

Field-reversal versus self-reversal hypothesis: The Ti-rich titanomagnetite bearing basalts and their partly self-reversed partial thermoremanent magnetization induced in the laboratory field

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Abstract: Three Ti-rich titanomagnetite bearing samples were subjected to inducing of the thermoremanent magnetization in the laboratory field of normal polarity and the intensity of about $H=50\ \mu\text{T}$. The high vacuum of about 10^{-4} to 10^{-5} Torr., was used during heating and cooling of the samples, to prevent an oxidation of original Ti-Mt-es. The original basalt and two artificial samples acquired intense PTRM, and an orientation of the total vector of the PTRM was antiparallel (reversed) with respect to the H component of the magnetizing field, but the inclination of the PTRM was of positive sense. The results have proven that in all three samples only non-complete, partly self-reversed PTRM was acquired during the laboratory inducing in the field of normal polarity. The original Ti-rich titanomagnetites were partly oxidized, despite the highly evacuated space, which is the primary cause for a non-complete self-reversal magnetization of samples during the experiment.

Key words: superparamagnetic-like state of high content of ulvöspinel titanomagnetites, partly self-reversal PTRM of Ti-rich Ti-Mt bearing basalts

1. Introduction

So far in routine paleomagnetic investigation the field-reversal hypothesis is frequently accepted by the specialists in accounting for essentially most of the reversed polarities of the RM of volcanic and sedimentary rocks. According to this hypothesis there is a normal state in which the geomagnetic field

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is directed toward the north, and reversed state in which the geomagnetic field is directed toward the south. The field switches back and forth between these two states at irregular intervals (*Cox, 1973*). According to such an idea, rocks can acquire the normal or reversed polarity of RM, depending on the direction of the geomagnetic field. The rocks containing the same amount of magnetic Fe-Ti minerals of the same grain sizes, magnetic state, the same chemical composition and their magnetic history should acquire approximately the same or very near intensity of remanent magnetization (mutually opposite sense), if the intensities of the normal or the reversed fields were approximately equivalent, during cooling of volcanic magma.

The basic magnetic minerals in volcanic rocks are the Fe-Ti oxides, the titano-magnetite and ilmenite-hematite solid solutions and their derivatives. Both these types of minerals have been considered as the ferrimagnetic state minerals. But I have revealed that the titanium-rich titanomagnetites behave as the superparamagnetic-like (SP) materials (*Orlický, 2004*). It means that they have not possessed a characteristic domain structure.

The development of basalt formations in the Southern Slovakia has been described by *Konečný et al. (2001)*. A local updoming in Southern Slovakia is contemporaneous with alkali basalts in the Cerová vrchovina Highland may indicate the presence of spatially limited mantle plume responsible for generation of basalt magmas. According to *Huraiová and Konečný (1994)* the estimate of equilibrium in pressure and temperature for mantle xenoliths indicates adiabatic uprise of mantle material. In such petrological conditions there was a lack of oxygen in melted basalt magma, so the basalts containing the titanium-rich titanomagnetites in the southern part of Slovakia, in the Podrečany basalt formation, and the Cerová basalt formation were formed (such types of basalts are present e.g. in the localities: Podrečany, Mašková, Trebeľovce, Filakovské Kováče). The presence of the Ti-rich Ti-Mt-es in these types of basalts was detected by *Orlický (2004)* , and the general conditions for forming such types of Fe-Ti oxides were described by *Lindsley (1991)*. The basalts from most of localities and very frequently also in one locality itself contain also the low-temperature oxidized phase, except of original Ti-rich Ti-Mt phase. This oxidized phase occurred probably during cooling of melted magma on the earth's surface (where a rich concentration of oxygen was present) and the process of oxidation continued until the basalts were solidified. In any case it has a secondary origin

and does not correspond to the primary composition of Fe-Ti oxide. The basalts of only appropriate composition (without any oxidized phase) could be selected for the study of the self-reversal process. According to previous experience the basalts from the Mašková locality were selected for the study. As has been shown by *Orlický (2004)* the volume magnetic susceptibility κ is a very characteristic criterion for the evaluation of the state of Fe-Ti oxides. The highest value of κ among the individual parts of Ti-rich Ti-Mt containing basaltic body represents the lowest portion of the oxidized Fe-Ti magnetic phase. The basaltic samples and their artificial equivalents with the Ti-rich Ti-Mt-es are the subject of this paper.

I will try to apply direct inducing of the reversed RM by self-reversal mechanism in the normal field in the type of basalt which has originally the reversed RM acquired in the field about 7.0 m.years ago.

2. Methodical setting

The subject of this work is the study of basalts which occur in the locality Mašková. The original basalts of the locality possess the reversed RM and some parts of basaltic body show relatively high values of volume magnetic susceptibility. As has been described by *Orlický (2004)* the parts of basaltic body with the highest values of volume magnetic susceptibility contained the Ti-rich Ti-Mt-es with the SP-like behaviour. It has been quite surprising experience that it is possible to find very heterogeneous values of volume magnetic susceptibilities in the individual positions within the basaltic body. This property has reflected not a different content of magnetic Fe-Ti oxides in the body, but the different oxidation state of basalt, despite belonging to the same volcanic body. In two different time stages altogether 6 larger samples were collected from the locality (the locality under consideration is in Fig. 1). Some basic results were previously published (*Orlický, 2004; 2004a*). In addition to compact basalts artificial samples containing the Ti-rich Ti-Mt-es were studied.

Preparation of artificial samples and basic measurements

The artificial samples were prepared by grinding the original (*in situ volcanics*) in ceramic bowl. The grinded material of the samples was sieved to

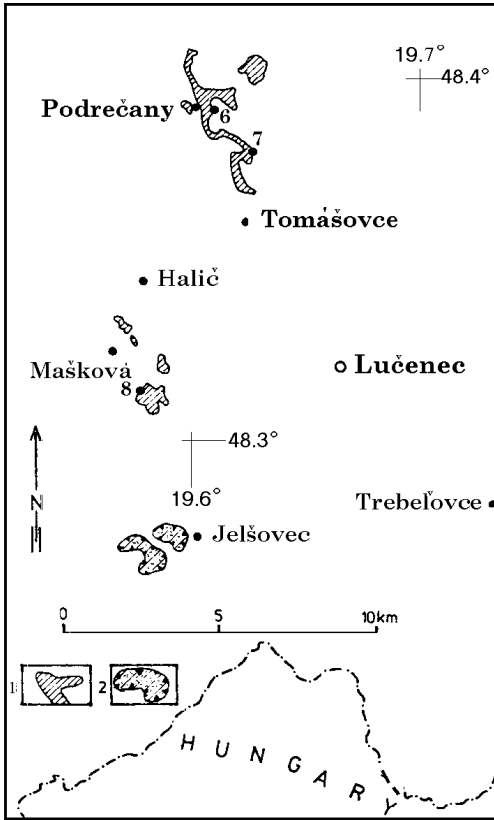


Fig. 1. A sketch map of selected localities; (The original map according to *Konečný et al. (2001)* was modified by author of this article) 6–8 - localities with basaltic rocks. 8 - the locality with the basalt under study (locality is in the western part of Lučenec Town; Explanations for Podrečany basalt formation (Early Pliocene): 1–basalt lava flows; 2–maars; 19.6° and 48.3° – geographical latitude (φ) and geographical longitude (λ), respectively.

preserve the sizes of the grains around of \varnothing 0.2 mm. The bar permanent magnet was used to separate the magnetic grains from the grinded material. The magnetic grains were fixed in nonmagnetic gypsum. The powdered gypsum was permanently mixed with the magnetic grains and the water in the ceramic bowl. This mixture of an appropriate consistency was put inside the plastic form of the cylindrical shape with the diameter of 25 mm and height of 22 mm. Above mentioned procedure, including a drying of the samples on the free air were made at room temperature. The basic measurements of the remanent magnetization (RM) and magnetic susceptibility (κ) of the compact basalts and the artificial samples were realized by the spinner magnetometer JR-5 and the kappabridge KLY-2, respectively. The results of the samples Mašková2a-c, Mašková 2a-04G and Mašková 2a-04G-I

are in Table 1.

Inducing of thermoremanent magnetization in the samples

The basic idea was to induce the thermoremanent magnetization (PTRM) of original basalt and artificially prepared samples in the laboratory field and compare these results with those of the same outcrop and the same petrographical type of original basalts of the locality in question. One original basaltic sample was chosen from the collection of large amount of cylinder's shape basalts of the locality and two artificial samples with the presence of grinded grains of original basalts were prepared. In these samples the PTRM was induced in the laboratory field of intensity $H \approx 50 \mu\text{T}$. The basalts containing the Ti-rich Ti-Mt-es were formed with a lack of oxygen, as has been described above under the adiabatic conditions. These basalts come probably from the mantle plume source. Owing to the very high sensitivity of Ti-rich Ti-Mt-es to oxidation, whole magnetization procedure must be realized under high vacuum conditions, or in the presence of nitrogen or argon gases, to prevent any oxidation of original Fe-Ti oxides. In our paleomagnetic laboratory there are going to be established the technical equipments for an arrangement of inducing of PTRM of magnetic materials in high vacuum conditions, unfortunately so far it has not been finished. So, Dr. P. Švec was so benevolent and has allowed to arrange the inducing of PTRM of three samples in the highly vacuum electric oven in the Laboratory of the Institute of Physics, Slovak Academy of Sciences, Bratislava. The intensity of total vector of magnetic field was about $H \approx 50 \mu\text{T}$ and the declination D was about 355° (approximately to the north) in the laboratory room (the intensity H and D of the field were only derived from the previous measurements made in the room No. 31 in the same building); No variations of the field and the changes of the inducing field inside the electrical oven were measured during experiment. We can deduce that there were no ideal conditions with respect to purity of magnetic field in the laboratory. For this reason the results of an induced PTRM of samples could be considered as the preliminary ones.

The following procedure for an inducing of PTRM of samples was held: The compact basaltic sample Mašková2a-c, and two artificial samples Mašková 2a-04G and Mašková 2a-04G-I were placed on the holder of the vacuum electrical oven with respect to the direction of the magnetic field inside the

laboratory. The whole oven space including the samples was evacuated during 60 minutes before the beginning of heating of the samples, to exhaust a remnant of air oxygen inside the space and samples. The vacuum was held at a level of about 10^{-4} to 10^{-5} Torr. The speed of heating of the samples was about $4^{\circ}\text{C}/\text{min}$. The samples were heated up to 400°C , at this temperature the heating was taken about 30 minutes. Cooling of the samples continued with a similar speed. This whole procedure, heating and cooling was realized under the presence of the laboratory field of the intensity about $H = 50 \mu\text{T}$ and under a permanent keeping of vacuum of the level mentioned above.

Except of the works described above, I have applied the results of the Curie temperature measurements and the method of thermal demagnetization of basalt samples. The results of these methods are in Figs. 2–4. The results of a study of magnetic phases and magnetic Fe-Ti oxides of basalts were studied by *Orlický (2004)* and will be taken into account as well.

Table 1. Magnetic characteristics of basalts from Mašková locality and artificially prepared samples.

Designation of sample	Magnetic characteristics 1					Magnetic characteristics 2				
	$\kappa \times 10^6$ SI Un.	PTRM [nT]	Q	I°	D°	$\kappa \times 10^6$ SI Un.	RM [nT]	Q	I°	D°
Maškov2a-c	47867	12491	5.2	37.4	182.9	47867	3087	1.2	11.4	218.7
Mašková2a-04G	6663	3154	9.5	31.5	196.3	6663	187	0.5	63.0	358.0
Mašková2a-04GI	2947	1105	7.5	49.5	151.2	2947	87	0.6	65.0	8.0

Magnetic characteristics 1–correspond to the samples in which the PTRM was induced in the laboratory field; Magnetic characteristics 2–correspond to the samples in its natural state (Maškov2a-c) or to artificially prepared samples, with non induced PTRM in the laboratory; G–in the designation of sample means gypsum κ –bulk magnetic susceptibility; RM–remanent magnetization; PTRM– partial thermo-remanent magnetization induced in the laboratory field; nT–nano Tesla; Q–Koenigsberger ratio; I° , D° – inclination, declination of PTRM or RM, respectively of the samples.

Results and basic interpretation

Previously the magnetic data of rocks from the same outcrop of the same petrography were mostly summarized, regardless of differences in their oxi-

dation state (e.g. for Mašková locality, see Table 1 in *Orlický (2004)*). But when we look at the results in a more detailed fashion we see that there are very large differences namely in magnetic susceptibility (see in Table 2). Their behaviour has been reflected in the Curie temperature measurements, also in the change of κ of the sample with temperature (Figs. 2–4).

Table 2. Magnetic characteristics of natural basaltic rocks from Mašková locality.

Designation of sample	Magnetic characteristics					Magnetic characteristics				
	$\kappa \times 10^6$ SI Un.	RM[nT]	Q	I°	D°	$\kappa \times 10^6$ SI Un.	RM[nT]	Q	I°	D°
Mašková1-1(1-2)	33421	3856	2.3	-77.2	158.4	31506	3208	2.0	-72.4	159.7
Mašková2-1(2-2)	58618	2861	0.9	-56.4	163.8	63553	2850	0.9	-47.5	164.0
Mašková2aA04(2aE04)	34404	4048	2.4	31.4	175.6	33348	2116	1.3	19.3	195.4
Mašková1aA04(1aC04)	8449	2300	5.4	54.1	202.2	10403	3012	5.8	12.9	221.6
Mašková1aD04(1aE04)	6698	1549	4.6	27.6	200.0	5783	2008	6.9	24.9	221.0

Designation in the round bracket belongs to the second sample e.g. Mašková 1-2 and the corresponded data are in the right part of the table; κ –bulk magnetic susceptibility; RM–remanent magnetization; nT–nano Tesla; Q–Koenigsberger ratio; I°, D° – inclination, declination of RM, respectively of the samples.

Explanation of the differences in magnetic characteristics of individual samples:

We see from Tables 1, 2 that the natural samples of basalts from the same outcrop are characterized by very variable values of volume magnetic susceptibilities, ranging from 5783×10^{-6} to 63553×10^{-6} SI Units. The samples of high values of κ contain a high portion of Ti-rich Ti-Mt-es and mostly are without the low-temperature oxidized phase. They are of low Curie temperature (Fig. 2, Mašková-2, $T_C \approx 120^\circ$ C), they have shown a rapid decreasing of κ down to nitrogen temperature (this behaviour can indicate the presence of small magnetic particles) and they do not show extreme changes of κ with temperature during a thermal demagnetization of samples (Fig. 3, Mašk2-2). The magnetic materials with a thermodynamically stable domain structure are athermal, it means that they do not show the

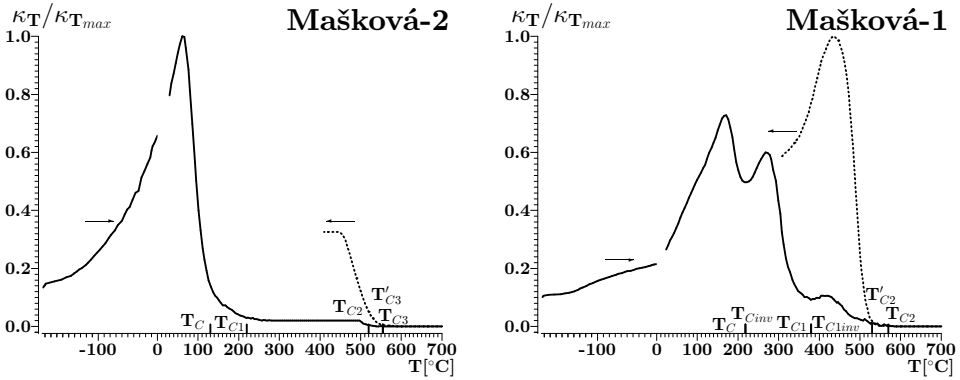


Fig. 2. Thermomagnetic curves of samples. Mašková samples – name of locality and number of sample; T_C , T_{C1} , T'_C , T'_{C1} – Curie temperatures during heating and cooling (T') of the sample; κ_T , κ_{Tmax} – magnetic susceptibility at temperature $T(\kappa_T)$; maximum susceptibility (κ_{Tmax}); T_{Cinv} – inversion temperatures.

change of κ (or other magnetic parameter) with temperature, only around the Curie temperature. As has been noted above, they behave as the SP - like particles. The basaltic samples of this type possess the reversed RM but mostly of low magnetic and directional stability (Fig. 3). We see from Fig. 3, Maš2-2 that the relatively stable component of the RM was preserved up to about 500° C. The mean direction for the thermally demagnetized 14 natural basalt samples of the locality is $I=-66.6^\circ$ and $D=178.5^\circ$ (the directions of the RM of the samples from Table 2 have not been included in evaluating the mean value of I and D of basaltic body as a whole, in the Table 2 the data correspond to only non corrected positions of the samples; after a correction with respect to azimuth and slope of the oriented samples the inclination and declination of the RM are very near those of $I=-66.6^\circ$ and $D=178.5^\circ$, computed for the whole basaltic body).

Completely different situation is in olivine basalts of the same outcrop, which have shown low values of κ . These basalts contain also the secondary - low temperature oxidized magnetic Fe-Ti phase, except of the Ti-rich Ti-Mt-es. There is an example of thermomagnetic curve in Fig. 2, Mašková-1. I have chosen the sample with $\kappa = 33421 \times 10^{-6}$ SI Units, but there are evident two secondary magnetic phases with the Curie temperatures over 180° C and the primary Ti-rich Ti-Mt phase itself has been oxidized from about

**Maskova2a-c; $\kappa=47867$; $J=12491$
 $Q=5.2$**

**Mašk2-2; $\kappa=63553$; $k=1.1$; $J=2850$
 $Q=0.9$**

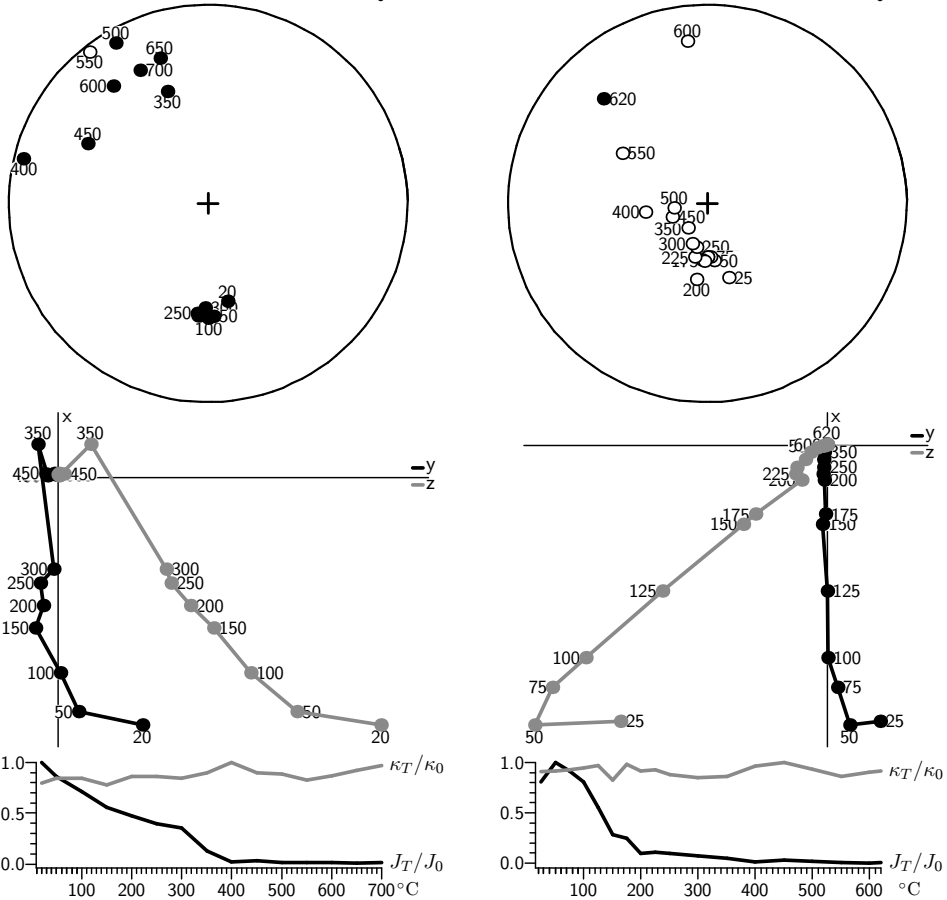


Fig. 3. Thermal demagnetization of the laboratory induced PTRM of original natural basalt - (the sample Maskova2a-c) and the natural RM of the sample Mašk2-2 from the same locality as previous sample; stepwise heating to 700 (600) °C; Zijderveld diagrams and stereographic projections; • (o) means positive (negative) polarity of RM; κ_T (κ_0) - magnetic susceptibility ($\times 10^{-6}$ SI units) at T (at 25°C, respectively); J_T (J_0) - remanent magnetization (in nano Tesla-nT) at T (at 25°C, respectively).

120° to about 180°. They do show only soft decrease of κ down to liquid nitrogen temperature. In such types of basalts the secondary low temperature

**Maskova2a-04G; $\kappa=6663$; $J=3154$
 $Q=9.5$**

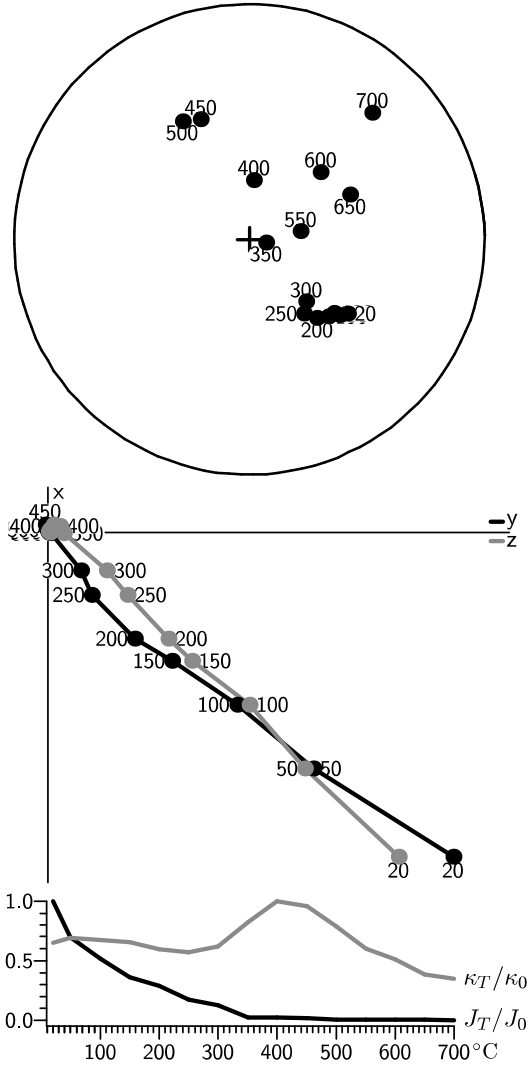


Fig. 4. Thermal demagnetization of the laboratory induced PTRM of artificial sample Maskova2a-04G; stepwise heating to 700°C; Zijderveld diagrams and stereographic projections; • means positive polarity of RM; κ_T (κ_0) - magnetic susceptibility at T (at 25°C, respectively); J_T (J_0) - remanent magnetization at T (at 25°C, respectively).

oxidized phase is detected by extremely increasing κ with the temperature, during thermal demagnetization process (Fig. 4). In the basalts of lower values of bulk κ the existence of the secondary magnetic Fe-Ti phases is

more extremely stressed. The characteristic feature of such types of basalts is a higher value of Q ratio compared to with that of basalts of high values of κ . I have assumed that the thermodynamically stable domain structure is nucleated during the oxidation process in these types of rocks.

3. Evaluation of the results of laboratory induced PTRM of samples

As has been described above the magnetizing process of 3 samples was performed at 400°C (30 min. heating of the samples at this temperature) and during cooling of the samples to room temperature. This temperature interval was chosen for several reasons: - the Ti-rich Ti-Mt containing basalts have commonly shown the directional stability of RM mostly to 400°C; - heating of such basalts over 450°C in the presence of oxygen leads to disintegration of original Ti-Mt-es and the creation of more oxidized Ti-Mt-es (frequently the Ti-maghemites); *Petersen and Bleil (1973)* applied the interval up to 400°C to induced the self-reversed PTRM in the synthetic Ti-rich Ti-Mt-es at a presence of air oxygen.

I suppose that during successive heating of the samples to 400°C, the original components of the RM were disintegrated and new components of partial thermoremanent magnetization (PTRM) originated at a presence of laboratory magnetic field. This process continued also during heating at temperature of 400°C during 30 minutes, and successively during cooling from 400°C to room temperature.

The magnetic characteristics of the original basalt and two artificial samples are in Table 1. We will consider the data before (Magnetic characteristics 2) and after laboratory inducing of the PTRM of the samples (Magnetic characteristics 1). The intensity of the RM (NRM) of the sample Mašková2a-c is 3087 nT, $Q=1.2$, $I=11.4^\circ$ and $D=218.7^\circ$. After the inducing of the PTRM in the laboratory field of positive orientation the sample acquired the intensity of PTRM = 12491 nT, $Q=5.2$, with the inclination $I=37.4^\circ$ and declination $D=182.9^\circ$. The declination is nearly opposite (reversed) to today's geomagnetic field, but the inclination of the PTRM vector is of positive sense. The intensity of the PTRM was 4 times higher than that of the original RM of the sample. The two artificial samples were thermally

magnetized only first time. They acquired also intense PTRM with high Q , with the orientation of PTRM vector very near to that of the compact basaltic sample. All three samples were intensively magnetized but only non-complete self-reversed PTRM was acquired.

When we analyze the results of thermal demagnetization in Fig. 3, we see that the total magnetization J_T/J_0 of the laboratory induced sample Mašková 2a-c has been removed at about 300°C. The directions of the PTRM (I, D) were relatively stable to 300°C (the PTRM of the sample was acquired not from 400 but from 300 to 25°C). At the temperatures over 300°C a large dispersion of the directions of RM is obvious in the stereoprojection and the directions no longer corresponding to the laboratory induced PTRM of the sample. In the original sample Mašk2-2 the total magnetization J_T/J_0 has been removed almost at 200°C. There is a discrepancy of about 100°C, comparing it with the results of the laboratory induced PTRM of the sample Mašková2a-c. What is a source of this behaviour? As has been described above, the inducing of the PTRM of samples was realized in the high vacuum space of electrical oven. The samples were evacuated during 60 minutes before the heating of the samples, to exhaust the whole volume of gases from the samples. Despite this procedure the oxidation of original Ti-rich Ti-Mt-es took place during heating. I suppose that the problem dwells in the following: when the hot melted magma ascends to the earth's surface it gets into contact with the air. Some part of magma is mixed with the air and there may be expected also some oxidative processes in the outer parts of magma. But in the inner part of the magmatic body there is commonly a lack of air and most of it is pressed out of the body during cooling of the basaltic body. Because this is generally the heterogeneous process, in some parts a very minor amount of air can be preserved and closed in a porous volume of some parts of the body, so the cases are not complete exhausted during evacuation of the samples. We see that there are small differences between the compact basaltic sample (Fig. 3, Mašková 2a-c) and that of artificially prepared gypsum sample (Fig. 4, Maskova 2a-04G) in which the oxidation was less intense. Because the artificial samples do not contain pure magnetic fraction of Ti-rich Ti-Mt-es, but only grinded grains of basalt with the Fe-Ti oxides inside of the gypsum sample, their behaviour could be nearly similar to those of compact original basaltic samples.

We can conclude that the laboratory induced PTRM is not linked with

the Ti-rich Ti-Mt-es only, but also with the more oxidized Ti-Mt phase. This is the reason for which the total self-reversal (reversed) PTRM was not induced in the samples.

4. Discussion and conclusions

The application of the laboratory induced self-reversed PTRM of natural basalt and the artificially prepared samples containing the Ti-rich titanomagnetites was the main task of the presented work. After the inducing of the PTRM in the laboratory field of positive orientation the samples acquired the intense PTRM (about 4 times more intense than that in original basalt) with the partially self-reversed orientation with respect to the magnetizing field. The results have proven that the three investigated samples acquired only non-complete, partial self-reversed PTRM. Additional knowledge has been achieved: the laboratory induced PTRM is only stable for oxidized magnetic Fe-Ti phases. The Ti-rich Ti-Mt-es are able to acquire only non-stable magnetic components, probably of the thermo-viscous origin during the magnetizing process.

I need to comment that the above described laboratory inducing of the PTRM was not perfectly technically established. In a near future the technically very well equipped high-vacuum, non magnetic oven and controlled inducing laboratory magnetic field will be established in our Paleomagnetic laboratory, in the Observatory of Modra area, where the new laboratory works will be arranged.

In spite of non perfection of laboratory arrangement mentioned above, the achieved results are of very high importance with respect to the so far gathered experimental results on the self-reversed origin of reversely magnetized many other volcanic complexes and formations. In many previous works I presented the results of a reproducible laboratory inducing of the partial thermoremanent magnetization (PTRM) of andesitic, basaltic andesite and rhyolite samples of rocks (*Orlický, 2001, 2002, 2002a, 2002b, 2002c, 2003, 2003a*). In the mentioned laboratory procedures the intensities of the PTRM in the range of about 2.0 to about 200 nT were acquired.

The results of this work have evidently shown that the basalts containing Ti-rich Ti-Mt-es have a tendency to be magnetized by the self-reversal

mechanism in the normally oriented magnetic field. In order to achieve the complete self-reversed reverse PTRM it is necessary to prevent any oxidation of original Ti-Mt-es during the laboratory experiment.

Support of the self-reversal idea by other authors

I will select only several from very many works which have dealt with the self-reversal of Ti-Mt bearing rocks or materials. *Petersen and Bleil (1973)* studied the synthesized sample of composition 60 mol% ulvöspinel and 40 mol% of magnetite (they belong to the Ti-rich Ti-Mt-es). The samples were heated in air at 400°C for different times. Complete self-reversal remanent magnetization was observed in samples that were kept at 400°C between 10 and 40 min., in the earth magnetic field. The reversal took place at about 150°C when the samples cooled down to room temperature in both, zero field and the earth magnetic field. When heated longer, only partial self-reversal occurs. Curie point determinations lead to the suggestion that the self-reversal is caused by two different magnetic phases interacting negatively. One phase has Curie temperature of 210°C which corresponds to the initial Ti-Mt, the second phase which was produced by partial oxidation has a Curie temperature about 500°C. The range of oxidation states, where the self-reversal takes place, seems to be rather restricted. The authors have suggested that this mechanism of self-reversal may also occur in natural basalts. From the experiment it is evident that when the oxidation of original Ti-rich Ti-Mt-es was performed, the only partial self-reversal was induced. A surprising property was revealed: the synthesized Ti-rich Ti-Mt-es are supposed to be more resistant against the oxidation, compared to those present in natural basalts.

Lewis (1968) studied the self-reversal of synthesized Ti-Mt-es of composition 60 and 80 mol% ulvöspinel and 40 and 20 mol% of magnetite, respectively. The samples were subjected to oxidation and subsequent annealing treatment in vacuum. After a heating (heating in air and in vacuum at 600 and 850°C respectively) he induced in the samples only partial (PTRM) self-reversal remanent magnetization in the intervals of 600 to 450°C, 550 to 500°C and 500 to 450°C, but in no case a total self-reversal PTRM was induced. The ilmenite-hematite (Ilm-Hem) solid solutions were formed due to oxidation of original Ti-rich Ti-Mt-es, which are supposed to be the self-reversal carriers of the PTRM. It was also found that oxidation caused the

magnetic susceptibility to fall, and this fact together with the increase of the PTRM gives rise to high Q values for oxidized samples. The coercive force always increases considerably after oxidation, the increase becoming greater as compositional parameter x increases. The last two results suggest that if a rock acquires a secondary magnetization as the result of an oxidation process, it seems likely that this secondary component would be magnetically hard and would have a Curie point higher than that of the original material. This knowledge is in good agreement with our results.

Heller and Petersen (1982) studied the basalts 35000 to 45000 years old, from Laschamp and Olby localities, from Central Massif, in France. Basalts from most of Olby and Laschamp localities are reversely magnetized. Thermomagnetic, microchemical and optical properties were studied. Continuous thermal demagnetization indicates that under laboratory conditions the NRM of many Olby samples undergoes complete or partial self-reversal. For a lesser extent this deduction is valid also for the Laschamp basalt samples. The authors suggested that the self-reversal mechanism may be an explanation for the reversed NRM direction of the basalts in question.

The considerations about the self-reversal process were presented also by *Stephenson (1975)*. He observed theoretically the moment of permeable magnet embedded in permeable medium and he applied it to the case of the titanomagnetite particles containing minor quantities of an exsolved magnetite-rich phase of higher Curie point such as are found in basalts.

Shcherbakov (2005) deduced the fact that in most cases the self-reversed component of the remanence is magnetically quite soft, which favours a magnetostatic origin of the self-reversal. He described a concept of the self-reversal of multi-domain Ti-Mt grains in rocks. This new concept is developed on the basis of the theoretical approaches of *Stephenson (1975)* to show, that partial self-reversal is due to magnetic screening of PTRM of phase A with relatively higher Curie temperature $T_C(A)$ by the surrounding soft phase B, which possesses lower Curie temperature of $T_C(B)$ and has the susceptibility κ . If in addition to κ , a coercivity is assigned to phase B, the induced screening magnetization becomes blocked on cooling giving a possibility for a total self-reversal. To quantify this idea, the dependence of the net magnetic moment $M(T)$ was calculated analytically. To account for possible irregularity of the content and shape of phases, a three dimensional numerical quasi-micromagnetic model is developed, which considers a coarse

MD particle as an assemblage of magnetostatically interacting elementary Néel's hysteresis cycles. According to *Shcherbakov (2005)* the understanding of physics of the self-reversal process is still far from comprehension.

As we have seen from the above mentioned considerations, the theoretical assumptions have resulted from a MD and two phase model to provide good grounds to account for the self-reversal acquisition of the reversed RM of the Ti-Mt bearing rocks. There is no appropriate theory in common paleomagnetic literature to explain the self-reversal origin in Ti-rich Ti-Mt bearing rocks, which behave as the SP-like (small) particles. Despite we are not able to solve this problem immediately, it is possible to outline some perspective way which we could follow. According to *Hubert and Schäfer (1998)*, if a particle is too small, no domain structure will develop. For such particles the behaviour in magnetizing field will have other theoretical ground as in the MD particles. The authors have deduced that above a certain size an inhomogeneous magnetization state with a low average magnetization takes over. This state is not more continuously related to the uniformly magnetized state. The initial high-remanence or single-domain configuration is called the flower state, because the magnetization in the corner spreads outward like the petals of a flower. The low remanence state, which has a lower energy beyond the single-domain limit, is called the curling or vortex state. If a small particle is first saturated at high field and the field is then reduced (and reversed, if necessary) it will in general switch at some point to opposite magnetization direction or to some other state closer to equilibrium. Blocked transitions between these equilibrium states lead to *hysteresis*. The (almost) saturated state is usually metastable on approaching the equal energy limit, it cannot switch without some excitation as long as there is an energy barrier. The barrier may be overcome by thermal activation, depending on its height and shape. This leads to magnetic *viscosity* (*disaccommodation*) and thermally induced loss of magnetization (*superparamagnetism*). The switching field is defined as the point of instability of the near-saturation state. It is also known as the *nucleation* field although not in all cases anything particular is nucleated at or close to this point.

The principal problem in small-particle magnets is their orientation. While magnets consisting of larger particles can be readily oriented in a field before compaction, this becomes increasingly difficult with decreasing particle size. Non-oriented permanent magnets cannot achieve large values

of the energy product and can be applied in low-cost bonded materials only (*Hubert and Schäfer, 1998*). More detailed analysis about the magnetizing processes of small particles are beyond the limit of this article and will be described in the next paper.

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