptibilitás anizotrópia mérések eredményeit mutatja be. Arra a következtetésre jut, hogy a kőzetek mágneses szövetére hatással volt a miocén vagy annál fiatalabb feszültségtér. A közepes szuszceptibilitás tengelyek alapján két nyomásirány ismerhető fel: Bogácsra (felső ignimbrit szint) 11°–191°, Sályra pedig (alsó ignimbrit szint) 135°–315°. Ezek a meghatározások megegyeznek a mikrotektonikai mérésekkel felismert nyomásirányokkal.

ИЗМЕРЕНИЯ АНИЗОТРОПИИ МАГНИТНОЙ ВОСПРИИМЧИВОСТИ МИОЦЕНОВЫХ ИГНИМБРИТОВ В БЮККАЛЬЯ.

Роберт БОРДАШ

Приводятся результаты измерений анизотропии восприимчивости, проведенные на образцах миоценовых игнимбритов, отобранных на 4-х участках Бюккалья. Делается вывод, что на магнитную структуру пород оказывало влияние поле напряжения миоценового или более молодого возраста. По осям средней восприимчивости определяется два направления давления: в Богач (верхний ингимбритовый горизонт) — 11°–191°; в Шай (нижний игнимбритовый горизонт) — 13°–135°. Приведенные результаты совпадают с направлениями сжатия, установленными микротектоническими измерениями.