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The self-reversal origin of the reversed remanent magnetization in the igneous rocks containing the oxidized Fe-Ti oxide solid solutions

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Abstract: I study the magnetic and paleomagnetic characteristics of the Pleistocene to Quaternary basalts from the West Carpathian Mountains. I have revealed the existence of the so-called *self-reversal remanent magnetization bearing disordered-antiferromagnetic Fe-Ti phases*, with the Néel temperatures of either $T_N = 430-450\,^\circ$C (the Ti-Mgh phases) or with $T_N = 460 - 470\,^\circ$C (Hem-Ilm phases). I have suggested for the first time to name of these phases in this article. It is very important that these phases are the only sources of the reversed RM, of the self-reversal origin, probably of the chemical remanent magnetization (CRM) origin. The basalts of Southern Slovakia were differentiated to these of the magnetite and Ti-rich Ti-Mt bearing rocks with normal polarity of RM, and those with the presence of the self-reversal RM bearing disordered-antiferromagnetic Ti-Mgh phases of the $T_N = 430$ to $450\,^\circ$C, and those of the disordered-antiferromagnetic Hem-Ilm phases of the $T_N = 460 - 470\,^\circ$C, both of only reversed RM of the self-reversal origin. I present the original model based on the principe that the magnetite, hematite and Ti-rich titanomagnetite bearing rocks, without any disordered-antiferromagnetic phases, carry only normal – positive RM. The *self-reversal remanent magnetization bearing disordered-antiferromagnetic magnetic phases of Fe-Ti oxide solid solutions* carry only reversed remanent magnetization in the rocks. This model has been involved to explain the reversed or normal RM of submarine igneous rocks published in the literature. We anticipate that in all continental or submarine reversally magnetized rocks the disordered-antiferromagnetic Fe-Ti phases would be revealed, either in their initial, complete developed stages, or as the remnants of these phases.

We suggest that the reverse remanent magnetization of rocks is due to the existence of the *self-reversal remanent magnetization bearing disordered-antiferromagnetic magnetic phases of Fe-Ti solid solutions* in the rocks, but not due to the existence of the reversals of the geomagnetic field.

Key words: Ti-Mgh and Hem-Ilm disordered-antiferromagnetic phases – the responsible carriers of reversed RM of rocks

1. Introduction

This article deals with the most important problem in paleomagnetism and in magnetic properties of rocks at all. The article deals with the problem of origin of the reversed remanent magnetization (RM) of rocks which are commonly present on the Globe. What is a real source of the reversed remanent magnetization of rocks? More than one centurage, since the year 1904, a field-reversal hypothesis has been accepted to explain the reversed RM of rocks. Is it well-founded to rely on the hypothesis that the reversed RM of rocks has been generated by the reversally oriented geomagnetic field in the time of origin of rocks? So far, no clear evidences have been found about the reversed orientation of the geomagnetic field.

I have applied a completely new approach for the explanation of the source of the reversed remanent magnetization (RM) of rocks. This explanation is based on the existence of the disordered-antiferromagnetic phases in the rocks, which I have named as the *self-reversal remanent magnetization bearing, disordered-antiferromagnetic magnetic phases.* If these phases are developed enough in the rocks, they carry only the reversed RM, mostly of the chemical (CRM) origin. The above mentioned phases have been revealed not only in the oriented rock samples, but also in the non-oriented rocks by the method which is described below. I present the results of some young volcanic rocks from Greece, the Tenerife Volcano and from the USA.

There has been suggested a preliminary version mechanism of an origin of the self-reversal RM of rocks, based on the existence of ionic reordering in the tetrahedral and the octahedral sublattices in the Fe-Ti mineral by *Orlický (2009).* I have tried to carry out investigation about the ordering of magnetically active Fe-ions in the respective minerals with the foreigner specialists, but so far, no newer data have been provided, to make the mechanism more realistic and precise. So, I will solve this problem later.

In this article, I review the experimental evidences on the self-reversal origin RM of rocks, including the correlation of a suggested model with data of some continental and submarine rocks of other authors.

The particular results have been described in the following chapters:

1. The results of a study of basalts from southern Slovakia. The methodical procedure of inducing the partial thermoremanent magnetization (PTRM) and parallel measurements of the change of magnetic

susceptibility (κ) of rocks with temperature – the basic method for the study of the so-called *self-reversal remanent magnetization bearing, disordered-antiferromagnetic magnetic phases*. We distinguish the reversally magnetized basalts of the two types, dependening on the different magnetic characteristics and magnetic behaviour influenced by temperature. There have been included also the results of a study of the nepheline basanite from the youngest volcano in West Carpathian Mts. central Slovakia – the Putikov vŕšok of the age of 142 to 200 k.y.

2. A proposal of the model for the explanation of sources of normal and reversed RM in the rocks, dependening on the type of magnetic Fe or Fe-Ti magnetic phases.

3. The application of the original model to explain of the RM of submarine volcanics, using and comparing the results from the limited number of sites and holes from the Mid Atlantic and Pacific Oceans. The part of limited results of this article was lectured also at the 12th International Castle Meeting in Nové Hrady, Czech Republic, 29th August – 4th September 2010.

2. Experimental results and their evaluation

The results of a study of basalts of southern Slovakia

Short description of the studied localities: The studied basalts belong to two formations (Fig. 1). The Early Pliocene Podrečany basalt Formation – dominantly lava flows of the age 6.44 to 7.17 m.y. – localities 6, 7 – Podrečany, 8 – Mašková. The Middle Pliocene – Pleistocene Cerová basalt Formation – dominantly lava flows, basaltic necks and dykes, rarely maars with basaltic tuffs of the age from 1.16 to 5.43 m.y. – localities 9 – Veľké Dravce, 10 – Husina, 11, 12, 13 – Čirinč, 14 – Poličko, 15 – NE of Šavoľ, 16, 17 – Konrádovce, 18 – Hodejov, 19 – Bulhary, 20 – N of Šíd, 21 – Trebeľovce, 22 – Fiľakovské Kováče, 23 – Blhovce, 24 – Blhovce-Buda, 25 – Veľké Hradište, 26 – Črep, 27 – NE of Ratka, 28 – Maar, 29 – SE of Ratka, 30 – Steblová skala, 31 – E of Steblová skala, 32 – Belinská skala, 33 – Ostrý vrch, 34 – Zaboda, 35 – Soví hrad, 36 – Ragáč, 37 – Veľký kopec, 38 – Hajnačka Castle, 39 – E of Hajnačka, 40 – Pohanský vrch, 41 – Mačacia, 42 – Dunivá hora, 43, 44 – Šomoška (neck), 45, 3A – Šomoška (small lava flow). The additional explanations (see also in the map): Basalts of the reversed RM of localities denoted with full red circle contain predominantly the magnetic phase of low-temperature oxidized titanomagnetites (Ti-Mt). This phase is of disordered-antiferromagnetic state with the Néel temperature $T_N \approx 430 - 450\,^\circ C$. Basalts of the reversed RM of localities denoted with full red circle contoured by black circle contain the high-temperature oxidized Fe-Ti oxides, predominantly with the hematite-ilmenite (Hem-Ilm) phase of the disordered-antiferromagnetic state with the Néel temperature $T_N \approx 460 - 470\,^\circ C$.

Induction of the PTRM of natural and artificially prepared samples of rocks

The basic method for the study of the source of the reversed remanent magnetization of rocks was induction of the partial thermoremanent magnetization in the rocks and parallel measurement of the change of magnetic susceptibility with temperature. Inducing the PTRM of samples in normally oriented external field of the intensity $H = 48\mu T$ was realized at the temperature steps: 50, 100, 150, 200, 300, 350, 400, 450, 500, 600, 700 °C. The samples were placed on the holder of the non-magnetic furnace. They were oriented in the positive direction of magnetic field. A speed of heating of the samples was about 3 °C/min. During about 30 min, the magnetization at a given temperature step in air was realized. The samples were then cooled to the room temperature. The RM of the samples was measured by the spinner magnetometer JR-5 at room temperature. After heating of the samples at the above selected temperatures and their successive cooling to room temperature, a change of magnetic susceptibility (κ) was measured by the susceptibility meter KLY-2 (Figs. 1, 2 and 4, 5, 7). For some samples a procedure of inducing the PTRM was different. The samples were magnetized only at the selected temperature step, but cooling of the samples to laboratory temperature was realized in the fully compensated external magnetic field (Fig. 5).

Firstly I present the results of a study of basaltic rocks of normal polarity RM (Figs. 2, 3). The results in Fig. 2 represent the samples containing predominantly the magnetite (Blhovce Buda and the silica diorite from the borehole KON-1). Because the magnetite is very easily trans-

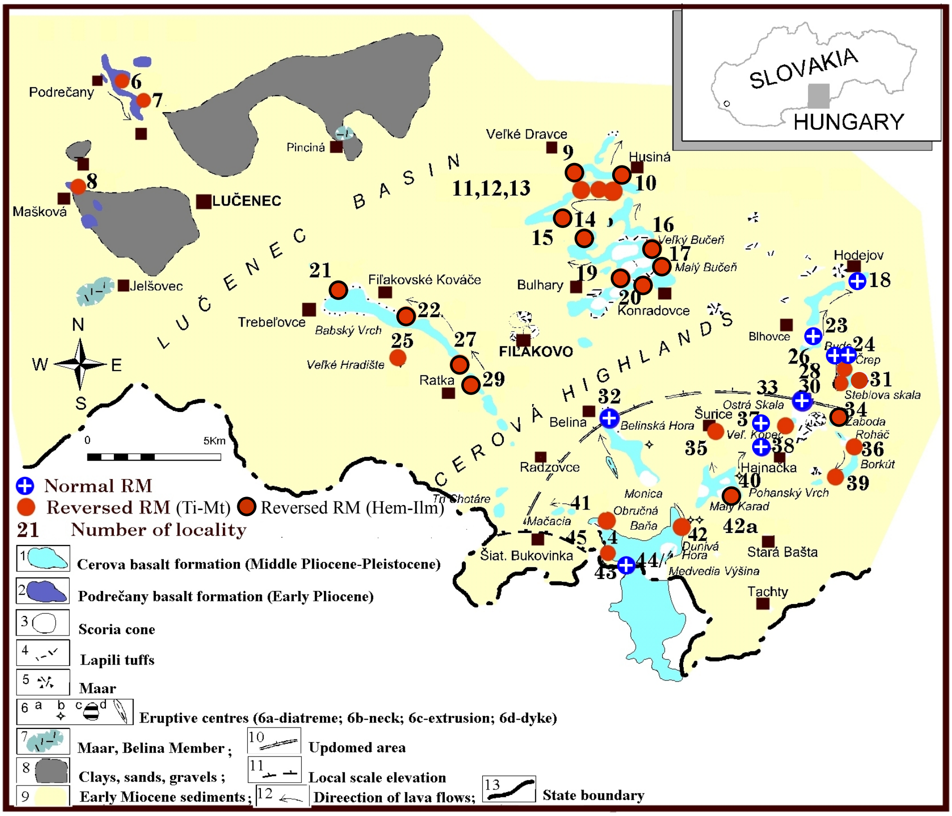
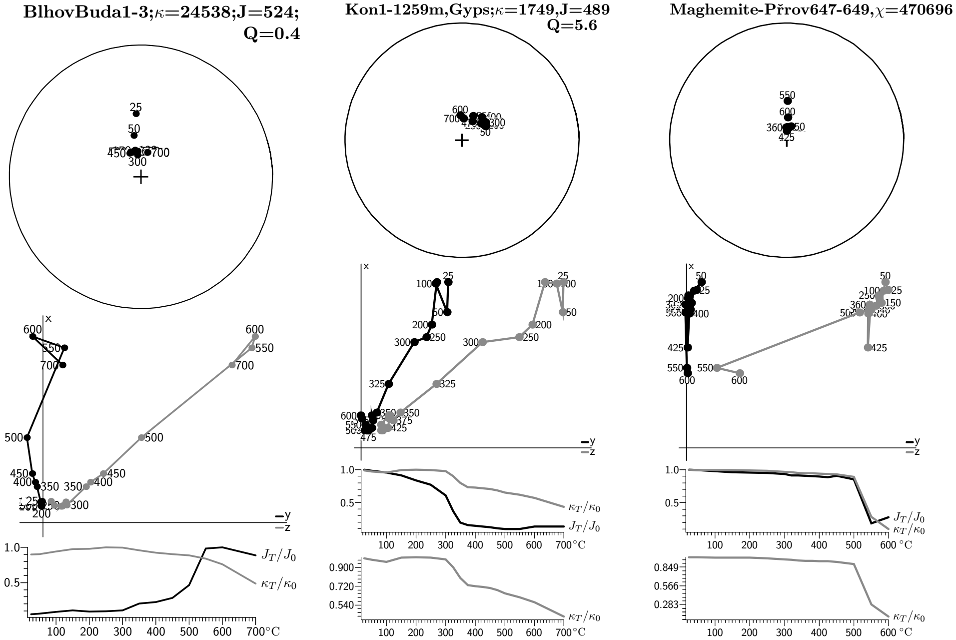


Fig. 1. The geological map according to *Konečný et al. (2001)*, which was additionally modified. The distribution and forms of the Late Miocene to Early Quaternary alkaline volcanics in southern Slovakia – for the geological explanations see the map. For the description of basalts of localities No. 6 to 45 see below.

formed to maghemite, we tested also the synthetic maghemite, to reveal if some disordered-antiferromagnetic phase is created during the thermal treatment of the sample. No sample in Fig. 2 has shown the existence of the disordered-antiferromagnetic phase. So, only normal polarity, without any tendency to acquire the reversed PTRM during inducing of the sample was detected. The samples of basaltic rocks of localities 18, 23, 26, 32, 33, 38 have shown a similar magnetic behaviour as the sample Blhovce Buda, without any Fe-Ti disordered-antiferromagnetic phase.

The olivine basalt of the neck of Šomoška locality (43, 44) contains pre-

Basalts and basaltic tuffs of normal RM of localities shown in blue colour and with white cross inside the circle in Fig. 1. Basalts of localities 24, 26, 32, 33, and basaltic tuffs of localities 18, 23, 38 contain predominantly either the magnetites with small portion of ilmenite or high-temperature oxidized products, such as pseudobrookite, or pseudorutile; for the example of magnetic behaviour see Fig. 2.


BlhovBuda1-3;κ=24538;J=524; Q=0.4

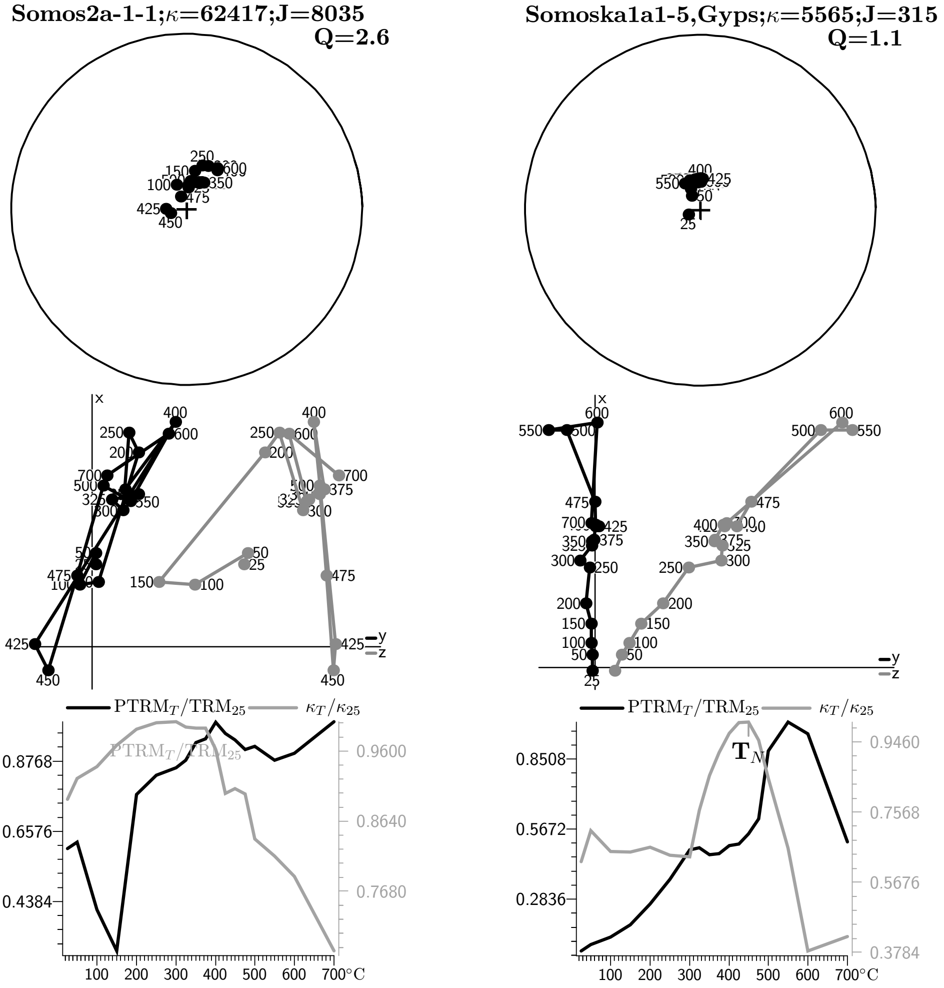
Kon1-1259m,Gyps;κ=1749,J=489 Q=5.6

Maghemite-Přrov647-649,χ=470696

Fig. 2. Thermally-induced of PTRM and the change of magnetic susceptibility at different temperatures of samples with magnetite (natural sample Blhovce Buda locality No. 24), artificially prepared sample of silica diorite porphyry of borehole Kon-1 from the depth of 1259 m, and synthetic maghemite produced in the laboratory in Přerov and then fixed in gypsum. Zijderveld diagrams and stereographic projections; χ represents the mass magnetic susceptibility of synthetized maghemite in $10^{-3}\mathrm{m}^3\mathrm{kg}^{-1}$. Explanations: • (◦) – positive (negative) polarity of RM; κ – magnetic susceptibility (above the pictures: the κ is × 10^{-6} SI Units, and remanent magnetization J is in nano Tesla (nT)); κ_T at T, κ_0 – at 25 °C; J_T (J_0)- remanent magnetization at T and at 25 °C, respectively.

dominantly high portion of Ti-rich titanomagnetite (Ti-Mt) of $T_C \approx 120\,°C$ of high κ, about $62\,000 \times 10^{-6}$ SI units or more. The oxidized phases are also in this basalt. One of the $T_C \approx 230\,°C$ and the second one with $T_C \approx 560\,°C$

Basalts of normal RM of localities 43, 44 shown in blue colour and with white cross inside the circle, see Fig. 1. The results of two tested samples with the titanium-rich titanomagnetites are exemplified in Fig. 3.



Somos2a-1-1;κ=62417;J=8035 Q=2.6

Somoska1a1-5,Gyps;κ=5565;J=315 Q=1.1

Fig. 3. Thermally-induced of PTRM and the change of magnetic susceptibility at different temperatures of natural sample of olivine basalts (Somos2a-1-1) and artificially prepared sample (Somoska1a1-5), both from Šomoška localities (43, 44). T$_N$ – Néel temperature; PTRM$_T$ – partial thermoremanent magnetization acquired at temperature T, TRM$_{25}$ – thermoremanent magnetization at 25 °C. Zijderveld diagrams and stereographic projections; for other symbols, see Fig. 2.

in basalt. A typical behaviour of κ and PTRM of natural basalt of sample Somos2a-1-1 is shown in Fig. 3. We see that κ gradually increases from the room temperature to about 200 °C and then decreases. The PTRM decreases from the room temperature to about 150 °C, due to demagnetization of remaining natural remanent magnetization (NRM) of the Ti-rich Ti-Mt phase. Then the PTRM gradually increases up to 400 °C and then decreases to 550 °C. In the olivine neck there is a part of basaltic body which contains also the disordered-antiferromagnetic Fe-Ti phase, except of the original Fe-Ti oxide. This type of basalt possesses lower κ and differs also in the declination and inclination of RM, about 22 and 8 °, respectively. The behaviour of κ and PTRM of the artificially prepared sample Somoska1a1-5 is shown in Fig. 3. We see that there is the disordered-antiferromagnetic phase with $T_N \approx 440\,°C$ on κ curve in Fig. 3. The PTRM increases from the room temperature to 300 °C, then the increase is hampered to 440 °C (to the T_N) due to a presence of disordered-antiferromagnetic phase, followed by a sharp increase to 560 °C due to a presence of ferrimagnetic magnetite and then decreases. The behaviour of PTRM reflects the presence of the individual magnetic Fe-Ti and Fe phases in the sample. The RM of the whole olivine basalt neck's body is still only of normal polarity, due to only negligible portion of the disordered-antiferromagnetic phase.

The source of the reversed polarity of basalts with reversed RM; for the numbers of localities, see Fig. 4.

All basalts of this group contain the low-temperature oxidized Ti-Mt-es (titanomaghemites), the *self-reversal remanent magnetization bearing, disordered-antiferromagnetic magnetic phases*, with the T_N from 430 to 450 °C as the carrier of the reversed RM. In all 13 localities, a similar behaviour of κ and PTRM as in the sample Somos3a1-5 in Fig. 4 has been detected. In basalts of localities 26 – Črep, 30 – Steblová skala, 31 – E of Steblová skala, there was detected also a small part of high-temperature oxidized disordered-antiferromagnetic phase.

A secondary Fe-Ti phase, so far called an inversion phase (Néel temperature about 450 °C), is detected on the thermomagnetic curves, with the same T_N at the κ curve detected during inducing of PTRM of samples. The disordered-antiferromagnetic Fe-Ti phase was detected in all studied samples. There was detected also the tendency for acquiring the reversed

PTRM in the interval from 250 °C, mostly to 450 °C. Basalts of most localities have shown lower values of κ. The reversed RM of all studied rocks survived mostly to 450 °C, during thermal demagnetization, i.e. to T_N of the disordered-antiferromagnetic phase – to a completely antiferromagnetic arrangement of the magnetic moments of the two sub-lattices of magnetic mineral. As can be seen from the results, there are two Fe-Ti phases in all these basalts. One with ferrimagnetic phase of the Curie temperature about 150–220 °C that acquires the normal PTRM, and one of the disordered-antiferromagnetic state, that acquires the reversed PTRM, during inducing of the sample. The resultant PTRM of the sample is mostly of normal polarity, because the normal PTRM component overprints the reversed one, passing through the first Ti-Mt phase during cooling of the sample to room temperature. For this reason I arranged a new methodical procedure, in which the PTRM of the sample was induced only at a given temperature and then the cooling to room temperature was performed during full compensation of the external magnetic field (see Fig. 5). From these results the more expressive decreasing of PTRM in the temperature interval from 300 °C to 500 °C is evident. Both samples, Maar3-4kG and Velkop2-4kG (in Fig. 5), acquired reversed PTRM of intensity –36 nT and –100 nT, respectively, after inducing at 500 °C and their cooling to room temperature. A similar behaviour has been shown also by other 5 tested samples, but they did not acquire full reversed PTRM under the same conditions as the samples in Fig. 5 (this methodical procedure must be modified, the results may be more conclusive). The results of such basaltic rocks were presented by *Orlický (2004, 2006, 2006a, 2009)* and *Orlický and Funaki (2008).*

The detection of the disordered-antiferromagnetic phase and the reversed RM were revealed also in the youngest basaltic body in Western Carpatian Mts.

The results of the youngest nepheline basanite from the Putikov vŕšok locality, near Nová Baňa town

The samples come from the large basaltic quarry. The age of these basaltic rocks is 140 to 200 k.y. (the latest radiometric data approved the age of only about 95 k.y.). From a number of published paleomagnetic evidences, the polarity of geomagnetic field was of normal orientation at the time of origin of this volcanic body (*Orlický, 2004*). I studied the samples from 22

Basalts of the reversed RM of localities denoted with full red circle containing predominantly the magnetic phase of low-temperature oxidized titanomagnetites of the disordered-antiferromagnetic state with the Néel temperature $\mathbf{T}_N \approx 430 - 450\,^{\circ}$C. Localities (see in Fig. 1): 6, 7, 8, 11, 12, 13, 25, 26, 28, 30, 31, 36, 37, 39, 41, 42, 45; for example of inducing of PTRM, see Fig. 4.

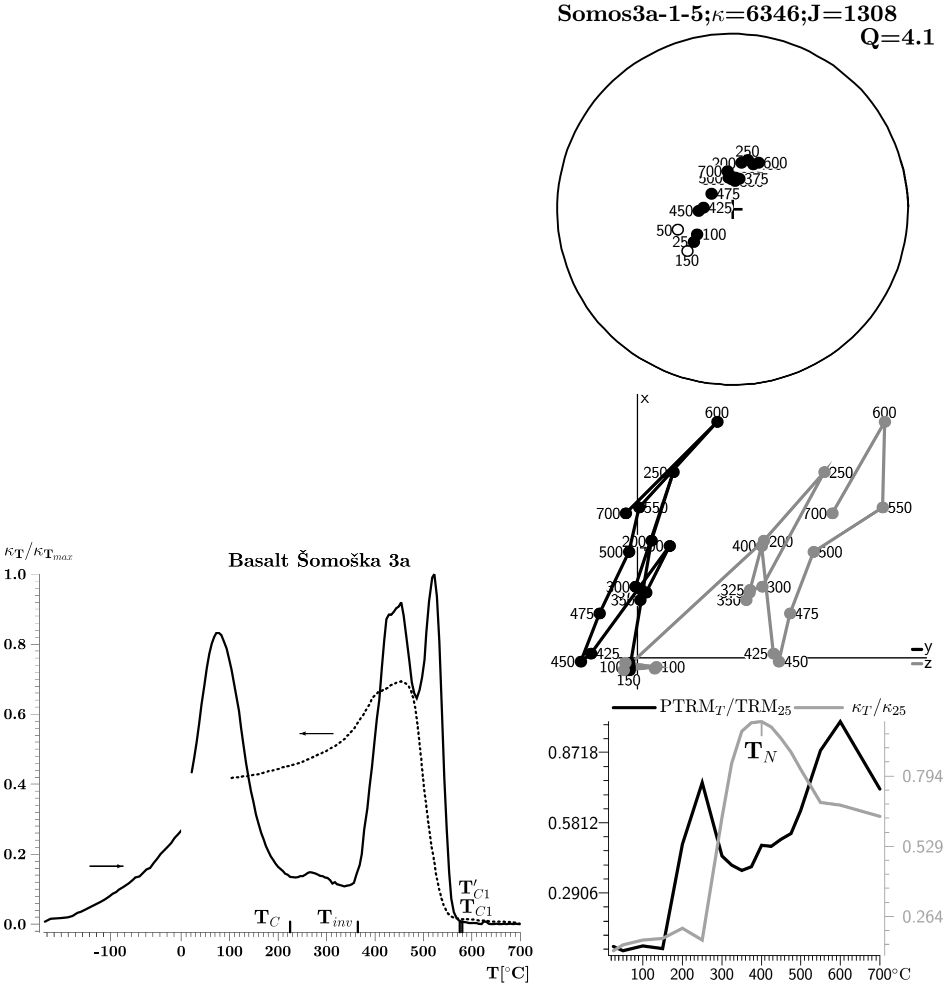
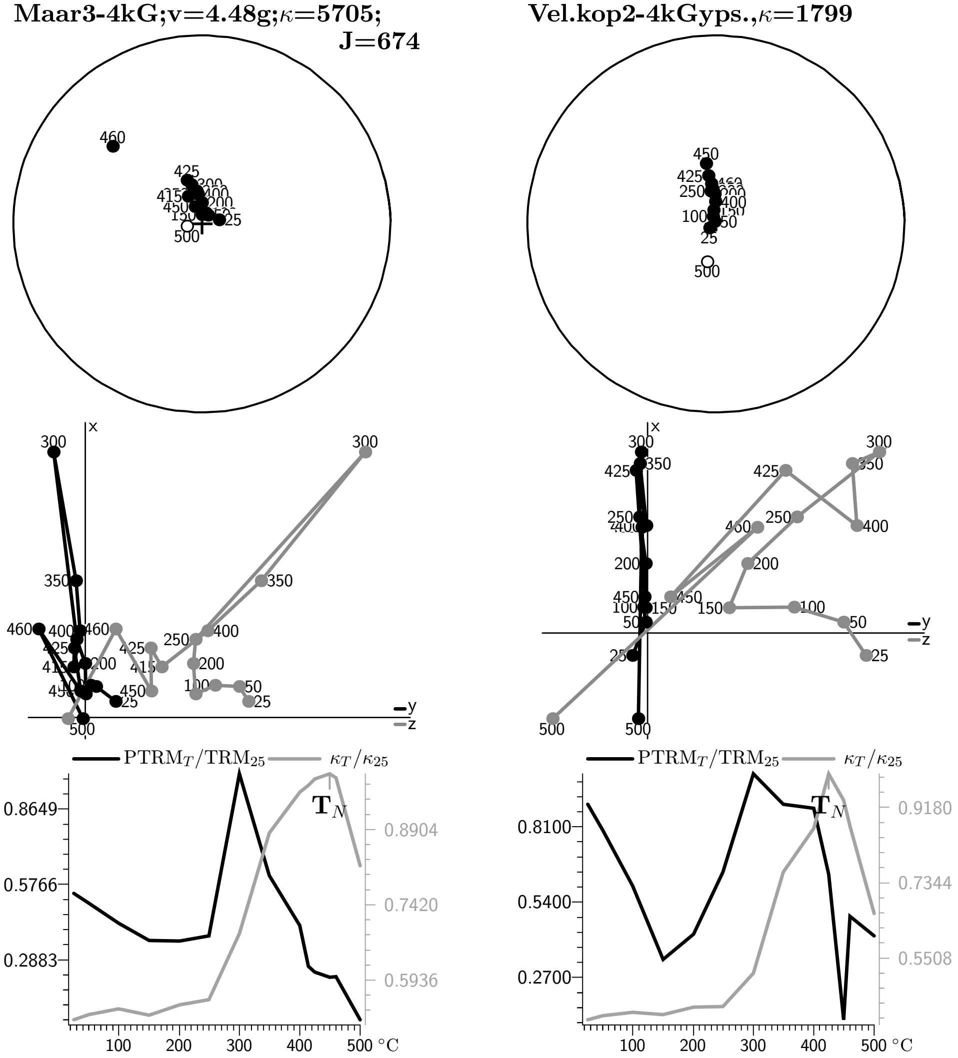


Fig. 4. The Curie temperature measurements of the sample Šomoška 3a (left); the thermal inducing of PTRM and the measurements of the change of magnetic susceptibility at different temperatures of the sample Somos3a-1-5 (right). Zijderveld diagrams and stereographic projections; explanation of other symbols is given in Figs. 2, 3.

Basalts of the reversed RM of localities 28 – Maar, and 37 – Veľký kopec, containing dominantly the magnetic phase of low-temperature oxidized titanomagnetites of the disordered-antiferromagnetic state with the Néel temperature $\mathbf{T}_N \approx 430 - 450\,^\circ$C.



Maar3-4kG;v=4.48g;κ=5705; J=674

Vel.kop2-4kGyps.,κ=1799

Fig. 5. Thermal inducing of PTRM and the change of magnetic susceptibility at different temperatures of artificially prepared samples with oxidized titanomagnetites (separated magnetic fraction fixed in gypsum; Maar3-4kG, Velkop2-4kG). Zijderveld diagrams and stereographic projections; v – weight of basalt grains (g – gram) within a gypsum cylindrical sample. The explanation of other symbols is given in Figs. 2, 3.

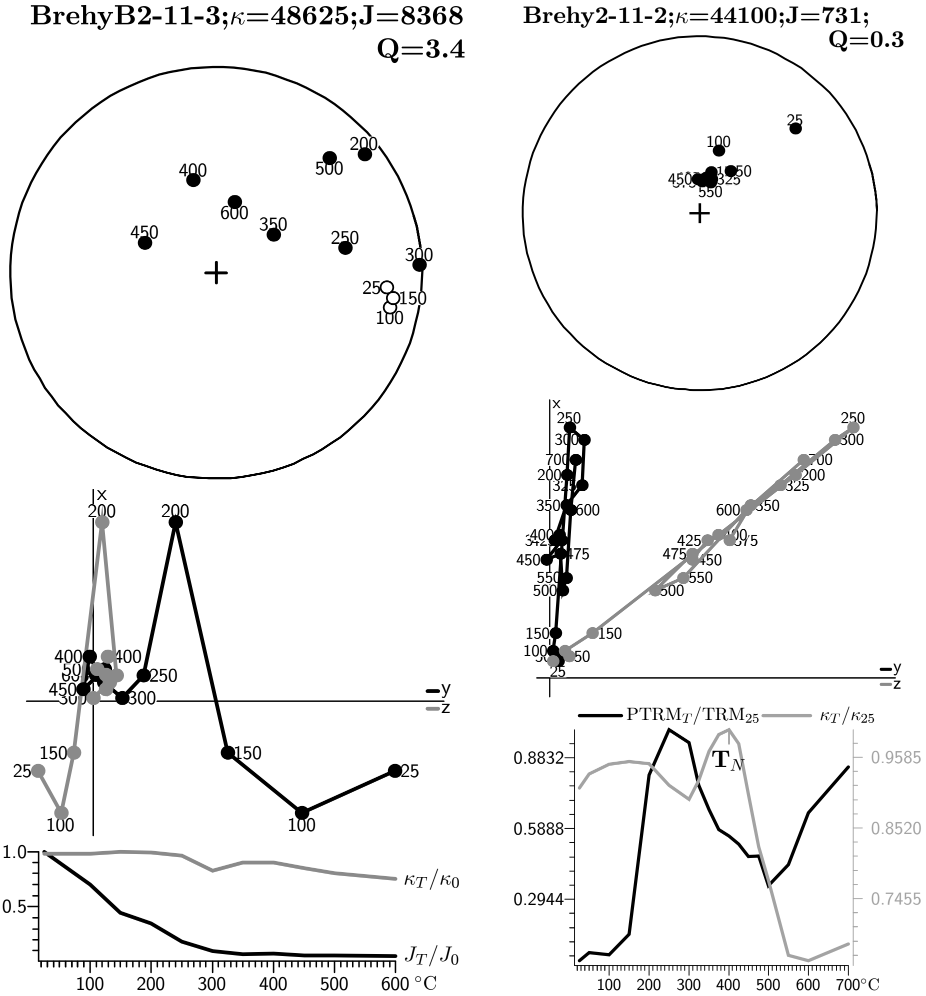
individual places of the large quarry. Basaltic rocks from most of places contained predominantly the Ti-Mt-es, the basalts which were in contact with the surrounded sediments during their ascending on the surface were altered and contained predominantly the magnetites. The basanite rocks from 17 places showed normal RM, but those from 4 positions showed a partially reversed RM. We see from Fig. 5 that the reversed polarity of RM of the sample b2-11-3 survived up to 250 °C during its thermal demagnetization. This reversed RM cannot be the reflection of the reversed geomagnetic field, because the field was in normal orientation in that time. I tested the samples for a self-reversal of RM. The results of the sample b2-11-2 are given in Fig. 2. There are depicted the change of the $\mathrm{PTRM}_T/\mathrm{TRM}_{25}$ and that of the change of magnetic susceptibility (κ) with temperature, except of Zijderveld diagram and the stereographic projection in Fig. 6. Smooth increase and then decrease of κ to 300 °C corresponds to the first Ti-Mt ferrimagnetic phase. During the magnetization the change of $\mathrm{PTRM}_T/\mathrm{TRM}_{25}$ rapidly increases from about 100 to 250 °C, the positive PTRM is acquired, corresponding to the first Ti-Mt phase. Then a rapid increase of κ from 250 is evidenced with a maximum 400 °C. This maximum κ characterizes the Néel temperature of the Fe-Ti disordered-antiferromagnetic phase of the sample. At the same time the decrease of the change of $\mathrm{PTRM}_T/\mathrm{TRM}_{25}$ from 250 °C to about 500 °C is evidenced. This decrease of PTRM corresponds to the inducing of the reversed PTRM in this interval. This effect is evidenced also by the opposite direction of PTRM curves at the Zijderveld diagram. At the stereographic projection there is evidenced only the normal PTRM. The intensity of positive PTRM increased from 750 nT at 250 °C to 19105 nT at 250 °C (difference = 18355 nT, M_1). Decrease of intensity of PTRM represents a value of 12411 nT (M_2) from 250 °C to 500 °C. We see that the absolute value of positive PTRM in the interval 100 to 250 °C dominated over that of absolute value of negative PTRM in the interval 250 °C to 500 °C. It means that the reversed PTRM induced in the interval 250 °C to 500 °C will be overprinted by the normal magnetic phase inducing only positive PTRM. So, the presence of this Fe-Ti phase resulted in a creation of overprinted normal PTRM during inducing at the temperature steps corresponding to inducing of the reversed PTRM. We suggest that the disordered-antiferromagnetic phase is responsible for an inducing of the reversed PTRM in the sample. We assume that if this disordered-antiferromagnetic Fe-Ti phase will be preserved in part of original natural basanite body, the reversed RM, probably of a chemical origin will be at least consolidated and stabilized as the reversed chemical remanent magnetization (CRM).

Basalts of the type presented in Fig. 7 occurred under other conditions as those with the low-temperature oxidized basalts. Both these basalts have contained disordered-antiferromagnetic phases, both are a carrier of the self-reversed RM (if certain the conditions are fulfilled), of course, they are of different composition. In the low-temperature oxidized basalts prevail the titanomaghemite (Ti-Mgh), as dominant magnetism carrier prevails, except of part of original Ti-Mt phase. In the high-temperature oxidized basalts He-Ilm-es have dominated, containing only small portion of Ti-Mt phase, or with this phase completely absent. The visualization of the disordered-antiferromagnetic phase through the increase of κ and so a detection of the Néel temperature in Hem-Ilm bearing basalts is mostly less expressive than in those of the low-temperature Ti-Mgh bearing basalts. In general, the He-Ilm bearing basalts possess the lower values of bulk κ, but mostly higher magnetic stability of RM than those of the Ti-Mgh, or Ti-Mt bearing basalts. We see in Fig. 7 that the reversed RM of the sample Polič1-1-1 survived up to 500 °C (in other samples more) during thermal demagnetization of the sample. In the course of inducing of the sample Poličko1-1-1 (Fig. 7) the PTRM acquired the positive polarity. But in the interval 500–700 °C most of tested samples acquired the self-reversed PTRM, corresponding to a presence of the Hem-Ilm disordered-antiferromagnetic phase. Similar behaviour with the reproducible self-reversed PTRM was revealed in a very large amount of basic, intermediate and volcano-sedimentary volcanics (*Orlický, 2001, 2002, 2002a, 2002b, 2002c, 2002d, 2003, 2003a, 2004, 2006, 2006a, 2006b* and *Orlický and Funaki, 2008*).

2. The proposal of an original model for the explanation of sources of normal and reversed RM in the rocks

I have accounted for an origin of the reversed RM of volcanics on the basis of experimental results and the self-reversal hypothesis. I have proposed an original model about the sources of normal and reversed RM of rocks

The nepheline basanite samples, originally of the reversed RM, containing the low-temperature oxidized disordered-antiferromagnetic phase of the Néel temperature T$_N$ ≈ 400 °C. The age of basanite is about 140–200 k.y.



BrehyB2-11-3;κ=48625;J=8368 Q=3.4

Brehy2-11-2;κ=44100;J=731; Q=0.3

Fig. 6. Thermal demagnetization of sample Brehy B2-11-3 and inducing of PTRM and the change of magnetic susceptibility at different temperatures of natural nepheline basanite sample Brehy B2-11-2. Zijderveld diagrams and stereographic projections. The explanation of other symbols is given in Figs. 2, 3.

Basalts of the reversed RM containing the high-temperature oxidized Fe-Ti oxides, dominantly with the hematite-ilmenite (Hem-Ilm) phase of the disordered-antiferromagnetic state with the Néel temperature $\mathbf{T}_N \approx 460 - 470\,^\circ$C. Localities (see in Fig. 1): 9, 10, 14, 15–17, 19–22, 27, 29, 34, 35, 40; the example of inducing of PTRM see Fig. 7.

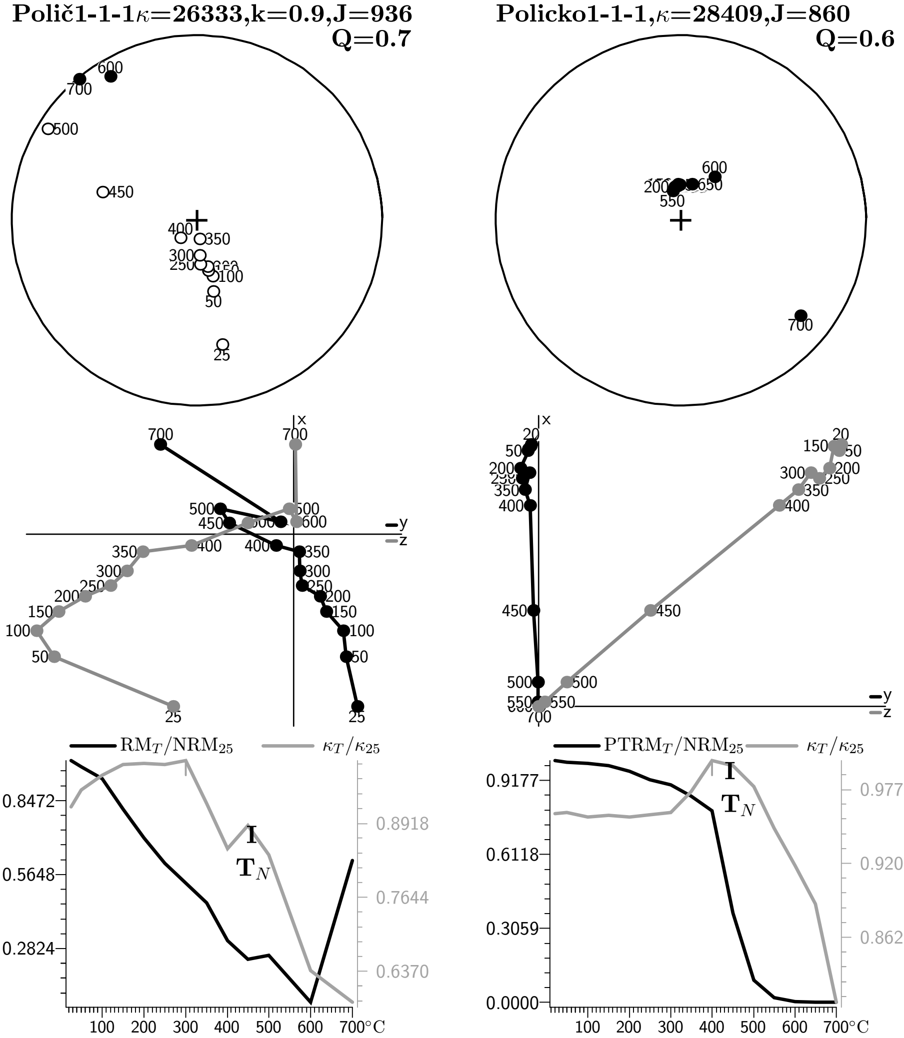


Fig. 7. Thermal demagnetization of sample Polič1-1-1, inducing of PTRM of sample Poličko1-1-1 and the change of magnetic susceptibility at different temperatures. Zijderveld diagrams and stereographic projections; RM$_T$–remanent magnetization at temperature T, NRM–natural remanent magnetization. The explanation of other symbols is given in Figs. 2, 3.

(*Orlický, 2006, 2009, 2010, 2010a*).

The principle of the model: The NORMAL (positive) RM have been present in the following rocks:

1. The Ti-rich titanomagnetite (Ti-Mt, $Fe_{3-x}Ti_xO_4$) bearing rocks (mostly basalts). These rocks have shown high bulk magnetic susceptibility (κ, mostly from 40 to 100 × 10^{-3} SI units), high parameter $x \approx 0.6$ and low Curie temperature ($T_C \approx 170\,°C$) with low oxidation parameter $z \approx 0.0$. The RM of these rocks is of thermoremanent (TRM), of primary origin.
2. The magnetite (Fe_3O_4) bearing rocks. The RM of the intrusive rocks is mostly of primary origin, (κ from 20 to 30 × 10−3 SI units, The T_C is near to 580 °C. The rocks are characterized also by a Verwey transition temperature ($T_V \approx -155\,°C$). In the effusive and extrusive rocks it is frequently of the secondary, TRM, or CRM origin. Some altered basalts have attained a very high κ (40 to 80 × 10^{-3} SI units).
3. The hematite (Fe_2O_3) bearing rocks, mostly more acidic volcanics, e.g. rhyolites and andesites. The hematites are mostly not of primary origin, but have been created from the Ti-Mt-es or the ilmenites during their oxidation. They are the last members of oxidation and frequently are present along with non-magnetic simple oxides of Ti, e.g. with rutile, brookite, pseudobrookite, pseudorutile etc. The hematites are of course frequently present in the rocks containing the hematite-ilmenites, often along with the associations of titanomagnetites. Such types can acquire also the self-reversal of RM of rocks. More detailed results concerning the magnetite and hematite bearing rocks are given in *Orlický (2010a).* The altered rocks with the hematite and the mentioned co-products have occurred in the continental volcanics, but in submarine volcanics are very rare, or entirely absent.

The source of the reversed remanent magnetization

The reversed RM can be found only in the rocks which contain either the low-temperature oxidized titanomaghemites of the disordered-antiferromagnetic state, or the high-temperature oxidized titanomagnetites, predominantly with the hematite-ilmenite disordered-antiferromagnetic phase. In most of oxidized Fe-Ti rocks, the original titanomagnetite phase with disordered-antiferromagnetic phase is present. The original Ti-Mt phase is characterized by low Curie temperature, mostly about 120 to 200 °C and by relatively high bulk κ. The disordered-antiferromagnetic Ti-Mgh phase is characterized by higher Curie temperature, mostly over 200–250 °C and having usually low values of bulk κ (lower than 40×10^{-3} SI units). The values of κ of rocks is very variable, depending upon the stage of development of the disordered-antiferromagnetic phase. The RM of the rocks is dominantly of CRM origin.

The highly oxidized Ti-Mt bearing volcanics with the reversed RM contain the disordered-antiferromagnetic phase predominantly with the hematite-ilmenites. They are present frequently in continental volcanics, but in submarine igneous rocks are rarely present.

A correlation between opaque petrological parameters and the polarity of RM was found previously by other authors. *Balsley and Buddington (1954)* revealed a correlation between the type of magnetic Fe-Ti minerals and that of polarity of RM of metamorphic rocks in the Adirondack Mountains. Rocks containing the magnetite invariably showed normal polarity of RM, but the reversed polarity of RM was detected in the rocks containing the ilmenite-hematite (Ilm-Hem) solid solutions. The author of this article has proposed an enlarged model of the sources of normal and reversed RM of rocks (*Orlický, 2010*).

Because the alterations of magnetic minerals result in heterogeneous phases in natural rocks, these minerals are not of perfect stoichiometry.

3. The application of the model for an explanation of the RM of submarine volcanics, using and comparing the results of other authors

I have applied the suggested model and the field-reversal hypothesis to compare it with the results of the submarine basalts. The analyses of the Fe-Ti oxides, the Curie temperatures (T_C), bulk magnetic susceptibility (κ), and the polarity of RM of rocks have been performed for the comparisons.

1. The Ti-rich Ti-Mt bearing basalts: they are present in the Mid-Atlantic Ridges and flanks in the FAMOUS AREAS, in the Hole U648B, in the Hole 483 in the East Pacific Rise (EPR), in 13 °N Sites, in the EPR2 Site, in Overlapping spreading center (OSC), near 9 °N of the EPR (with the positions of high magnetization), in small portion also in

places of Galapagos Spreading Centre (GSC, hole 507B), all of very young age ranging in 0.01 to 0.69 m.y. But they occurred also in older 3.5 m.y. old basalts in the Hole U1301 (see in Fig. 8). The Ti-rich Ti-Mt bearing basalts of all the mentioned localities showed low Curie temperature and predominantly normal polarity of RM, corresponding to that presented in the model.

2. The magnetite bearing volcanics: there have been published the results of serpentinized peridotites of the Holes 895E and 895D (Fig. 8) by *Kelso et al. (1996)*. During the metamorphism of the ultramafic peridotites (dunites and harzburgites) the serpentinization results in an alteration of the previous magnetic Fe-Ti minerals and creation of the magnetite. The magnetite was detected with Curie temperatures of $T_C \approx 560$ to $585\,^\circ$C and with Verwey temperature of $T_V \approx -150\,^\circ$C. Peridotites of the 895E hole were more altered and more magnetite portion was present in the altered material than in that of the 895D hole. So, there were 54 samples of normal polarity of RM and only 6 samples of reversed polarity in the 895E hole. But 16 samples of normal and 14 samples of reversed RM from the less oxidized rocks of the 895D hole were showed. The results have proved the expected predictions in the model, that a magnetite itself is not a carrier of the reversed RM in the rocks.

The source of the reversed RM

The low-temperature oxidized disordered-antiferromagnetic Ti-Mgh phase bearing rocks: They are frequently present in the submarine volcanics of the: Mid-Atlantic Ridge and its flanks, in the Famous areas of the Leg 37-Site 332 of 3.32 m.y. age rocks, in the Holes 395 of 7.0 m.y. old rocks, 396B of 13.0 m.y. old rocks, the Bermuda Triangle area – Holes 417A, 418A of 108 m.y. old basalts, the Pacific Ocean – 3.5 m.y. old basalts from the U1301B hole, the 482, 483 holes, the 0.7 m.y. rocks of the reversed Site of the EPR, the OSC Sites and from GSC of older basalts (Hole 504B) of 0.6 to 6.2 m.y. The basalts (mostly pillow basalts) of these localities have been largely altered-maghemitized. They showed high T_C (320–380 °C), some of them with a secondary low-temperature oxidized phase, exceptionally with $T_C \approx 580\,^\circ$C. All basalts showed mostly the reversed RM. E.g. in older basalts of the 504B hole, 17 samples were normally magnetized, but 76 samples were of the reversed RM. Basalts of 417D of the age of 108 m.y.

were nearly all of reversed RM in the interval of 345 to 710 m. But in the hole U1301B the sample of reversed RM are dispersed among the normal RM samples in the interval 465 to 580 m. It is very hard to expect that the geomagnetic field has changed its polarity so frequently in very short periods. The rocks with the reversed polarity of RM have been considered as the spurious ones by the respected authors.

The data of the submarine igneous rocks under consideration have been published by *Bina (1990); Furuta (1993); Kelso et al. (1996); Kirpatrik (1978); Levi (1983); Petersen (1979); Prévot et al. (1979); Sager et al. (2008); Sempere et al. (1988).*

The explanations of data in Fig. 8: FAMOUS – French American Mid Ocean Undersea Study and Leg 37–Site 332 (*Prévot et al., 1979*); EPR–(13°N) – The East Pacific Rise. Basalts from the ridge axis (age < 0.01 m.y), from 0.7 m.y. old crust on the flanks of the spreading Center, and basalts from the OSC – overlapping spreading centers near 9°N on the East Pacific Rise – high magnetized zone (*Sempere et al., 1988*); 648BU – recent basalts *(Bina, 1990);* 396B – 13.0 m.y. basalts (*Petersen, 1979; Kirpatrick, 1979*). There are different contents of TiO_2 in normally and reversally magnetized rocks; U1301B – 3.5 M.y. basalts (*Sager et al., 2008*). In 53 of 318 positions of basalts is a reversed polarity; GSC – Galapagos Spreading Center *(Levi, 1983);* Basalts Leg 54: Sites 424 – 0.63, 425-1.8 M.y.; Leg 70: Sites 506-0.54, 507-0.69, 508-0.85, 510-2.73 M.y. Also Site 504B-6.2 M.y. at 83.5° W; 895–Serpentinized peridotites (*Kelso et al., 1996*). Samples from Hole 895E were more altered than from the Hole 895D. Only 6 samples out 60 were reversed RM in of the Hole 895E and 14 reversed and 16 normal RM in the Hole 895d; dunites $\kappa = 53{,}000$ SI, harzburgites $\kappa = 23000$ SI.

Quite good correlations have been achieved between the type of magnetic mineral bearing rock and that of polarity of remanent magnetization, applying the present model. Because the correlations of the types of magnetic Fe and Fe-Ti oxides of the respective polarity of RM with the basic principle of the suggested model have been achieved only of the limited numbers of volcanics, we will continue with gathering of the additional data about the submarine volcanics, to make the model more precise.

Except for the correlation of our model with the results of other authors, we applied the method of inducing the PTRM and the measurement of the change of κ with temperature for some population of igneous submarine

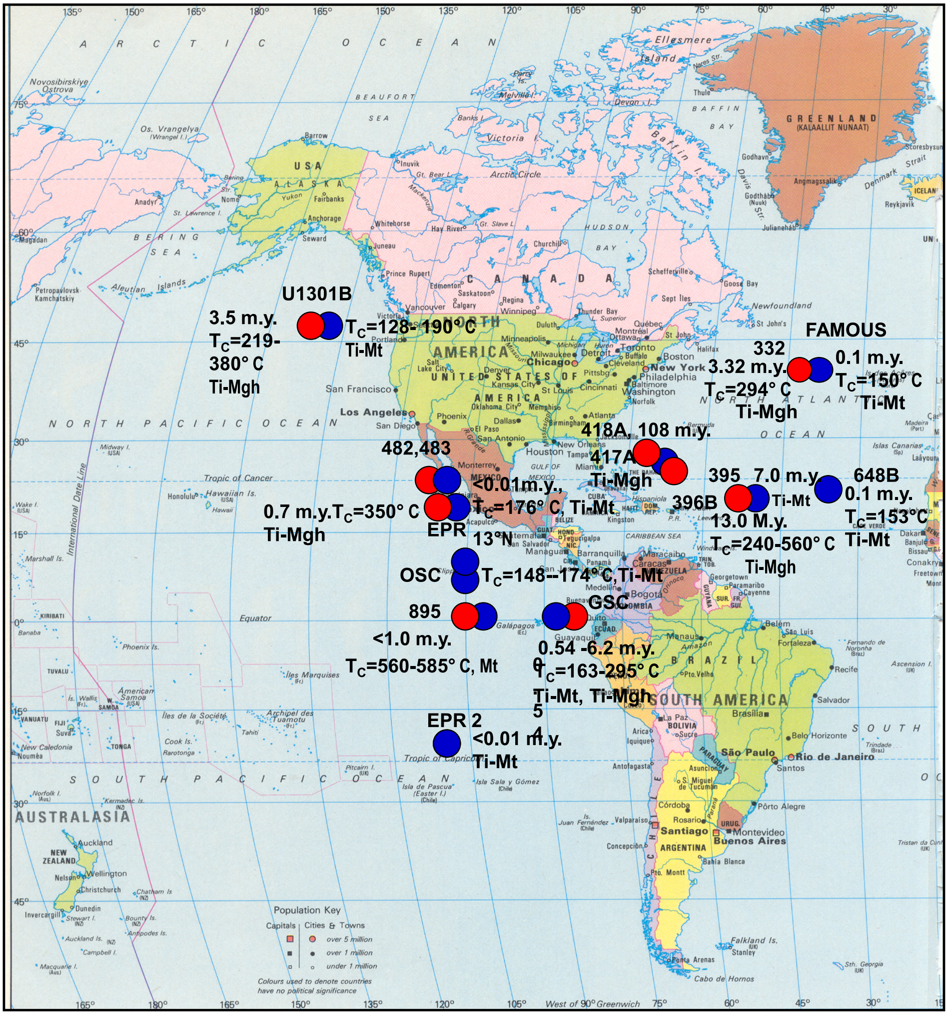


Fig. 8. A sketch map of magnetic data: 🔵 – normal, 🔴 – reversed RM T_C – Curie temperature of Fe-Ti minerals; other symbols are explained below.

rocks from the Holes 794 and 797 (from Yamato Basin, near Japan). The complete results will be published with the author *Vigliotti (1992)* who provided the samples. Only in two tested samples from the Hole 794 and in four tested samples of the first group from the Hole 797 the *self-reversal RM bearing disordered-antiferromagnetic Fe-Ti phases* of low-temperature oxidized Ti-Mt-es with the T$_N$ of 420–435 °C have shown. These phases have not been completely developed so far. According to *Vigliotti (1992)*, predominantly the negative inclinations in the central part of the borehole 794 were detected. In the basalts from the interval 570 to 807 mbsf (meters below sea floor), representing 18 lithological units of the Hole 797, the normal polarity of RM was detected. While in the first group (554–713 mbsf) are the low-temperature oxidized Ti-Mt oxides in the basalts (with an average $\kappa = 24993 \times 10^{-6}$ SI units, in the second group (724–884 mbsf) are the basalts with high-temperature oxidized Ti-Mt-es, with the predominant portion of magnetite (an average $\kappa = 82361 \times 10^{-6}$ SI units).

4. Discussion and conclusions

I studied the magnetic and paleomagnetic characteristics of the Pleistocene to Quaternary basalts from the West Carpathian Mountains. I have revealed the existence of the so-called *self-reversal remanent magnetization bearing disordered-antiferromagnetic Fe-Ti phases*, with the Néel temperatures of either T$_N$ = 430 – 450 °C (the Ti-Mgh phases), or with T$_N$ = 460–470 °C (Hem-Ilm phases). In the previous literature the phases were described only by the change of κ with temperature (increase of maximum mostly at 450 °C, or at 470 °C, respectively), and a parallel decrease of PTRM in this temperature interval. What is very important is that these phases are the only sources of the reversed RM, probably of the CRM origin. The above mentioned phases were revealed on the basis of laboratory measurements of the change of magnetic susceptibility of rocks with temperature. In parallel the existence and the inducing of the self-reversed RM was detected through inducing the partial thermoremanent magnetization (PTRM) in natural and in artificially prepared basaltic samples. As has been described above, the basalts of Southern Slovakia were differentiated into those of the magnetite and Ti-rich Ti-Mt bearing rocks with normal polarity of RM, those with the presence of the self-reversal RM bearing disordered-antiferromagnetic Ti-Mgh phases of the T$_N$ = 430 to 450 °C, and those of the disordered-antiferromagnetic Hem-Ilm phases of the T$_N$ = 460 – 470 °C, both of only reversed RM of the self-reversal origin.

I have revealed the *self-reversal remanent magnetization bearing disordered-antiferromagnetic phases* and the reversed RM also in the Neogene volcanics and the Paleozoic melaphyres of the Western Carpathian Mts., cited in the works above, but also in the Eocene to Miocene age volcanics from České Středohoří Mts. (*Orlický, 2002*), in the Cretaceous to Jurassic nepheline basanites from Nigeria and the Cretaceous basalts from the Syrian Arab Republic (*Orlický, 2003c*), and the Cambrian volcanics from the Red Sea Hills from the Sudan Republic (*Orlický, 2003b*).

I also tested some non-oriented igneous rocks from different locations of the Globe (*Orlický, 2009*). A goal of the work was to find and identify the low-temperature oxidized Ti-Mgh – disordered-antiferromagnetic phase. This phase was detected in the following volcanics: in the oxidized basaltic scoria from Tenerife volcano (28.209° – 28.109°N, 16.668° – 16.808°W), $T_N \approx 450\,^\circ$C, in the Cascade Range Volcanoes, USA – the dacite from Crater Lake (48.993 °N, 122.008 °W) $T_N \approx 450\,^\circ$C, the andesite from the Rainier volcano (age 20 k.y., 46.85 °N, 121.842 °W) $T_N \approx 400\,^\circ$C. In the basaltic scoria of the Death Valley, USA (age either 700 k.y. or more, 36.306 °N, 117.08 °W), $T_N \approx 410\,^\circ$C, in the biotite-hornblende andesite of Kaimeno-Chorio locality (37.618 °N, 23.332 °E; 2.26 k.y.) from Methana Peninsula. All these Fe-Ti disordered-antiferromagnetic phases containing volcanics will acquire the reversed CRM at some point in future, despite of their current normal polarity.

The self-reversed origin of reversed RM of submarine basalts was revealed also by *Doubrovine and Tarduno (2004)*, in basalts also by *Krása et al. (2005)*, also by *Pan et al. (2006)*. I have been studying the literature concerning the problem of the reversed RM bearing volcanics and the sedimentary rocks. There have been found the relations between the increase of magnetic susceptibility, and so a detection of the so-called disordered-antiferromagnetic Néel temperature and the reversed RM of the concrete rock. The mentioned increase of κ has been explained by the authors, mostly in terms of the alteration of a concrete magnetic mineral to other one (e.g. the Fe-sulphide into the magnetite), or so. These results, despite that they are available, must be gathered together very carefully, because in most articles there have not been presented any particular procedure for a detection of the so-called disordered-antiferromagnetic phases in the rocks and so, no correlations may be realized between these phases and the reversed RM itself.

I have presented the original model based on the principle that the magnetite, hematite and Ti-rich titanomagnetite bearing rocks, without any disordered-antiferromagnetic phases, carry only normal – positive RM. The *self-reversal remanent magnetization bearing disordered-antiferromagnetic magnetic phases of Fe-Ti oxide solid solutions* carry only the reversed remanent magnetization in the rocks. This model has been involved to explain the reversed or normal RM of submarine igneous rocks. But only a comparison of the data from literature with the suggested model was undertaken. I will continue with the investigation of this problem to verify that there exists the *self-reversal remanent magnetization bearing disordered-antiferromagnetic magnetic phases of Fe-Ti oxide solid solutions* in all the reversally magnetized continental and submarine rocks.

We can suggest that the reversal remanent magnetization of rocks is due to the existence of the *self-reversal remanent magnetization bearing disordered-antiferromagnetic magnetic phases of* in the rocks, but not due to the existence of the reversals of the geomagnetic field.

So far, we have not suggested a complete self-reversal mechanism in magnetic minerals concerned. Previously, I proposed the model based on the ionic reordering in Fe-Ti ferrimagnetics, taking into account the magnetic moments of A and B sub-lattices (*Orlický, 2009*). This model should be modified in order for the results to be more conclusive.

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