An origin and the source of extreme high intensity of natural remanent magnetization (NRM) of oxidized titano-magnetite bearing basaltic and andesitic rocks

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A b s t r a c t: The Late Miocene to Quaternary basalts from central and southern Slovakia, the Eocene to Miocene basalts from České Středohoří Mts., the Cretaceous and the Neogene basalts from Syrian Arab Republic, the Cretaceous, Jurassic nepheline basanites and the Quaternary basalts from Nigeria, the basalts from recent Etna and Kilauea volcanoes were studied. The high intensities of natural remanent magnetization (NRM) of volcanic rocks are mostly linked with the presence of the time-variable secondary inversion low-temperature magnetic phase in the rocks. The high NRM is of the chemico-viscous or the thermoviscous origin. An origin of this phase in volcanics is due to low-temperature oxidation (in the range 25 to above around of 350° C) of original Ti-rich titanomagnetites (Ti-Mt-es), which were in the superparamagnetic (SP) state. The successive creation of more oxidized Ti-Mt phase with the nucleation of the thermodynamically stable domains takes place. A magnetostatic interactions among a portion of the original SP state magnetic particles of Ti-Mt-es and those gradually originated oxidized (Ti-Mt-es - titanomaghemites - Ti-Mgh-es) is actual in this system. Due to these interactions a highly viscous and very easily excitable phase has arisen in this system. This phase is able to acquire a thermoviscous or chemico-viscous remanent magnetization having been exposed to the external magnetic field. This is quite new phenomenon. The importance of this knowledge has resulted in its application to the interpretation of geomagnetic anomalies. The high intensities of NRM contribute to the total magnetization of volcanic body and so, they can generate intensive geomagnetic anomalies with respect to the volume of the volcanic body. These anomalies do reflect the presence of only high intensities of NRM, but not the sources of the high Fe concentration of deposits.

Key words: basalts, Fe-Ti inversion low-temperature phase the source of intensive NRM (thermo-viscous or chemico-viscous origin) of rocks

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1. Introduction

In paleomagnetism of volcanics the subject of interest has been usually the stability and directions of the remanent magnetization (RM). The detailed study of magnetic susceptibility (κ) and the origin of natural remanent magnetization (NRM) have been mostly omitted. The importance of the study of κ has been proven by *Orlický (2004)* who has revealed that the behaviour of Ti-Mt-es with high content of ulvöspinel has corresponded to superparamagnetic (SP) state. This phenomenon is very important with respect to the explanation of the origin and mechanism of magnetization of Ti-Mt bearing volcanic rocks. Taking into account this idea, we have known from the experience that there are extreme large differences in the intensity of NRM in individual types of rocks. Typical representatives of rocks with high intensities of NRM are dominantly basalts, basaltic andesites, and rarely also some pyroxene andesites with a presence of Ti-Mt associations (*Orlický, 2001-Part I; 2002-Parts III, IV, V; 2004-Part XIII*). We can find the basaltic rocks with very high intensities of NRM also in localities abroad (*Orlický, 2003-Part XI*), hundreds of them worldwide. Commonly the induced magnetization of a geological structure is taken into account to interpret the field geomagnetic anomalies. The NRM plays very important role in the cases of extremely high intensities of NRM, because it contributes to the total magnetization of volcanic bodies and in such a way can generate intense geomagnetic anomalies in the field. Despite a large amount of publications concerning the interpretation of the geomagnetic anomalies, and the study of magnetic properties of volcanic rocks, no exhaustive resolution of magnetism carriers in such volcanics has been so far revealed. In this article I present the results of the study of the NRM of the Neogene basalts and basaltic andesites from Slovak volcanic fields, the Eocene to Miocene basalts from Bohemian Massif, different age basalts from Nigeria and Syrian Arab Republic, recent basalts from Kilauea (Hawai) and Etna Volcanoes.

Main goal of this article is to enrich the so far obtained results, make a comparison of intensity of NRM of different magnetic Fe-Ti phases bearing volcanics, and to find an appropriate explanation of their anomalous intensity of NRM.

2. The methodical setting

I have analysed the results of all my own works which focused on the magnetic, mineralogical and paleomagnetic problems. Without surprise, the highest values of NRM have been reached by the basaltic rocks. Generally there is an evident decrease of intensity of the NRM with increasing content of SiO_2 in the volcanic rocks - with the tendency: basalts and basaltic andesites (45–52% SiO_2), the intermediary volcanics - different types of andesites (52–65% SiO_2) and acidic rocks - rhyodacites and rhyolites (65–72% SiO_2). In some volcanics we can meet the cases of rocks with extreme high intensities of NRM (in this work I have conventionally considered the rocks with intensities more than 10000 nT as those with high intensities). As has been shown above, the carriers of magnetic properties in volcanics are the titanomagnetites (Ti-Mt-es). They can be very frequently the source of very intense NRM, but only in peculiar specific conditions - they are in an anomalous magnetic state. In the Fig. 1 the olivine basalt of the sample BP1-1 has $\kappa = 20957 \times 10^{-6}$ SI Units, but the intensity of NRM has reached extreme high value of 166873 nT. The sample possess the low-temperature oxidized inversion magnetic phase (Fig. 1, dashed line). According to *Özdemir (1987)* the product of oxidation is a highly non-stoichiometric cation-deficient spinel (titano-maghemite; Ti-Mgh), which is a single-phase metastable mineral (the phases with inversion temperatures of the samples are detectable as a rise of κ during heating of the samples in the interval 25–450° C). It has been shown that the starting Ti-Mgh-es were in stable single-domain (SD) state. After inversion the intergrowth texture of the inversion products reduced the effective dimensions of the spinel phase to nearly SP size. Magnetostatic interaction among the spinel subgrains may negatively influence the behaviour of magnetic characteristics. The magnetic viscosity results show that the inverted Ti-Mgh-es become more viscous as a result of the reduction of effective grain size, and perhaps also because of shift in the SP/SD boundary with change in the composition.

When one would like to detect e.g. the low-temperature oxidized phase in the rocks, a thermal treatment of samples could be taken in the laboratory. The thermal energy gradually reduces the interactive magnetostatic effect among of different magnetic state particles, and the magnetic susceptibility increases in its value during heating of the sample. Of course the decisive role is played by the SP state of the originated particles in the system. Commonly continuous measurements of the change of κ of magnetic fraction with the temperature are used to detect any changes of Ti-Mt-es, including the detection of low-temperature oxidized magnetic phase in the sample. Preferably a rate of 5–3° C/minute is applied to heating and cooling of magnetic Fe-Ti fraction of respective rocks during continuous measurements (see e.g. Fig. 1 Nigeria basalt BP1-1). This method has been applied to the so far investigated volcanics (particular results were published in many previous works, including those presented by *Orlický (2004a)*. Despite relatively low rate of heating, the inversion phase has been mostly non-expressively outlined on the graphs and it appeared only in the samples with intensively altered Ti-Mt-es (Fig. 2). Also more effective procedures were applied - the continual measurements of κ of the sample at constant preselected temperature in the interval 350–450° C (duration of heating 30–60 minutes), or stepwise heating of compact sample at individual temperatures (in the interval 25–600° C, duration of heating at each temperature of about 30 minutes). After successive cooling of the sample to laboratory temperature the measurements of κ of the sample were carried out. The results of the measurements are shown in the Figs 1, 2, and Tabs 1–6 (see the coefficients κ_{450}/κ_{25}).

Correlating the results of magnetic Fe-Ti phases with the NRM of rocks, the most intensive NRM is carried by the rocks with the developed low temperature oxidation magnetic phases, but especially when this phase has been developed due to long surviving the respective part of volcanic body in a higher temperature (around of 350° C), or when this part of body was heated by other contacted hot volcanic body. It means that the magnetic state of the inversion temperature secondary magnetic phase has been intensively influenced by temperature, the redox condition within concrete part of the volcanic body, but also a time duration is decisive. An acquiring of the thermoviscous or the chemico-viscous NRM has been linked with these types of magnetic phases.

There have been revealed also the rocks with a very pronounced inversion temperature secondary magnetic phases. They have not only one, but two inversion temperatures (Fig. 2, e. g. Šomoška-3a). These types of rocks carry low values of NRM and κ, and they are of the reversed polarity of NRM. These types of rocks have only very low intensity NRM.

I have grouped the results of several volcanics in the Tabs 1–6, applying this methodological knowledge.

In plutonic - intrusive rocks the main carriers of magnetism are mostly magnetites (Mt-es), or their altered derivates. Usually they are not the source of an intensive NRM. From the thermomagnetic curve, e.g. of the intrusive basaltic rock from Nigeria (Fig. 1, olivine basalt JP6-4; $\kappa = 92902 \times 10^{-6}$ SI Units, NRM = 4721 nT) it is evident that the Curie temperature $T_C = 580°$ C and the Verwey temperature $T_V = -145°$ C correspond to magnetite, which is probably in the multi-domain state. There is detected a transformation of Mt into maghemite, and successively into the hematite on the heating curve in Fig. 1 (full line). This effect is more expressively detected by decreasing κ on the dashed curve in Fig. 1 (from cca 300° C). This curve corresponds to the measurements of the change of κ after heating the compact sample to concrete temperature and successive cooling to laboratory temperature (dashed line, symbols x; the measurements were done at laboratory temperature). Despite very high magnetic susceptibility of samples, the intensity of the NRM and Q is very low. Such behaviour is shown also by the intrusive diorites and monzo diorites of the boreholes KON-1 (Javorie volcanic field). The 72 samples have reached in average the value of $\kappa = 39000 \times 10^{-6}$ SI Units, NRM = 3500 nT (*Orlický, 1986*). The magnetism carriers are also the magnetites, probably of the multi-domain state. According to *Lindsley (1991)* in plutonic, also in intrusive, rocks the composition of Fe-Ti oxides differs from that of volcanic rocks because the oxides tend to re-equilibrate readily during cooling. This leads to a complex series of re-equilibration reactions and oxyexsolution. As a result of these processes the dominant magnetic host spinel in many plutonic and intrusive rocks is nearly pure magnetite.

The basic magnetic data of volcanics

The basic magnetic characteristics (κ, NRM and other data - if any) of rocks were chosen from previously published works (*Orlický, 2002, 2002a, 2002b, 2003, 2004 and Orlický et al., 2003*). Other, so far unpublished results, and those presented in the Tabs 1–5 were computed from the data of primary laboratory measurements.

In the tables below data on rocks were selected and grouped only as

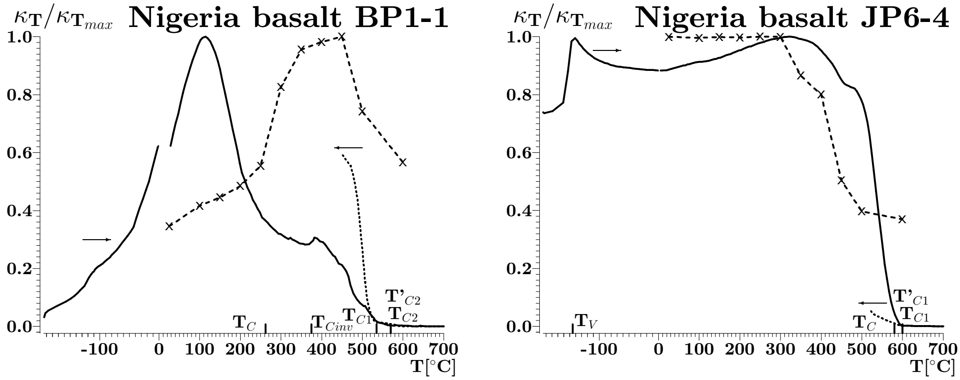

Fig. 1. Thermomagnetic curves of samples of basalts from Nigeria: The samples were collected from the Biu Plato (Bp1-1; $\varphi_L = 10.61°$; $\lambda_L = 12.14°$: -basaltic lava flow) and the Jos Plato (JP6-4; $\varphi_L = 9.559°$ and $\lambda_L = 8.641°$: - basalts which come from the two cca 40 cm thick dikes of the W - E direction, which were intruded (approximately in a vertical position) into the large granitic massif. The continual measurements of the change of κ of sample during heating (full line) and successive cooling (dotted line). T_C, T_{C1}, T'_C, T'_{C1} – Curie temperatures during heating (full line) and cooling (T') of the sample; T_V – Verwey transition temperature; T_{Cinv} and T_{C1inv} - inversion temperatures; κ_T, κ_{Tmax} – magnetic susceptibility at temperature $T(\kappa_T)$; maximum susceptibility (κ_{Tmax}). The discrete measurements of the change of κ after heating of the sample to concrete temperature and successive cooling to laboratory temperature (dashed line; symbols x at the curves represent a value of κ after heating of the sample to conctere temperature and its cooling to laboratory temperature).

examples, to consider that the anomalous intensities of NRM of rocks from different localities and areas all over the globe have similar properties and magnetic behaviour. The positions of individual localities in question on the Earth's surface are determined by their geographical coordinates φ_L and λ_L.

The inversion temperature secondary magnetic phases have developed in basalts of all 14 localities (see Tab. 1). The basalts from 10 localities have reached NRM in the interval 11564 to 48643 nT and κ in the range 12500 to 41889×10^{-6} SI Units. Olivine basanites of Putikov vršok locality, which is the youngest volcano in the West Carpatian Mts., has NRM = 5777 nT, $\kappa = 42224 \times 10^{-6}$ SI Units. I can point out an exceptional behaviour of magnetic characteristics of samples of basalts coming from different places of the neck body of Šomoška locality. From Tab. 1 it is evident that sample 43-2A-1

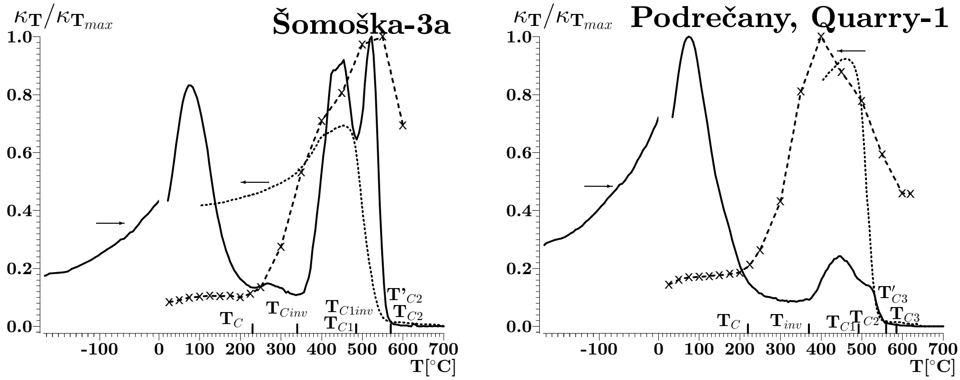

Fig. 2. Thermomagnetic curves of samples of basalts from souther part of Slovakia: The samples were collected from the lava flow below Šomoška locality (Šomoška-3a: φ_L = 48.170°; λ_L = 19.842°: -basaltic lava flow) and Podrečany (Podrečany, Quarry-1; φ_L = 48.390° and λ_L = 19.625°: - basaltic lava flow in the abandoned quarry. Other descriptions and explanations have been presented in Fig. 1.

has very high value of magnetic susceptibility ($\kappa = 75197 \times 10^{-6}$ SI Units, NRM = 9565 nT), Q = 2.5 and that the inversion temperature secondary magnetic phase has not properly developed in this sample ($\kappa_{450}/\kappa_{25} = 1.09$). On the other side the sample 43-1 comes from the other place of the same neck body. It has a substantially lower volume κ (only about 50 % of the sample 43-2A-1) but its intensity of NRM is extremely high (NRM = 48693 nT), Q = 26.6 while it has very well developed the inversion temperature secondary magnetic phase ($\kappa_{450}/\kappa_{25} = 2.0$).

In basaltic andesites of all in Tab. 2 presented samples the inversion temperature magnetic phases have developed. Intensities of NRM of samples are relatively high, despite not too high values of volume magnetic susceptibilities. Previously the high intensities of NRM of such rocks were considered to be acquired as a consequence of intense lightning during thunderstorms.

To consider a homogeneity of magnetic characteristics within the large volcanic body, I investigated in a more detailed mode the hornblende pyroxene andesites of a quarry (designated as TR-11; φ_L = 48.552°, λ_L = 19.336°), W of Detva Town in the Javorie and Poľana volcanic area (*Orlický, 2002*). The rocks collected from 13 individual outcrops of the quarry have shown in average high intensities of NRM = 25732 nT (in the range of 13717–34443 nT), $\kappa = 34961 \times 10^{-6}$ SI Units (in the range $29167 - 41713 \times 10^{-6}$

Tab. 1. Magnetic characteristics and magnetic Fe-Ti phases of basaltic rocks from central and southern Slovakia

Name of locality	Volc. form	Age (Ma)	φ_L	λ_L	$\kappa \times 10^6$ SI Un.	NRM nT	Q	Mag.phases T_C, T_{C1}, T_{C2}(°C)	κ_{450}/κ_{25}
Putikov vršok	l.f.	0.22	48.41	18.65	42224	5777	2.7	220,560	1.19
Šibeničný vrch	e.b.	8.7	48.59	18.88	20070	38668	38.5	410,570	2.75
Kalvária	neck	7.29	48.46	18.92	41889	14781	7.1	520,580	1.5
Devíčie	l.f.	8.0	48.32	19.03	25307	11564	9.1	160,420,570	1.23
Podrečany	l.f.	6.44	48.39	19.63	13320	3046	4.6	220,560	6.9
Maškovál-1	l.f.	7.17	48.32	19.58	33421	3050	1.8	220,380,560	2.2
Šomoška 43-2A-1	neck	4.06	48.17	19.82	75197	9565	2.5	120,230,560	1.1
Šomoška 43-1	neck	4.06	48.17	19.82	36553	48643	26.6	120,230,560	2.0
Šomoška 45	l.f.	4.06	48.17	19.82	8282	1157	2.8	230,360,560	9.6
Trebeľovce	l.f.	–	48.29	19.72	12500	14690	23.5	130,570,605	3.8
Črep	l.f.	4.10	48.26	19.99	34917	19262	11.1	220,550	1.3
Ostrá skala	neck	2.6	48.23	19.95	25118	25863	21	150,570,605	1.4
Zaboda	l.f.	2.03	48.23	19.95	26601	19172	14.4	150,560,605	1.2
Dunivá hora	dyke	1.3	48.18	19.87	23800	24780	10	280,350,560	2.01

l.f–lava flow; e.b.–extrusive body; Ma–million year; φ_L, λ_L– geographical coordinates; κ– bulk magnetic susceptibility; NRM–natural remanent magnetization in nano Tesla (nT); Q–Koenigsberger ratio; Mag. phases–magnetic phases of sample with Curie temperatures T_{C1},T_{C2}, T_{C3}; κ_{450}/κ_{25}–relation of κ of compact sample after its heating to 450° C (κ_{450}) and successive cooling to laboratory temperature with respect to κ of sample in its natural state at laboratory temperature (κ_{25}). The symbols are valid also for Tabs below.

SI Units), an average value of Q= 14.7. The polarity of inclination of NRM of samples from nine places was positive but the declination of NRM nearly of all samples was dominantly negative. The samples with high intensities of NRM have contained dominantly the two magnetic phases with the Curie temperatures 520, 560° C and the relation of $\kappa_{450}/\kappa_{25} \approx 1.2$ (the behaviour like the low temperature oxidation titanomagnetite phase). But the samples from other 13 places of the same quarry have shown in average only low intensities of NRM and that of κ values; NRM = 5390 nT (in the range 3096–9769 nT) and $\kappa = 12128 \times 10^{-6}$ SI Units (in the range $1510–34537 \times 10^{-6}$ SI Units). An average value of Q = 8.9. Both the inclination and declination of NRM of these rocks were dominantly the reversed ones. The samples from these places of the quarry contained only highly

Tab. 2. Magnetic characteristics and magnetic Fe-Ti phases of about 15.5 Ma old basaltic andesites from Javorie and Poľana volcanic fields (mostly from Blýskavica, Javorie and Rohy formations)

No. of sample	Volc. form	φ_L	λ_L	$\kappa \times 10^6$ SI Un.	NRM nT	Q	Mag.phases T_C, T_{C1}, T_{C2}(°C)	κ_{450}/κ_{25}
306-c2	e.b.	48.67	19.47	20175	30094	29.8	520,570	1.2
362-1	e.b.	48.61	19.43	29798	15188	810.2	520,570	1.3
397-b1	l.f.	48.59	19.38	23400	19595	16.7	520,580	1.12
404-c2	l.f.	48.58	19.40	23898	14531	12.2	520,570	1.37
421-a2	l.f.	48.55	19.35	26850	21729	16.2	520,560	1.25
445-b1	l.f.	48.52	19.28	24825	47978	38.6	510,570	1.62
448-c3	l.f.	48.52	19.29	21905	79303	72.4	510,570	1.52
477-b1	l.f.	48.53	19.39	25775	14445	11.2	510,580	1.23
485-c2	l.f.	48.51	19.37	34375	14254	8.3	520,570	1.45

Explanations as below Tab. 1

oxidized Fe-Ti magnetic phases with the Curie temperatures near or over 580° C. There is evidence in Fig. 7 (Scheme of distribution of individual sampled places.., and Tab. 3, in *Orlický (2002)*), that there are magnetic Fe-Ti phases of different composition and magnetic state in the whole volcanic body of the respective quarry, and that they are inhomogeneously distributed within the volcanic body. We can find a similar inhomogeneity of magnetic characteristics also in other larger outcrops of volcanics (e.g. in the quarry of Mašková the samples collected from different places differ in κ, NRM, magnetic phases; *Orlický (2004)*, such behaviour regards also other outcrops among of basalts, basaltic andesites and some types of andesites).

Olivine basalt of Klimberg locality did not contain the inversion temperature secondary magnetic phase and so it has shown relatively low intensity of NRM, despite its volume κ being relatively high. Olivine basalts from the two other localities and that of picritic basalt from locality Řetouň have shown the mentioned secondary magnetic phase and they have also relatively high values of NRM (Tab. 3).

We see from Tab. 4, that basalts from most of localities have shown very high values of κ but at the same time they have mostly extreme high intensities of NRM. In all presented basalts the inversion temperature secondary

Tab. 3. Magnetic characteristics and magnetic Fe-Ti phases of the Eocene to Miocene age basalts from České Středohoří Mts.– North Bohemia

Name of locality	Type of rock	φ_L	λ_L	Number of samples	$\kappa \times 10^6$ SI Un.	NRM nT	Q	Mag.phases T_C, T_{C1}, T_{C2}(°C)	κ_{450}/κ_{25}
Obrnice	Ol.basalt	50.43	13.76	2	46250	10910	4.7	70,230,590	1.3
Klimberg	Ol.basalt	50.59	15.32	2	38850	4740	2.4	220,570	1.0
Smřečiny	Ol.basalt	50.63	15.28	2	29800	45652	30.6	250,550	1.9
Řetouň	Picr.basalt	50.60	14.14	2	83790	15502	3.7	90,520	1.12

Ol.–olivine; Picr.–picritic, other explanations are below Tab. 1

Tab. 4. Magnetic characteristics and magnetic Fe-Ti phases of individual sample of the Cretaceous basalts from Syrian Arab Republic

Name of locality	Type of rock	φ_L	λ_L	$\kappa \times 10^6$ SI Un.	NRM nT	Q	Mag.phases T_C, T_{C1}, T_{C2}(°C)	κ_{450}/κ_{25}
S3-7-1	Ol.basalt	35.38	35.38	65565	103100	32.2	260,500,570	
S-8-2-1	Ol.basalt	35.00	36.26	59180	31650	10.7	305,560	1.3
S-9-9-1	Ol.basalt	34.77	36.26	9038	24990	55.3	160,560,640	6.2
S-12-3-1	Ol.basalt	34.77	36.30	28975	17550	12.1	570,605	
S-6-3	Alb.basalt	35.38	36.16	18475	19794	21.4	220,550	
S-6-5-1	Alb.basalt	35.38	36.16	17550	93610	106.7	40,150,570,605	1.4
S-8-1-1	Alb.basalt	35.00	36.26	56550	22360	7.9	45,390,570	2.2
S-3-3-1	Spil.	35.05	36.18	57688	9114	3.2	280,350,560	
S-3-8-1	Spil.	35.05	36.18	78126	101300	25.9	260,560	1.2
S-3-10-1	Spil.	35.05	36.18	86098	87840	20.4	280,350,560	
S-3-11	Spil.	35.05	36.18	86500	38841	9.0	430,560	1.3
S-1-15-1	Spil.	35.20	36.17	19574	16050	16.3	300,480,570	

Ol.–olivine, Alb.–albitized, Spil.–spilite; Other explanations are below Tab. 1.

magnetic phases are present.

We see from Tab. 5, that when the inversion temperature secondary magnetic phase is present, mostly extreme high intensities of NRM have been shown, despite in some rocks only low values of κ have been detected. Olivine basalt e.g. from locality JP-2 has $\kappa = 25113 \times 10^{-6}$ SI Units, but NRM only 5740 nT. It has only one highly oxidized magnetic phase of $T_C =$ 605° C. Olivine basalt of locality JP6-4 has extreme high $\kappa = 92902 \times 10^{-6}$

Tab. 5. Magnetic characteristics and magnetic Fe-Ti phases of the Cretaceous (cca 121 Ma) to Jurassic (cca 171 Ma) nepheline basanites from Runka localities (RK-1, RK-2), and the Quaternary basalts from Jos Plato (JP), Biu plato (BP) and Samunaki localities (cca 0.9 to 7.0 Ma) - Nigeria

Name of locality	Type of rock	φ_L	λ_L	N	$\kappa \times 10^6$ SI Un.	NRM nT	Q	Mag.phases T_C, T_{C1}, T_{C2}(°C)	Coef.
RK-1	Neph.bas.	12.5	7.18	25	37065	20235	10.9	150,310,500,590	
RK-2	Neph.bas.	12.5	7.18	37	33709	103716	61.5	170,450,560,590	1.9
BP-1	Ol.basalt	10.61	12.14	2	20957	166873	159.3	280,540	2.9
JP-1	Diab.with ol.	9.71	8.45	5	10028	74292	148.2	310,590	1.6
JP-2	Ol.basan.	9.7	8.47	21	25113	5740	4.6	605	
JP-3	Ol.basalt	9.58	8.32	3	12294	15610	25.4	220,550	2.2
JP-4	Ol.basalt	9.58	8.34	6	17948	80702	89.9	450,560	1.13
JP-5-5	Ol.basalt	9.63	8.39	19	22486	126908	112.9	120,520,570	1.22
JP-6a-3	Ol.basalt	9.56	8.64	2	14457	30962	42.8	354,560	1.57
JP-6-4	Ol.basalt	9.56	8.64	8	92902	4721	1.0	580	0.48
JP-7	Diab.with ol.	9.56	8.67	4	11544	110703	191.8	520,560	1.21
JP-8	Ol.basalt	9.58	8.71	5	9455	131783	249.4	350,560	4.26
SMKI-1	Ol.basalt	10.61	12.14	3	18486	182188	197.0	520,605	
SMKI-2	Ol.basalt	10.61	12.14	4	21000	2042	1.9	580	

Neph.bas.–nepheline basanite, Diab.–diabase; N–number of samples; Coef.– coefficient κ_{450}/κ_{25}; other explanations are below Tab. 1.

SI Units, but only very low NRM = 4721 nT. It has only one magnetic phase with T_C = 580° C, corresponding to magnetite. Olivine basalt from locality SMKI (SMKI-1) has the second magnetic phase, detected only by continual measurements of the change of κ with temperature and extreme high NRM has been detected. The olivine basalt from the same locality, but from other vein system (SMKI-2) has not shown the secondary magnetic phase, so only very low intensity of NRM has been detected, despite the values of κ of both samples being very similar.

The origin of the low-temperature oxidized phase in Ti-Mt-es: The low-temperature oxidation of high titanium content of Ti-Mt-es takes place in the interval from the atmospheric temperatures to about 350° C, or

Tab. 6. Magnetic characteristics and magnetic Fe-Ti phases of recent age basalts from Italy Etna volcano (Hornitos; Zafferani; Etna 1983; Etna 1992; and Kilauea volcano (Hawaii, USA))

Name of locality	Type of rock	φ_L	λ_L	Number of samples	$\kappa \times 10^6$ SI Un.	NRM nT	Q	Mag.phases T_C, T_{C1}, T_{C2}(°C)
Hornitos,2002	Hawaite	37.73	15.00	2	25635	1633	1.3	290,510
Zaf.,1992	Bas.cinder	37.73	15.00	1	21450	1856	1.8	250,480,550
Etna,1983	Basalt	37.77	15.00	2	29453	2886	2.0	500,565
Etna,1992	Basalt	37.77	15.00	2	36956	3876	2.1	250,555
Kilauea,1971	Thol.basalt	19.43	155.29	2	45875	3453	1.5	125,420,560

Zaf.–Zafferani; Bas.–basaltic; Thol.–Tholeitic; other explanations are below Tab. 1.

little bit more, in mild hydrothermal environments. Before the oxidation reaction the SP state of these Ti-Mt-es is the characteristic feature. According to experimental data my own idea is that the rocks of this oxidized group have mostly lower κ in-situ state than that at the beginning of the emplacement of this volcanic material on the earth surface, or as the same types of basalts without the magnetic phases having inversion temperatures. The lower values of volume κ of these samples are the consequence of magnetostatic interactions among of portion of original SP state magnetic particles of Ti-Mt-es and those gradually originated oxidized Ti-Mt-es (maybe the titanomaghemites - Ti-Mgh-es). In the gradually developed secondary oxidized Ti-Mt phase the nucleation of the thermodynamically stable domains took place during low-temperature oxidation. The intensity of the oxidation increases at the higher temperatures (exchange anisotropy, shape and magnetocrystalline anisotropies can be developed during this process). As a consequence of this interactions a highly viscous and very easily excitable phase system has arisen (except of the original thermoviscous SP component the thermodynamically stable more oxidized phase with the developed domain structure existed in the system). Highly excitable system is able to acquire a chemico-viscous or thermoviscous remanent magnetization having been exposed to the external magnetic field.

The volcanic rocks following their primary acquisition of the TRM are continuously exposed to the Earth's magnetic field. Those grains of Fe-Ti oxides that have shorter relaxation time can acquire a secondary magnetization long after the formation of the rocks. Such a secondary magnetization - the *viscous remanent magnetization (VRM)* is of other age than that of the TRM (*McElhinny and Fadden, 2000*). The VRM (and the magnetic moment M_{VRM}) at a given temperature is acquired according to the relation M_{VRM}=Slogt (t=time in seconds; S=viscosity coefficient). Because of the logarithmic growth of VRM with time, VRM is usually dominated by that acquired in the most recent field to which the rock has been exposed. Rocks with large VRM components generally have their NRM aligned in the direction of the present geomagnetic field. Rocks that have been heated to temperatures below the Curie temperature of their magnetic minerals for a geological short time during their history, and then subsequently cooled again in the prevailing magnetic field, will acquire a *thermoviscous remanent magnetization - TVRM* according to *Butler (1992),* in *McElhinny and Fadden (2000).* Basic equations and graphs of the dependence of the relaxation time on the temperature of SD magnetite and hematite grains were presented by *McElhinny and Fadden (2000).* From the mentioned graphs it is evident that the SD grains of magnetite with the relaxation time 10 million years (Ma) are able to acquire a substantial TVRM if held at 260° C for 10 Ma and then cooled to 0° C. However the same grains can acquire the same TVRM at relaxation time only of about 30 minutes if held at 400° C. From this is follows that the temperature and the relaxation time are the decisive parameters, but except of this the composition of Fe-Ti oxides, Curie temperatures (T_C) and magnetic state of Fe-Ti minerals of rocks are important with respect to the acquisition of intensity of TVRM of rocks.

Nožarov et al. (1981) studied the Plio-Pleistocene basalts from 10 localities of Northern Bulgaria (in the areas defined by geographical coordinates: Latitude N-φ_L = from 43.183 to 43.517° and Longitude E-λ_L = from 25.133 to 25.283°). There were detected the Ti-Mt-es with the Curie temperatures $T_C \approx 180$ to 220 or to 280° C in basalts. The authors have commented that the Ti-Mt-es were in different degree of low-temperature oxidation state. It means that in some cases also the inversion temperature low-temperature magnetic phases might be present in these rocks. Their magnetic susceptibilities were in the range 15840 to 45840×10^{-6} SI Units and intensities of NRM were in the range 1290 to 8519 nT. No extreme intensities of NRM of basalts were detected, despite the values of κ being relatively high, comparable with those collected e.g. from Slovak basaltic fields or with other types of basalts commented above.

4. Discussion and conclusions

The source, the origin and the type of the highly intensive (conventionally over 10000 nT) NRM in the volcanic rocks have been investigated. Presented are the separate results of the Neogene basalts and basaltic andesites from Slovak volcanic fields, the Eocene to Miocene basalts from Bohemian Massif, the different age basalts from Nigeria, Syrian Arab Republic and the recent basalts from Kilauea (Hawai) and Etna Volcanoes.
The following results have been achieved:
- Among different types of volcanics the most intensive NRM is revealed in basalts and basaltic andesites. Generally, the decrease of intensity of NRM follows with the increase of the content of SiO_2 in volcanics - basalts (45–52% SiO_2) and basaltic andesites - the intermediary volcanics - andesites (52–65% SiO_2) and acidic rocks - rhyodacites and rhyolites (65–72% SiO_2). But some exceptions may exist.
- The intensively alterated volcanics have shown only negligible intensities of NRM, similar to like the intrusive and plutonic rocks, which contain dominantly the magnetites - preferably in multi-domain state.
- The main magnetism carriers in basaltic rocks are the titanomagnetites which are of the ferrimagnetic state. Only recently a completely new phenomenon was revealed by *Orlický (2004a)* that the so called homogeneous Ti-Mt-es (with dominantly high content of ulvöspinel in the composition of $Fe_{3-x}Ti_xO_4$, which generally have very high values of κ), are *in superparamagnetic state* in the rocks in question. With regard to very high magnetic susceptibility the rocks my acquire relatively high intensity of NRM influenced by the geomagnetic field. According to experience such rocks have never attained the value of NRM over 10000 nT. It means that the extreme high intensities of NRM cannot be explained only on the basis of the SP behaviour and the high volume κ of rocks. As we have known the Ti-Mt-es are not too stable magnetic minerals. They have a tendency to be altered very easily during their heating. In volcanics, except of a high-temperature oxidation, a low-temperature oxidation of Ti-Mt-es takes place in the range

of about 25 to above 350° C in mild hydrothermal environments.
- My own experience allows me to suggest that the rocks of this group have mostly lower κ in-situ state than the same types of basalts without the inversion temperature magnetic phases. The lower values of volume κ of these samples are the consequence of magnetostatic interactions among of a portion of the original SP state magnetic particles of Ti-Mt-es and those gradually originated more oxidized titanomagnetites which have arisen due to oxidation of original Ti-Mt-es. In the gradually developed secondary more oxidized Ti-Mt phase the nucleation of the thermodynamically stable domains took place during low-temperature oxidation (exchange anisotropy, shape and magnetocrystalline anisotropies can be developed during this process). As a consequence of this interactions a very easily excitable SP phase has arisen in this system (except of this unstable SP phase, the thermodynamically stable phase with the developed domain structure have existed in the system). Highly viscous unstable SP phase is able to acquire a chemico-viscous or thermoviscous remanent magnetization having been exposed to the external magnetic field.
- The volcanic rocks after their primary acquisition of TRM are continuously exposed to the Earth's magnetic field throughout their history. Because of the effect of magnetic viscosity, those grains that have shorter relaxation time can acquire a secondary viscous magnetization long after the formation of the rocks, due to the influence of the geomagnetic field. Rocks with large VRM components generally have their NRM aligned in the direction of the present geomagnetic field.
- Among of all investigated rocks there are very young basalts (only about 0.15–0.2 Ma) from Putikov vršok locality (Tab. 1). In many samples collected from 22 individual places of the large fresh quarry there were developed very soft inversion temperature secondary magnetic phases. But in the samples from only one place of the quarry the intensity of NRM was over 10000 nT. In the Plio-Pleistocene basalts from Norther Bulgaria the Ti-Mt-es were revealed as the dominant magnetism carriers (*Nožarov et al., 1981*). In the two samples of rocks among of those from 10 localities have the inversion temperature magnetic phases, but there were detected mostly low values of NRM (in one of them was NRM = 8519 nT). Among of basalts from recent Etna and Kilauea volcanoes no inversion temperature secondary magnetic phases were developed. The intensities of NRM in the range 1633

to 3876 nT have been detected. So, no intensive NRM has been acquired in these recent basaltic rocks.

- The high intensities of NRM of rocks are linked with the presence of the inversion temperature secondary magnetic phase. But if one takes into account the equation for computing the intensity of VRM mentioned above, the experimental - viscosity coefficient must be expressed very precisely, which involves the specific property of the so called inversion temperature secondary magnetic phase. Very important parameter is the temperature at which the mentioned phase was generated. The higher the temperature, the higher the intensities of NRM of the system are expected.

- The inversion temperature secondary magnetic phase and the resulting very high intensities of viscous RM (in the Tabs 1–6 are termed as NRM) of basaltic and some type of andesitic rocks are very important characteristics. In basaltic rocks the intensities of viscous or thermoviscous RM, and also the Koenigsberger coefficient Q have reached the following values: 11564 to 48643 nT and Q = 7.1 to 38.5 in central and southern Slovakia; 14445 to 79303 nT and Q = 10.2 to 72.4 in Javorie and Poľana volcanic fields; 10910 to 45652 nT and Q = 3.7 to 30.6 in the Eocene to Miocene age basalts from České Středohoří Mts.– North Bohemia; 16050 to 103100 nT and Q = 9.0 to 106.7 in the samples of the Cretaceous and the Neogene basalts from Syrian Arab Republic; 15610 to 182188 nT and Q = 10.9 to 249.4 in the Cretaceous (cca 121 Ma) to Jurassic (cca 171 Ma) nepheline basanites and the Quaternary basalts from Nigeria. These high intensities of NRM have contributed to the total magnetization of volcanic structure and so, with regard to the volume of the respective body may generate intensive geomagnetic anomalies. It is necessary to emphasize very strictly that these anomalies have not reflected the places or positions with the economically interesting concentrations of the Fe deposits. With respect to their origin they must be a time-variable, dependent on the stage of development of the inversion temperature secondary magnetic phase due to low-temperature oxidation of Fe-Ti oxides and the magnetostatic interactions of the superparamagnetic and the thermodynamically stable magnetic Fe-Ti phases.

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