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ANISOTROPY OF MAGNETIC SUSCEPTIBILITY OF QUATERNARY LAVA FLOWS FROM THE EAST CARPATHIANS*

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Abstract. The presence of well preserved volcanic structures in the East Carpathians is an opportunity to test if anisotropy of magnetic susceptibility can be used to identify the flow directions. Our results show that the direction of the maximum susceptibility is in agreement with the expected direction from the eruption center.

Key words: anisotropy of magnetic susceptibility, rockmagnetism, volcanic rocks, Quaternary, East Carpathians.

1. INTRODUCTION

Petrological structures due to the movement of lava flow during its emplacement such as lineation and foliation are often difficult to measure. The anisotropy of magnetic susceptibility (AMS) might be related to the shear history of lava and can be used as a flow indicator in absence of other macroscopic markers. The interpretation of AMS in lava flows and dykes was review recently [1]. An AMS measurement of one rock specimen result in an ellipsoid of magnetic susceptibility (K) defined by the length and orientation of its three principal axes, $K_{max}>K_{int}>K_{min}$ which are the eigenvectors of the susceptibility tensor (*e.g.* [2]). The long axis of the magnetic susceptibility ellipsoid K_{max} defines the magnetic lineation, while the short axis, K_{min}, defines the normal to the plane of the magnetic foliation. According to [1] an expected model is that the magnetic lineation

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coincides to the flow directions while the K_{min} is perpendicular to the surface of the flow. This model is called normal fabric. However, for highly magnetic rocks in which AMS is principally carried by ferromagnetic minerals, various factors could complicate the interpretations of the data: (1) the presence of the single domain (SD) magnetite grains with shape anisotropy leads to an inverse susceptibility fabrics; (2) interaction between magnetic grains; (3) variation of strain in a viscous magma; (4) post-flow alteration or tectonic stresses [3].

In this contribution we report AMS from lava flows erupted in the last 2.7 Ma in the Southern Harghita Mountains (East Carpathians). The relative well preserved volcanic structures in this area create an opportunity to test if flow directions can be deduced from geographically distributed sampling sites.

2. GEOLOGICAL SETTING AND METHOD

The oriented samples were collected from 24 sites (Table 1) distributed in various volcanic rocks from the South Harghita Mountains (andesites, dacites and shoshonites). They were obtained using a portable drill and oriented using both a magnetic and solar compass. The location of each site was determined with a GPS Magellan 600. Geological information about the sampling area can be found in [4]. The age of the sampled volcanic edifices are: (1) 2.7–2.2 Ma for the Cucu volcano [4]; (2) 2.4–1.5 Ma for the Pilişca Volcano [5, 6]; (3) 2.2–1.4 Ma for the Malnaş and Bixad domes [5]; 0.56 Ma for the sampling sites in the Ciumadu volcanio [4].

In laboratory standard 25×22mm cylinder specimens were cut from each sample. Magnetic mineralogy was identified at each site using the variation of magnetic susceptibility (MS) with the applied field and temperature. Field dependence was measured with a MFK1-A kappabridge (AGICO) applying a field variation between 5A/m and 700 A/m. The thermal change of the magnetic susceptibility during a heating-cooling cycle from room temperature to 700°C in argon was investigate using an AGICO CS-3 apparatus coupled to the MFK1 kappabridge. To determine the magnetic state of the AMS carriers we used hysteresis parameters and the First Order Reversal Curves (FORC) obtained using a Micromag VSM model 3900 [7]. The AMS of each specimen was determined using the spinning method with the MFK1-A kappabridge in a magnetic field of 200 A/m and a frequency of 976 Hz. The analysis of the AMS data was performed using the Anisoft 4.2 software and temperature dependence of magnetic susceptibility was analysed using the Cureval 8.0 software. FORC diagrams were obtained using the FORCinel algorithm [8].

3. RESULTS

3.1. IDENTIFICATION OF AMS CARRIER

Low field variation of magnetic susceptibility was investigated in 10 distinct fields ranging from 5 A/m to 700 A/m. To characterize the field dependence of magnetic susceptibility we calculated the V_m index [8]:

$$V_m=100(K(700)–K(40))/K(40).$$

$K(700)$ and $K(40)$ denote the magnetic susceptibility measured at 700 A/m and 40 A/m. Representative curves are presented in Fig. 1. All samples show a moderate gradual increase of the magnetic susceptibility in higher fields. Vm values are between 0.04% and 3.0%. These values suggest the presence of magnetite or Ti-poor titanomagnetite. Most of the shoshonites samples from the Malnaş-Bixad area has a higher content of Ti.

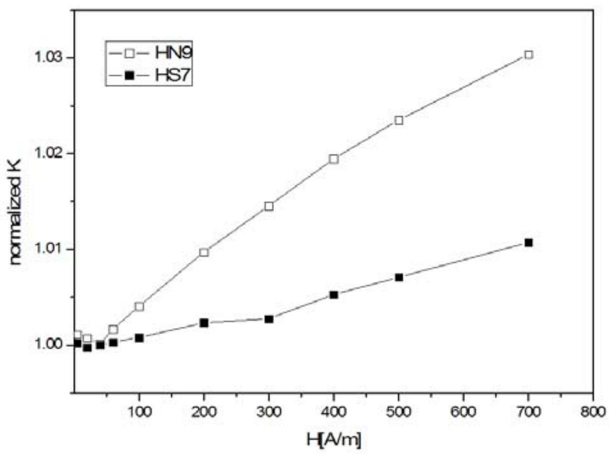


Fig. 1 – Field dependence of magnetic susceptibility for samples with variable content of Ti-magnetite.

Selected magnetic susceptibility versus temperature curves are presented in Fig. 2. Most of samples show a significant drop in two steps after 500°C which suggest the presence of both Ti-poor titanomagnetite and magnetite. In a few samples the ferromagnetic signal survives up to 630°C.

Hysteresis parameters (coercivity, coercivity of remanence, saturation field) are compatible with the presence of a dominant low coercivity magnetic phase. Typical FORC diagrams are presented in Fig. 3. The data point out a complex magnetic domain structure, a mixture of fine grains (pseudo-single domain, PSD, and single domain, SD) and multidomain grains (MD). The presence of PSD and MD grains in all samples suggest that the magnetic fabric can be considered as normal (K_{max} is parallel to silicate fabric flow) and is not significant weakened by SD grains [9]. Most of samples show different vertical spreading which can be interpreted as indication of magnetostatic interactions [7].

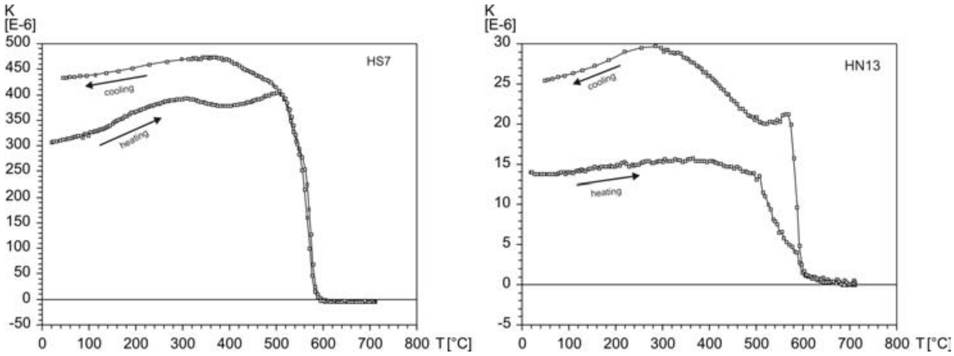


Fig. 2 – Examples of temperature dependence of magnetic susceptibility.

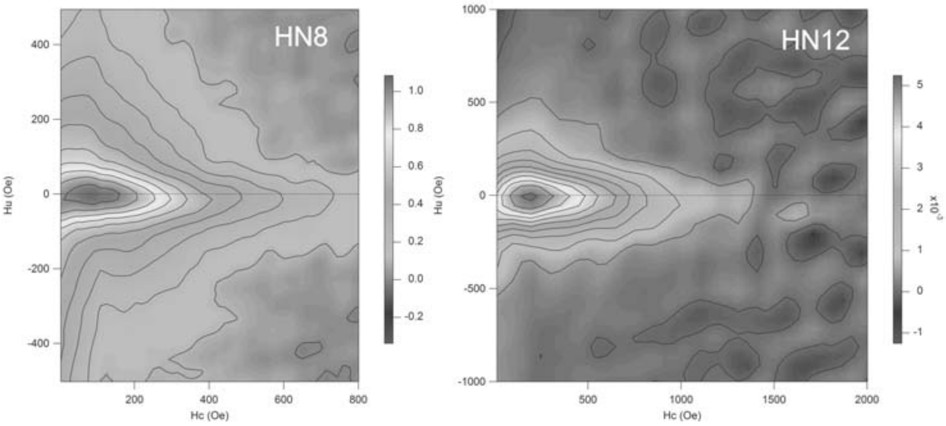


Fig. 3 – Representative FORC diagrams.

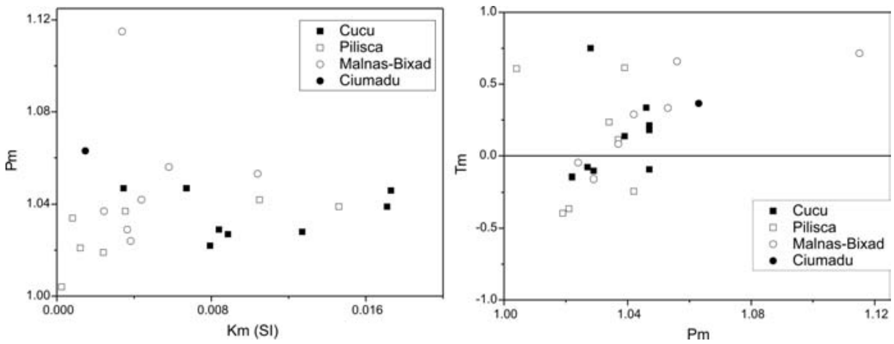
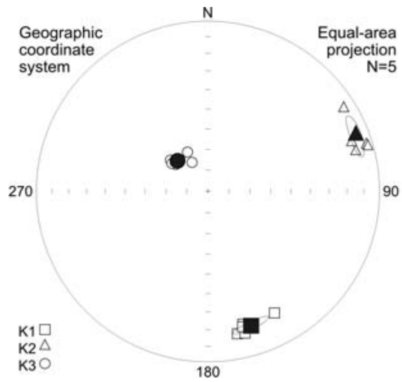


Fig. 4 – Anisotropy degree, P_m, and shape parameter, T_m, *versus* magnetic susceptibility K_m.



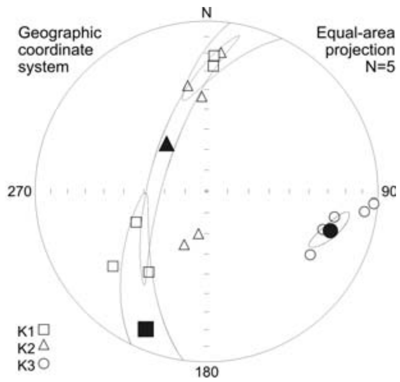


Fig. 5 – Typical examples for magnetic liniation (left) and magnetic foliation (right). Open symbols represent specimen eigenvectors; full symbols are mean eigenvectors: K_1=K_{max}, K_2=K_{int}, K_3=K_{min}.

Table 1

AMS and rockmagnetic parameters

Site	N	K_m (SI)	P_m	T_m	K_{max} (°)	K_{min} (°)	V_m (%)
Cucu volcanic structure (andesite)							
HS1: 46.207633°N, 25.8102°E, 1007m	5	8.39E-03	1.029	-0.10	**124/11**	250/71	0.28
HS2: 46.206383°N, 25.807517°E, 958m	5	1.73E-02	1.046	0.33	**89/7**	321/78	1.20
HS3: 46.206517°N, 25.80745°E, 973m	5	3.45E-03	1.047	0.18	**359/49**	189/39	0.51
HS4: 46.2056°N, 25.808867°E, 938m	5	6.70E-03	1.047	0.21	**107/6**	210/62	0.23
HS5: 46.204783°N, 25.816417°E, 895m	5	1.27E-02	1.028	0.75	203/12	**107/25**	0.50
HS6: 46.2046°N, 25.82035°E, 927m	5	6.72E-03	1.047	-0.09	**93/4**	196/69	0.73
HS7: 46.216267°N, 25.714883°E, 1078	5	1.71E-02	1.039	0.13	**207/0**	115/74	1.10
HS9: 46.2017°N, 25.746983°E, 1093m	5	8.86E-03	1.027	-0.07	**225/21**	59/68	0.61
HS10: 46.201067°N, 25.74205°E, 1082 m	5	7.93E-03	1.022	-0.14	**34/8**	278/71	0.70
Pilişca volcanic structure (andesite)							
HN1: 46.15431°N, 25.84633°E, 870m	5	1.46E-02	1.039	0.61	**273/10**	181/10	2.30
HN2: 46.13747°N, 25.85379°E, 622m	5	2.41E-03	1.019	-0.39	**162/18**	315/69	0.05
HN11: 46.107283°N, 25.846283°E, 604m	5	1.05E-02	1.042	-0.24	**354/19**	84/0	0.54
HN12: 46.111383°N, 25.84685°E, 633m	5	3.54E-03	1.037	0.11	**268/6**	2/35	0.03
HN13: 46.126217°N, 25.849683°E, 646m	5	1.21E-03	1.021	-0.36	**149/20**	281/60	0.67
HN14: 46.1232°N, 25.85405°E, 612m	5	8.07E-04	1.034	0.23	**74/53**	177/9	0.30
HS11: 46.133800°E, 25.818133°E, 929m	5	2.45E-04	1.004	0.60	327/54	**76/34**	0.04
Malnas dome (shoshonite)							
HN4: 46.052117°N, 25.8194°E, 632m	5	3.64E-03	1.029	-0.15	**65/2**	334/27	2.00
HN5: 46.051°N, 25.820317°E, 612	5	5.80E-03	1.056	0.65	246/7	**7/76**	2.90
HN6: 46.03955°N, 25.822433°E, 622m	5	3.82E-03	1.024	-0.04	**288/25**	78/61	1.20
HN7: 46.048933°N, 25.813267°E, 643	5	2.44E-03	1.037	0.08	**78/9**	169/7	1.10
Bixad dome (shoshonite)							
HN8: 46.078133°N, 25.833067°E, 601m	5	1.04E-02	1.053	0.33	**357/9**	261/34	0.90
HN9: 46.08255°N, 25.834183°E, 584m	5	3.38E-03	1.115	0.71	363/19	**144/4**	3.00
HN10: 46.090933°N, 25.837117°E, 626m	5	4.38E-03	1.042	0.28	**206/18**	348/66	0.24
Ciumadu volcanic structure (dacite)							
HN15: 46.120767°N, 25.90308°E, 1105m	5	1.47E-03	1.063	0.36	**81/14**	175/14	0.63

3.2. AMS PARAMETERS AND EIGENVECTOR DIRECTIONS

To characterize the AMS we used the following parameters, *e.g.* [10]:
(1) the mean susceptibility: $K_m = (K_{max}+K_{int}+K_{min})/3$;
(2) the degree of anisotropy: $P = K_{max}/K_{min}$;
(3) the shape parameters:

$$T =(2\ln(K_{int}) - \ln(K_{max}) - \ln(K_{min})/(\ln(K_{max})-\ln(K_{min})).$$

The parameter T characterizes the symmetry of the AMS ellipsoid. If $0 < T < +1$ the AMS ellipsoid is oblate (the magnetic fabric is planar); $T = +1$ means that the AMS ellipsoid is rotationally symmetric (uniaxial oblate). If $-1 < T < 0$ the AMS ellipsoid is prolate (the magnetic fabric is linear); $T = -1$ means that the AMS ellipsoid is uniaxial prolate.

The site-mean values of these parameters are presented in Table 1 and are plotted in Fig. 4. With two exceptions the mean degree of anisotropy varies between 1.02 and 1.06 for all sampled volcanic structures. These values could be explained by the low aspect ratio of titanomagnetites and the position of our samples in central part of the lava flows. Close to the lava edges the degree of anisotropy usually displays higher values with respect to the central part [9]. Most of the shape parameter values are between –0.5 and 0.5. Larger values are only in the foliation field where four sites have means around 0.7.

The site-mean values of azimuth and inclinations of the K_{max} and K_{min} eigenvectors are presented in Table 1. Typical distributions of the eigenvector directions at the sampling site level are presented in Fig. 5. Most of the sites (20) have a significant grouping of the K_{max} axes (well define magnetic lineation). The other sites with a significant oblate ellipsoid have a good groping of the K_{min} axes (well define magnetic foliation).

4. DISCUSSIONS

It has been emphasized that the AMS fabric is carried by a Fe–Ti oxide phase, likely Ti-poor titanomagnetite and magnetite. In these phases, shape anisotropy of the grains (*i.e.*, aspect ration and relation to the silicate fabric) controls the AMS signal over the crystalline anisotropy of the grains [1, 9]. They display a large size and shape range, so the population is heterogeneous. They are most PSD particles, so that there is a normal magnetic fabric signature.

To interpret the AMS data in terms of flow directions we have used only the directions of the magnetic lineation disregarding the sites dominated by magnetic foliation (bold K_{max} directions in Table 1). Most K_{max} plunge directions have inclinations lower than 25°. In two lava flows the inclination of K_{max} is greater than 45° (sites HS3 and HN14, Table 1). It has been assumed that lava flows are mainly submitted to simple shear, but K_{max} dips greater than 45° suggest pure shear [9]. Our data suggest that majority of our sites are affected by simple shear and pure shear

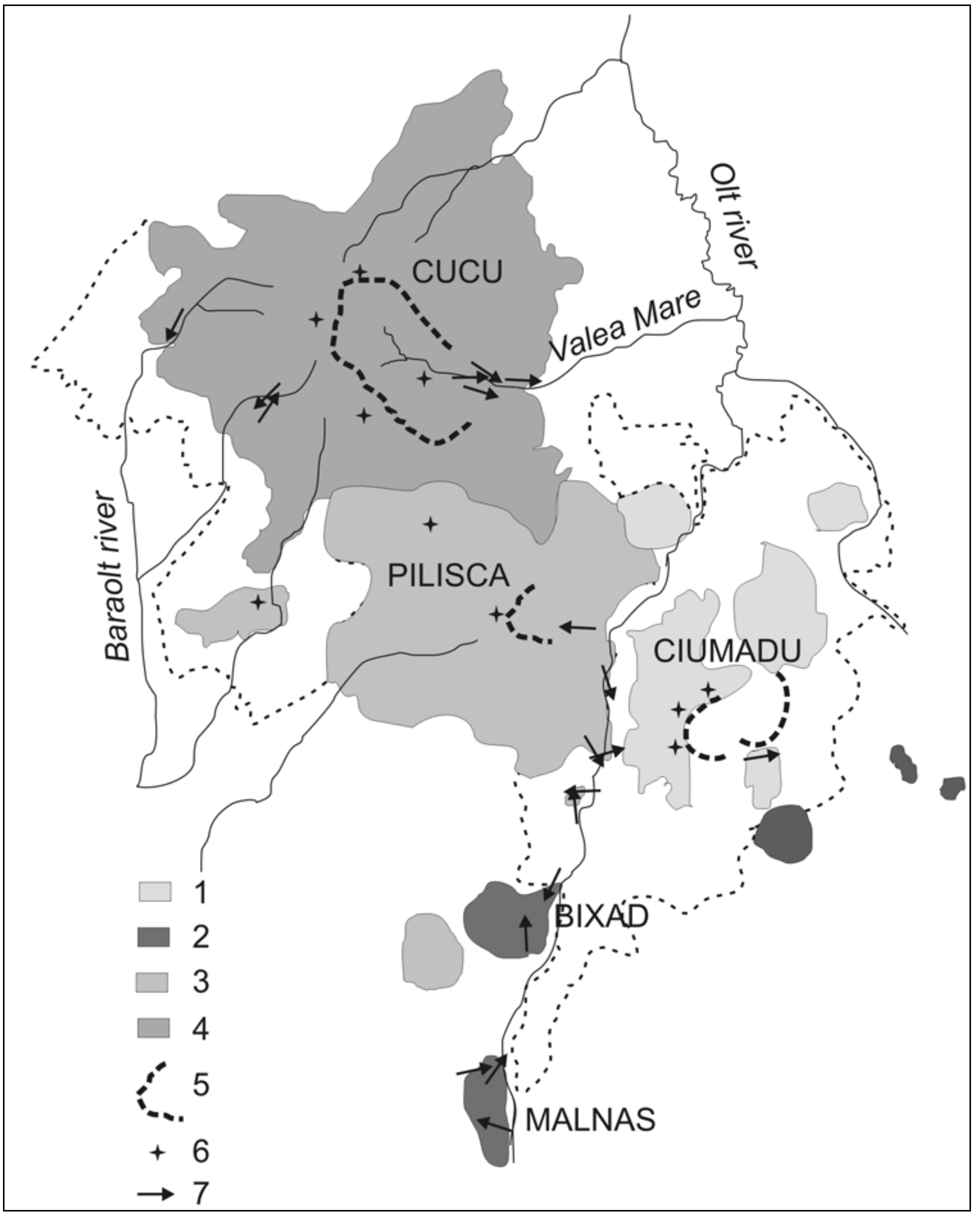


Fig. 6 – Distribution of magnetic lineation (K_{max} directions). Symbols: (1) Ciumadu volcano; (2) Malnaş-Bixad domes; (3) Pilişca volcano; (4) Cucu volcano; (5) crater; (6) eruption center; (7) K_{max} direction and plunge. Simplified geological map after [12].

signature is dominant only at site HN14 which is probably situated near the front of the lava. Sites HS3 which also have a large inclination is located in the Cucu volcanic edifice along the Valea Mare River. Both the direction and the plunge of K_{max} at this site is different from neighboring sites (HS1, HS2, HS4, HS6). This site was sampled in an andesite with significant hydrothermal alteration. We suspect that the magnetic fabric at this site is altered by the hydrothermal transformations and cannot be used to infer the flow direction.

The expected regional lava flow directions can be inferred taking into account the position of the eruption centers and the geometry of the volcanic edifices. The arrows in Fig. 6 mark the direction and plunge of magnetic lineation (K_{max}). As it can be noticed from Fig. 6 most of K_{max} directions for all three volcanic structures (Cucu, Pilişca and Ciumadu) are compatible with expected local lave flow directions. In three cases (HS10 from the western part of the Cucu volcanic edifice, HN1 and HN11 from the Pilişca volcanic edifice) the K_{max} plunge direction switch from the expected plunge direction to the opposite plunge. Such changes can also be found in other flows [9 and references there in]. Several explanations can be invoked [9]: (1) a succession of several lava units each undergoing a basal and top shear; (2) an inhomogeneous flow with rheological steps; (3) the lava flow had occasional upstream flow events; (4) the flow is wavy and the vertical profile is recording the progressing lateral set of undulations. To distinguish the correct mechanism a more dens sampling scheme is necessary at such sites corroborated with petrographic and mineralogic data.

The K_{max} directions from the shoshonitic domes from Malnaş-Bixad area are more dispersed. Such dispersion in different parts of large domes is not unusual *e.g.* [11]. The magnetic fabric is controlled by the position of the feeder system of the dome and position of the sampling sites with respect to the dome margins.

5. CONCLUSIONS

In this investigation we have studied for the first time the AMS for lava flows produced by the last volcanic eruptions from the East Carpathians. Detailed rockmagnetic experiments have allowed us to identify that the main AMS carriers are mainly PSD Ti-poor titanomagnetites and magnetite. All investigate sites have statistical significant magnetic lineation or foliation. There is a general good agreement between the expected lava flow directions and the K_{max} directions for all the studied volcanic edifices. The AMS has dominant simple shear component in most of sites. Our study shows that in these types of volcanic rocks which can be found in the Southern Harghita Mountains geographical distributed sampling sites can provide useful information from AMS about lava flow direction.

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