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A new original conception in rock magnetism, paleomagnetism and geomagnetism: An origin of the reversed magnetization of rocks on Earth

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Abstract: So far the field-reversal theory has been accepted to account for the reversed remanent magnetization (RM) of rocks on the Earth. *Orlický (2014)* revealed a frequent occurrence of the antiferromagnetic (AFM) Fe-Ti oxides in the rocks. Now I have renamed these minerals as the Fe-Ti ferrimagnetic-antiferromagnetic chemical phases (Fe-Ti FriM-AFM ChPs). They may have either cubic spinel, or tetragonal spinel symmetry, respectively. They behave as the Fe-Ti polycrystalline materials. These Fe-Ti FriM-AFM ChPs are the two sublattice A and B ChPs, with some specific magnetic behaviour. The titanomagnetite (Ti-Mt, Curie temperature, $T_C = 230\,^{\circ}C$; FriM alignment) and the titanomaghemite (Ti-Mgh, Néel temperature, $T_N = 450\,^{\circ}C$; AFM alignment) containing rocks have been identified as the representants of the the Fe-Ti FriM-AFM cubic spinel ChPs. The interactions with the magnetizing field, with the Weis molecular fields (Weiss-Heisenberg forces) have generated the reversally oriented internal field. The reversally oriented spontaneous magnetization has arosen in the rock. This internal field has been identified as the most important phenomenon leading to the production of the reversally oriented magnetization in the Fe-Ti FriM-AFM ChPs containing rocks. The equations expressing the magnetic behaviour of the magnetic susceptibility (κ) of rocks versus temperature have been derived. The Fe-Ti FriM-AFM cubic spinel can undergone the transition in favour of the Fe-Ti FriM-AFM tetragonal spinel in the rocks, due to a change of the thermodynamic conditions in nature. The reversed RM has supposed been inparted from the Fe-Ti FriM-AFM cubic spinel during this alteration-transition processess. Such tetragonal spinel is more stable and it is able to survive in the rocks in nature. The results of laboratory magnetization of the selected groupings of rocks have been presented below. The basic laboratory methods for the detection of the magnetic behaviour of the Fe-Ti FriM-AFM ChPs containing rocks are described as well. The presented results have shown that we do not need to apply the field reversal theory, because I have revealed the realistic mechanism which is able to generate the reversed RM of rocks under a presence of the normal geomagnetic field.

Key words: The Fe-Ti FriM-AFM cubic and tetragonal spinels, exchange interactions, Weiss molecular field, the reversed magnetization of rocks

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1. Introduction

The most frequent magnetic minerals in the rocks are the Fe-Ti solid solutions, titanomagnetites (Ti-Mt-es, $Fe_{3-x}Ti_xO_4$) and titanohematites (Ti-hem-es, $Fe_{2-x}Ti_xO_3$). The Fe-Ti magnetic minerals have been largely studied by many authors as the carriers of magnetic and paleomagnetic properties of rocks. Many specialists have believed that these minerals are very stable and are able to survive from their origin up to the present in an unchanged state in nature. I have found that most of the magnetic minerals have undergone dramatic transformation not only in chemical composition but also structurally.

I revealed a very frequent occurrence of the Fe-Ti antiferromagnetic (AFM) phases in the rocks (*Orlický, 2014*). They could be now designated as the two sublattice containing polycrystalline chemical phases (ChPs). In such ChPs the ferrimagnetic-antiferromagnetic (FriM-AFM) alignment exists and they have produced a negative exchange interaction between the two sublattices (it was anticipated by *Néel (1948)*, in (*Goodenough, 1963*).

The Fe-Ti FriM-AFM phases originated nearly in each type of rock on the Earth. Some of them have been preserved, but most of them were either decayed or transformed to the other type of AFM phase, depending on thermodynamic conditions. I discovered the Fe-Ti FriM-AFM ChPs in about 288 samples from 78 localities of volcanic rocks and in about 346 samples of the sedimentary rocks (*Orlický, 2014*).

The two basic phenomena: the Fe-Ti FriM-AFM ChPs in the rock, the local molecular fields with so called Weiss-Heisenberg forces (*Néel, 1971*) are decisive for the acquirement of the reversed magnetization in the rock. It is a completely new field in paleomagneetic research, because such category of knowledge is missing completely in standard literature.

2. A review about the self-reversal origin of rocks

2.1. The results of rocks having the self-reversed origin of RM

I have completed my results with those of available works of other authors. A dominant topic is a solution of an of origin of the reversed RM of rocks.

2.2. The rocks containing the Hematite-Ilmenite solid solutions

Many scientific papers and books were devoted to the self-reversal origin of the reversed RM of the Haruna rhyodacite pumice, erupted in Japan about 1420 years ago (*Nagata, 1952; Ishikawa and Syono, 1963; Stacey and Banerjee, 1974; Orlický et al., 2000; Orlický and Funaki, 2000a; 2000b; 2001; Ozima and Funaki, 2001; Orlický, 2011*) and Late Brunhes dacite from Mt. Natib, from Philippines (*Kennedy, 1981*) and dacite and dacite pumice pyroclastics having ages between 9000–10000 years, from Mt. Shasta, California (*Lawson et al., 1987*), the pyroclastics and andesitic pumice from the disastrous 1985 eruption of the Nevado del Ruiz, Colombia (*Heller et al., 1986; Haag et al., 1990*), dacite pumice from the 1991 Pinatubo eruption from Philippines (*Ozima et al., 1992; Hoffmann and Fehr, 1996; Bina et al., 1999; Goguitchaichvili and Prévot, 2000*), and the dacite ash from the 1991 Pinatubo eruption from Philippines (*Orlický and Funaki, 2001*), the synthetic hematite – ilmenite solutions (*Carmichael, 1961; Hoffman, 1975; Lawson et al., 1981; Nord and Lawson, 1989; 1992; Westcot-Lewis and Parry, 1971*).

The rhyo-dacite pumice from Haruna volcano and from Pinatubo volcano contains the hem-ilm with a composition of ilm_{45} to ilm_{75}. Many petrographic types of acidic, intermediate and basic volcanic rocks contain the hem-ilm-es with ilm composition of ilm_5–ilm_{12} to ilm_{15}–ilm_{25}. According to *Nagata et al. (1951)* the reversed RM of Haruna rhyodacite pumice resulted from the hem-ilm phase acquiring a self-reversed thermoremanent magnetization (TRM). The magnetite-ulvöspinel (Mag-Usp) is also in these rocks. The ratio of the Mag-Usp to Hem-Ilm was approximately 100 to 1 in the Haruna rocks (*Nagata et al., 1951; Uyeda, 1958*). For these rocks it is typical that their magnetic properties differ from sample to sample. Some samples have shown only normal polarity, while other samples showed only reversed RM, due to the different state of Fe-Ti alterations. The authors ascribed the dominant remanence signal to the hem-ilm phase. *Uyeda (1958), Ishikawa and Syono (1963)* found that the acquisition of the self-reversed TRM requires that the bulk of the ferrimagnetic sample be ordered and that it needs to contain a second phase. They called it as the x phase. They proposed the antiphase-contact-two phase model to explain the self-reversal TRM of the rocks of Haruna volcano. The striking result is that the reverse TRM exists in the intermediate state and it is not found in either the fully

ordered or fully disordered state. I was very surprised that such negligable amount of the ilmenite-hematite grains – 1 grain among of 100 Ti-Mt grains is able to generate the relatively intense reversed RM in the rock.

I found the AFMP in these rhyodacites (*Orlický, 2011*). The Néel temperature of this phase is $T_N = 420\,^{\circ}C$ and there is also the hem-ilm of $T_C = 230\,^{\circ}C$, and Ti-Mt of $T_C = 520\,^{\circ}C$) in the rock. The AFM phase corresponds to the anonymous x phase, which was predicted by *Ishikawa and Syono (1963)* in the Haruna dacite.

2.3. The rocks containing the titanomaghemites

Havard and Lewis (1965) studied the basalt lava flows from India which showed self-reversed RM during laboratory magnetization of samples. *Ozima and Ozima (1967)* studied 8 samples of dredged submarine basalts. Three samples showed self-reversed TRM when they were heated to 300 °C during 30 minutes and cooled to room temperature in geomagnetic field. Similar results were achieved by *Ozima and Larson (1968).* Only normal TRM was induced after repeated magnetization in the sample. The authors suggested some models and mechanism of self-reversed magnetization of the rocks, based on either magnetostatic or exchange interactions of the two Fe-Ti phases, differing by Curie temperatures. *Krása et al. (2005)* studied the basalt samples from Olby (France) and Vogelsberg (Germany). During acquisition of a thermoremanence the two phases are magnetically coupled, leading to a remanent magnetization of the two Curie temperature phases which is antiparallel to the applied external magnetic field. They suggested coupling of the two phases by magnetostatic interaction which resulted in the self-reversal origin of RM in the rock. *Heller and Petersen (1982)* studied the self-reversal of young basalts from Olby and La Shamp area, from Massif Central, France. *Doubrovine and Tarduno (2004)* reported on partial and complete self-reversal due to N-type behaviour in some oceanic basalts. They suggested that this magnetization is carried by the Ti-Mgh Fe-Ti associations. They detected a normal PTRM until 250–275 °C, followed by a component antiparallel self-reversed to the normal applied magnetic field, between 275–350 °C. At higher temperatures they again observed the acquisition of a PTRM oriented parallel to the applied field. No self-reversal of the same sample was observed in repeated

runs. Hemoilmenite, if present, would retain its self-reversing properties after such thermal treatment. *Pan et al. (2006)* studied the Thellier-Coe paleointensity of Al-substituted Ti-Mt-es of the Neogene Hannuoba basalts from northern China. The laboratory experiments were done in argon gas to prevent oxidation of Fe-Ti oxides. The samples acquired the thermoremanence with the antiparallel direction to the external field, leading to intensity decreases. They explained the decrease of PTRM as being due to partially self-reversed thermoremanence carried by Al-substituted Ti-Mt and newly formed magnetite. *Schult (1971)* pointed out that the titanomaghemites undergo self-reversal by ionic reordering. According to *Schult (1968)* if one assumes that the vacancies are all on the B-site the magnetization of the B-sublattice becomes smaller with oxidation and it is possible that for a certain composition the spontaneous magnetization of B-sublattice equals that of the A-sublattice or becomes even less. *Carvallo et al. (2010)* studied the X-Ray Magnetic Circular Dichroism (XMCD) spectra of magnetite (Mt), maghemite (Mgh) and natural titanomaghemite (Ti-Mgh-te). For Ti-Mgh-te, all features of the XMCD spectrum reverse with temperature, indicating that the magnetization of each individual site is reversed. The intensities of the three peaks (A,B,C) remain almost in the same ratio for XMCD at high and low temperatures. This indicates that there are the antiferromagnetic magnetic interactions between octahedral and tetrahedral sites. In Ti-Mgh-te with a high Ti content, Fe^{2+} ions are present both in tetrahedral and octahedral sites, but at room temperature, the ratio of intensities of peak A and B is lower than at low temperature (20 K). One even observes that peak A is dominating the pre-edge XMCD signal. This can indicate that there is a high magnetic disorder of Fe^{2+} on octahedral sites at high temperatures, i.e. the magnetic moments are not aligned along the direction of external magnetic field. At low temperature, the magnetic moments from Fe^{2+} on tetrahedral sites are more ordered and the moments of Fe^{2+} on tetrahedral sites overcome the moments of Fe^{2+} on octahedral sites, probably causing the magnetization to reverse. The reversal of these two structures with temperature indicates that the dominant subnetworks are reversed at high temperature, the magnetic moment of the octahedral subnetwork is larger than that of the tetrahedral magnetic moment, and at low temperature the tetrahedral magnetic moment dominates.

A distinguished category of rocks are those having dominantly the mag-

netite. *Balsley and Buddington (1954)* discovered a correlation between magnetic Fe-Ti minerals and that of the polarity of RM of metamorphic rocks in the Adirondack Mountains. The rocks of reversed polarity invariably contained hematite-ilmenite, the rocks of normal polarity contained magnetite. These mineralogical differences indicate self-reversal and also indicate that the geomagnetic field was not reversing its polarity during the long interval when these rocks were acquiring their RM. *Orlický (2002b; 2006; 2010a; 2010b).* I revealed that, if there are dominantly Ti-rich quasi homogeneous titanomagnetites (Ti-Mt-es), or magnetites in the rocks, they have always normal polarity of RM, in continental and submarine volcanics (*Orlický, 2010a; 2010b*).

According to *Stacey and Banerjee (1974)* even in the 1950's the reality of field-reversal theory was not proven. The above presented ideas about the self-reversed magnetization of rocks have not fully solved the origin of the reversed magnetization of the rocks in general. Many authors have solved the problem of the decrease of magnetic characteristics in submarine basalts, but the origin of the reversed RM of rocks was not a subject of their interest. The transformation of titanomagnetite to titanomaghemite (maghemitization of Ti-Mt oxides) due to the low-temperature oxidation were solved e.g. (*Irving, 1970; Kelso et al., 1996; Kirkpatrick, 1979; Lowrie et al., 1973; Marshall and Cox, 1972; Petersen, 1979; Petersen et al., 1979; Zhou et al., 2001; Xu et al., 1997*).

3. Experimental part

3.1. A temperature oxidation of Fe-Ti spinels and ilmenite

Oxidation of titanomagnetite: Cubic Ti-Mt (Usp-Mt) can be oxidized by two mechanisms (*Lindsley, 1991*): (a) oxidation at low pressure and below 600 °C to yield cation-deficient spinels of the metastable titanomaghemite series (Usp-Mt-γ-Fe_2O_3, which in some cases may then subsequently convert to members of the Hem-Ilm series; (b) Oxidation at low to moderate pressures and above 600 °C with the direct formation of Ilm-Hem. Distinct textural stages of oxidation are recognized and have been classified as follows (the prefix C distinguished primary cubic phases from primary

ilmenite-rhombohedral): C1 stage: Optically homogeneous Usp-rich magnetite solid solutions; C2 stage: Magnetite enriched solid solutions with a small number of exsolved ilmenite lamellae parallel to 111; C3 stage: Ti-poor magnetite with densely crowded exsolved ilmenite lamellae parallel to 111 of the host. Typical reactions that apply to the C2 and C3 assemblages, with the partial and more complete oxidation ulvöspinel are as follows:

$$\mathrm{C2}: 6\mathrm{Fe_2TiO_4} + \mathrm{O_2} = 6\mathrm{FeTiO_3} + 2\mathrm{Fe_3O_4}; \tag{1}$$

$$\mathrm{C3}: 4\mathrm{Fe_2TiO_4} + \mathrm{O_2} = 4\mathrm{FeTiO_3} + 2\mathrm{Fe_2O_3}; \tag{2}$$

The previous mineralogical composition of rock has been enriched by higher content of magnetite (Fe_3O_4) after an oxidation of ulvöspinel and the rock became more ferrimagnetic. This process has taken place under the influence of the normally oriented geomagnetic field in the nature. The level of magnetic susceptibility of rock will be enhanced and the direction of RM of rock will be changed. If the RM was previously of a reversed nature, it will become more positive; (a mineral enriched with higher concentration of Fe_3O_4 in the rock would acquire the positive RM). Its intensity and the direction will depend on a portion of transformed Fe-Ti material during the above described oxidation.

3.2. An explanation of $1/\kappa$ curves presented in the article

According to *Néel (1971)* the magnetic susceptibility of magnetic minerals of rocks could reflect the effect of magnetic arrangement of active cations and the internal field in the minerals. The exchange interactions between their magnetic moments M_A and M_B will be actual. As an example, the author considered an alloy composed of two kinds of randomly distributed atoms A and B. *Néel (1971)* introduced local molecular field. Weiss' hypothesis amounts to writing that the energy E_c of the system of A and B atoms is expressed in the form:

$$E_c = -\frac{1}{2n}(J_A + J_B)^2 \tag{3}$$

where J_A and J_B denote the magnetizations of the A and B atoms respectively. Actually, since their energy is the sum of the contributions made by

pairs of close-neighbour atoms, three types of exchange interactions $A-A$, $A-B$, and $B-B$ are involved in the process, so we should rather write:

$$E_c = -\frac{1}{2}(n_{AA}J_A^2 + 2n_{AB}J_AJ_B + n_{BB}J_B^2) \tag{4}$$

Then will be actual the introduced local molecular fields, $h_A = n_{AA}J_A + n_{AB}J_B$, and $h_B = n_{AB}J_A + n_{BB}J_B$, acting on the A and B atoms respectively. The author has showed that the susceptibility χ of an alloy containing proportions P and Q of A and B atoms, with Curie constants C_A and C_B, was expressed by:

$$\chi = \frac{T(PC_A + QC_B) - PQC_AC_B(n_{AA} + n_{BB} - 2n_{AB})}{T^2 - T(Pn_{AA}C_A + Qn_{BB}C_B) + PQC_AC_B(n_{AA}n_{BB} - n_{AB^2})} \tag{5}$$

Instead of being represented by a straight line, the temperature dependence of the reciprocal susceptibility $1/\kappa$ was now represented by a hyperbola. It means that the shape of temperature dependence of the κ or $1/\kappa$ curves is in relation with the proportions of active atoms of A and B sublattices, their Curie constants C_A and C_B, portions of other quantities, and also with the forces of three types $n_{AA}J_A$, $n_{AB}J_AJ_B$ and $n_{BB}J_B$ exchange interactions in the two sublattice system. The most intense is the $A-B$ interaction. The antiferromagnetics are characterized by the critical temperature – Néel temperature T_N. After heating beyond T_N the partial or total decomposition of the AFM phase might occure. A short-range order (a tendency of atomic moments to be coupled, which are near each other in the lattice), or long-range order (a tendency of atomic moments to be coupled in the lattice, over many lattice spacings – which is responsible for ferromagnetism and which disappears at T_C).

4. The effective methodical procedures

The magnetic behaviour of the Fe-Ti FriM-AFM chemical phases (ChPs) can be studied by the: 1) temperature dependent measurements of magnetic susceptibiliy (κ) of a powdered sample during continual heating (Curie temperature measurements), 2) temperature dependent measurements of κ of compact sample during stepwise heating, 3) temperature dependent partial

thermoremanent magnetization (PTRM) and demagnetization of compact sample during stepwise heating. The Fe-Ti FriM-AFM ChPs are characterized by a Néel temperature (T_N, in the Fe-Ti FriM-AFM ChPs cubic spinels at about 450 °C). The results of these methods have shown that their characteristics and the features of the curves have reflected the two sublattice (A and B) composition. The temperature dependent behaviour of κ and the magnetization of the two sublattice FriM-AFM systems are governed by their Curie constants C_A and C_B, proportions of their quantities, and also with the forces of three types $n_{AA}J_A$, $n_{AB}J_AJ_B$ and $n_{BB}J_B$ exchange interactions. The most intense is the $A-B$ interaction. We can say that their behaviour has reflected the principles of the two sublattice FriM-AFM alignment, respecting the the principles of the local molecualar field, according to *Néel (1971)*.

4.1. The measurements of Curie temperatures and the detection of the Fe-Ti minerals in the rocks

The analysis of the magnetic minerals of rocks was dominantly done by the Curie temperature measurements in air. The first prototype of CS-1 device combined with the KLY-2 susceptibilitymeter was used (the CS-1 device was originally suggested and dominant part of the instrument was also constructed by the author of this article (*Orlický, 1990*). Several samples were measured in argon atmosphere by Tiu Elbra, Geological Institute of Czech Academy of Sciences, Prague, Czech Republic. The results of X-ray diffraction analysis, the electron microprobe analysis and that of the Mössbauer spectroscopy analysis were used as the complementary methods. The demonstration of the behaviour of the powdered sample is in Fig. 1.

The Curie temperature measurements of softly grinded sample somska3a (κ versus temperature) was mesured in air (Fig. 1 A) and sample Šomoška3a1g was measured in inert argon gas (Fig. 1 B). The following magnetic phases were detected: a) heating of sample Fig. 1 A: $T_C = 230$ °C = Ti-Mt (only partly oxidized), $T_{C1} = 570$ °C = Ti-Mgh; the Néel temperature $T_N = 450$ °C of Ti-Mt/Ti-Mgh AFM phase was mostly detected; $T_{N^*} = 530$ °C corresponds to Ti-Mgh/Ti-He AFM phase; b) cooling of sample: $T'_{C1} = 570$ corresponds to Ti-Mgh, $T_N = 450$ °C reflects the Ti-Mt/Ti-Mgh AFM phase. **B**: a) heating of sample: $T_C = 230$ °C = Ti-rich Ti-Mt (only partly oxidized), $T_{C1} = 580$ °C = Ti-Mgh, T_{N^*} = Ti-Mgh – Ti-He AFM

phase; b) cooling of sample: $T'_{C1} = 580\,^{\circ}C$ = Ti-Mgh, T'_{N^*} = Ti-Mgh + Ti-He AFM phase; $T'_C = 120\,^{\circ}C$ = Ti-rich Ti-Mt phase; magnetic susceptibility of magnetic mineral was about twice enhanced of κ before heating to 700 °C and cooling of sample to room temperature. It appeared due to the partial decay of the Fe-Ti AFM phase and its breaking down to the two constituents, Ti-rich Ti-Mt and that of Ti-Mgh. No such or similar behaviour appeared in the case of sample after heating it to 700 °C and cooling to room temperature in air (Fig. 1, A). Instead, a partial oxidation of the sample took place. A partial decay of the Fe-Ti AFM phase took place. A dominant part of this AFM phase has been preserved. The Ti-Mt/Ti-Mgh AFM phase has been then considered as the Fe-Ti FriM-AFM chemical phase.

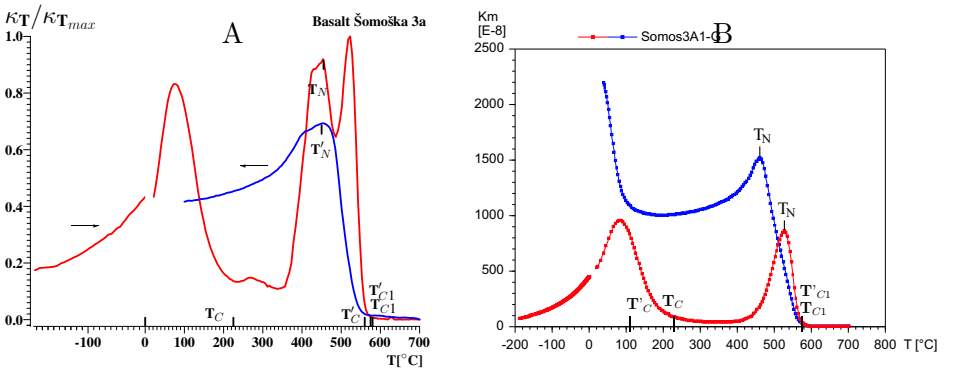

Fig. 1. Demonstration of magnetic behaviour of AFM Ti-Mt – Ti-Mgh phase during continual heating to 700 °C and cooling of coarsely grinded samples; κ versus temperature of grinded olivine basalt sample Šomoška3a1g mesured at air (A) and in inert argon gas (B). (Curie temperature measurements).

5. The description of the different magnetic behaviour of κ of the rocks versus temperature

I have described below the newly established categories of κ versus temperature behaviour, dependently on the inducing fields: 1) The rocks containing only the ferrimagnetic Fe-Ti oxides; 2) The rocks containing the Fe-Ti FriM-AFM ChPs cubic spinels; 3) The rocks containing the Fe-Ti FriM-AFM ChPs tetragonal spinels. This knowledge, together with the derived Eqs. (6), (7), (see below), have provided a complete new approach to

interprete the results in the rock magnetism, paleomagnetism and in the geomagnetism.

I have pondered the results of the samples like the rhyolite from Malý Kamenec locality (Fig. 2) having the only normal RM. There is present only ferrimagnetic phase. I deduce that there is a dominant magnetite in this rhyolite. The two different cation sites in the structure form two magnetic sublattices with a strong antiferromagnetic couping. The spin arrangement can be: $(Fe^{3+}\downarrow)_A(Fe^{3+}\uparrow)_B(Fe^{2+}\uparrow)_BO_4$. We see from a formula that the spins of the Fe^{3+} in A and B sublattices are cancelled, so, the resultant magnetic moment of the magnetite is that of the $Fe^{2+}\uparrow$ of B sublattice. In that case the internal field $|H_{T,int}|$ will be of a positive orientation and it will contribute to the normal field. So, the κ of this rock will decrease gradu-

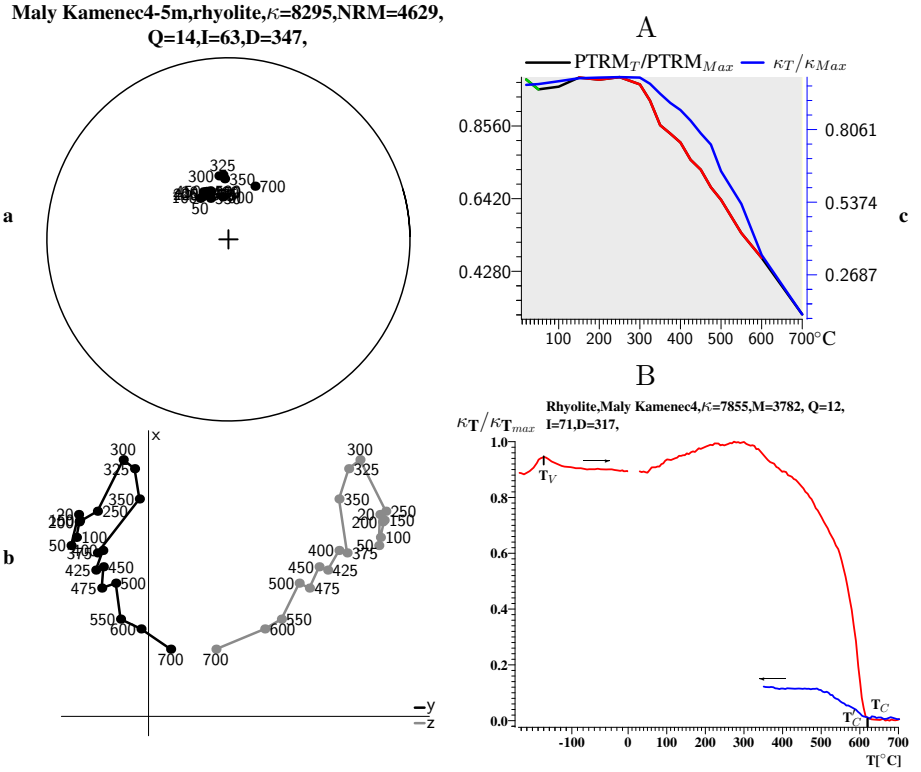

Fig. 2. A: The PTRM and κ versus temperature of rhyolite, sample malkam45, B: Curie temperature measurements of powdered sample mkamerh4, both from locality Malý Kamenec, Coordinates: 48.360 N, 21.790 E, Easthern Slovakia.

ally, according to the Eq. (7). There are dominantly the magnetite and the hematite in this rhyolite sample, respecting the Verwey temperature T_V, corresponding the magnetite and the Curie temperature T_C, corresponding to the non-stoichiometric hematite (see in Fig. 2).

5.1. The type of the κ curve versus temperature for the rocks with the ferrimagnetic alignment

The behaviour of the κ versus temperature can be very effectively applied to define the magnetic state of magnetic mineral. The equations (6) is the basic one to express the physical nature.

$$\kappa = \mu \frac{J_m}{H_{ef}} \tag{6}$$

μ – permeability (for (6) and (7) equations $\mu = 1$); J_m – magnetization of sample; H_{ef} – the effective inducing magnetic field, in our cases the geomagnetic field H.

We substitute the J_m with the PTRM, and the H_{ef} with the $H_{ef} = H + |H_{int}|$; then it can be expressed by the Eq. (7); H_{int} – internal molecular field.

$$\kappa = \mu \frac{PTRM}{H + |H_{T,int}|} \tag{7}$$

PTRM – magnetizations acquired during the temperature dependent magnetization of rock.

I have pondered the results of the samples like the rhyolite from Malý Kamenec locality (Fig. 2) having the only normal RM; the FriM-AFM ChPs has been missed or it has been completely desintegrated. There are dominantly the magnetite and the hematite in this rhyolite sample, respecting the Verwey temperature T_V, corresponding the magnetite and the Curie temperature T_C, corresponding to the non-stoichiometric hematite (see in Fig. 2).

I computed the relation of κ/PTRM data versus temperature in the interval from 25 to 700 °C. The data of the 16 individual temperature intervals are in the range 0.558 to 0.493. This relation has shown that the intensity of the inducing field H_{ef} does generate non-variable, nearly constant κ versus temperature. The Eq. (7) is valid for the rocks containing the pure

magnetite or quasi pure magnetite, the Ti-rich Ti-Mt, or the hematite containing rocks (*Orlický, 2010a*). The interanal field $H_{T,int}$ is of the normal orientation with respect to the magnetic field H. It is possible to suppose that the elementary magnetic moments (spins) of these minerals are parallel in the state of the lowest energy of the system. So, the field H will get gradually more intense, thanks to appearance of the positive internal field $H_{T,int}$. The magnetic behaviour of this Fe-Ti ferrimagnetic system will be similar to that of the ferromagnetic material.

5.2. Short background for magnetic behaviour of the κ versus temperature for the two sublattice Fe-Ti FriM-AFM cubic spinel ChPs

The results of samples of olivine basalt from a small lava dyke of Šomoška Castle locality; Coordinates: 48.171 N, 19.857 E, Southern Slovakia. The results have been applied for an explanation of the antiferromagnetic behaviour of the Fe-Ti FriM-AFM ChPs of the cubic spinels (Fig. 3).

5.3. The processing of the data in Fig. 3

The sample Som3A – the olivine basalt was of the reversed RM *in situ state*, without demagnetization of sample before its magnetization. There are the basic descriptions of the respective data, the quantities and the curves below the Fig. 3. The value of κ NRM, the differences Δm1,2,3,4 of PTRM of the sample are above, on the top in Fig. 3. The respective values were computed from the basic data. But I derived the real data, taking into account the law of additivity of the PTRM after cooling of the sample in the interval from an applied temperature T_n to room temperature. They are: The Δm1 corresponds to original reversed RM (spontaneous magnetization). It was completely removed during magnetization by the geomagnetic field and by the heating of the sample in the interval 25 to 150 °C. The Δm2 has a real value of 905 mA/m, because no other magnetic phase has lower blocking temperature below this phase. The Δm3 phase has shown the value = 779 mA/m of a reversed sense. But, its net value has been summed from the m3 = −779 and the m2 = −905, because the measured value −779 is a result of reduction of 905 mA/m due to cooling o sample through the m2 phase

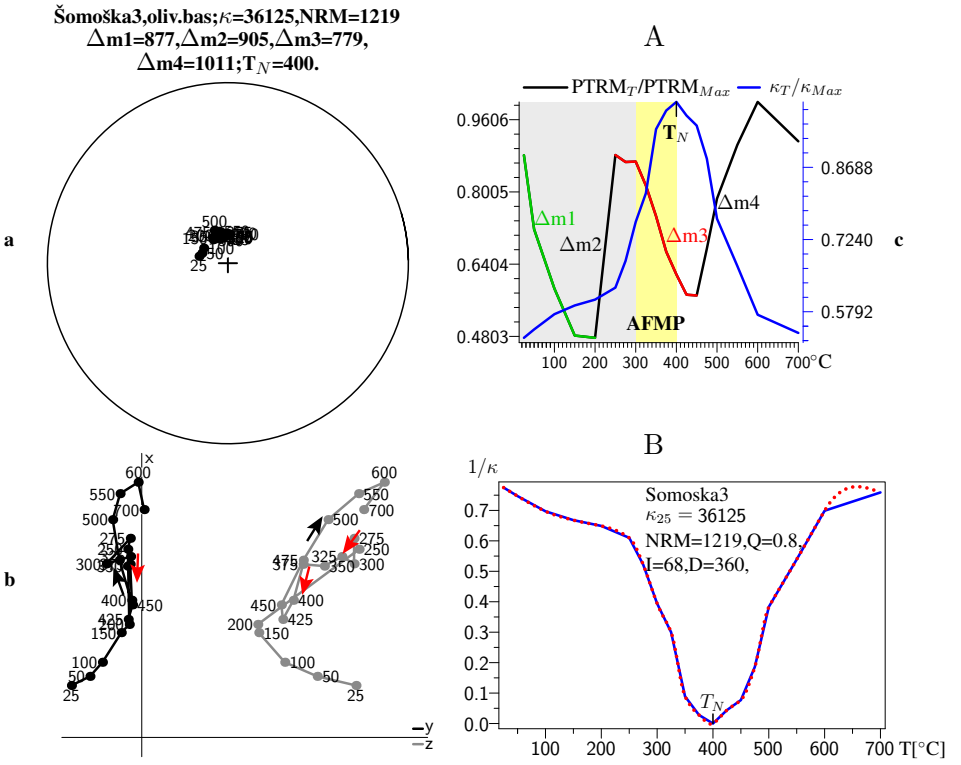

Fig. 3. A: The PTRM and κ versus temperature of olivine basalt from lava dyke, sample Som3A; locality Šomoška Castle; **a** – stereographic projection; **b** – Zijderveld diagram: arrows along the lines – a direction of either increase (black colour) or decrease (red colour) of the PTRM within a respective interval; **c** – susceptibility versus temperature curve (κ, blue curve) and partial thermoremanent magnetization – PTRM: Δm1,2,4 – the differences in PTRM between minimal and maximal values within the respective temperature intervals; Δm1 (green colour) – removal of original reversed spontaneous magnetization; Δm2 (black colour) – normally oriented magnetic moment of ferrimagnetic titanomagnetite (Ti-Mt) constituent of the AFM phase; Δm3 (red coloured curve) – reversally oriented magnetic moment of titanomaghemite constituent of the AFM phase; Δm4 (black colour) – normally oriented magnetic moment of more oxidized Ti-Mt (Ti-He) constituent of the AFM phase; soft yellow coloured area – the AFM phase; T_N – Néel temperature at 400 °C; κ values are in $\times$ 10^{-6} SI units; all NRM and PTRM data are in milli Ampere over meter, mA/m; AFMP – antiferromagnetic phase; B: $1/\kappa$ versus temperature of sample Somos3A1; curves of red, blue colour – the measurements at discrete temperatures and after smoothing of curve respectively.

to room temperature, respecting the additivity rule. It means that the net PTRM of Δm3 should be $-779 + (-905) = -1684$ mA/m. The Δm4 = 1011 contains the Δm3 = -1684 and the Δm2 = 905 = 1790 (106 + 1684).

5.4. Shortly about the law of additivity

According to *Stacey and Banerjee (1974)*, a specimen will acquire a PTRM if it is cooled in a field through a limited temperature range, being cooled in a zero field through the remaining ranges. Those grains whose blocking temperatures are within the range of field cooling acquire the thermoremanence, other do not, the resulting magnetization of the specimens, a whole being known as the PTRM. Tellier first noticed that the PTRMs acquired in different temperature intervals are independent. This means that the total TRM acquired by cooling a specimen in a field from the highest Curie point of its magnetic minerals to laboratory temperature is equal to the sum of the PTRMs acquired separately in several temperature intervals which together make up the whole temperature range. This is known as the *law of additivity* of PTRM (*Nagata, 1961*). The sum of PTRM:

$$\sum_{T_{i-1}=T_0}^{T_i=T} J_{T_i,H_{ex}}^{T_i-1}(T_0) = J_T, H_{ex}^{T_0}$$

Only normal polarity of the PTRM at individual temperature steps was detected in the stereographic projection. I have presented above also the corresponding κ and $1/\kappa$ curves versus temperature with the $T_N \approx 450\,^{\circ}$C. These types of Fe-Ti ChPs are characterized by the domain structure in magnetic grains (*Orlický, 2009*). The volume κ of this Fe-Ti FriM-AFM ChPs of the cubic spinels versus temperature has been governed by the above quantities of A and B sublattices, but also by the internal field $H_{T,int}$, at the temperature T, except of the normally oriented magnetizing field (H) during induction of the PTRM in the laboratory. I deduce that $H_{ef} = H + H_{T,int}$ are actual for this process.

The internal field $H_{T,int}$ is generated due to an activation of domains (or spins) and the exchange interction with the two sublattice systems (the $H_{T,int}$ is a function of the volume of domains in the respective material).

The orientation of this field is always antiparallel against the normal geomagnetic field. There is gradually generated the spontaneous magnetization of a value proportional to the intensity of the internal field $H_{T,int}$. The intensity and the direction of the net magnetization ($PTRM_{net}$) will be the vector sum of the normal PTRM ($PTRM_{nor}$), corresponding to the magnetizing geomagnetic field and that of the reversally oriented PTRM ($PTRM_{rev}$), corresponding to the intensity and the orientation of the internal field $H_{T,int}$, during the laboratory magnetizing of the Fe-Ti FriM-AFM cubic spinel ChPs containing rock sample.

We can see an elegant example of a certain mutual coupling of both, the κ and the PTRM magnetic behaviour (the shape of the PTRM curve and that of the reciprocal $1/\kappa$ curve versus temperature are nearly similar in the interval of temperatures where the AFM character of the sample has appeared. These characteristics were generated in the same sample during temperature dependent magnetization. The behaviour of κ versus temperature has been governed by the Eq. (7), dominantly by the gradual change of the internal magnetic field $H_{T,int}$, while the geomagnetic field H held sustained nearly in a constant level. We see a sharp increase of κ in the interval 250 to 400° C, with a maximum at T_N temperature, whereas the PTRM sharply decreased itself in the same interval, with a minimum at 400 °C (Fig. 3 A, B). This decrease of a previous positive value of the PTRM corresponds to the gradual increase of the negatively oriented internal magnetic field in the sample. The PTRM has becommed gradually of the reversed magnetization of the sponataneous origin in the sample. The behaviour of the κ and the PTRM is an opposite behind of the T_N of the Fe-Ti AFM phase. The internal field $H_{T,int}$ has gradually disappeared behind the T_N. It has been detected by the rapid decrease of κ and increase of the PTRM in Fig. 3. So, the internal field $H_{T,int}$, figured in the equation (7) has playied the decisive role in the magnetizing of the Fe-Ti FriM-AFM cubic spinel containing rocks in the nature and in the laboratory.

5.5. The transition of the Fe-Ti FriM-AFM cubic spinel ChP to the Fe-Ti FriM-AFM of the tetragonal spinel ChP

The Fe-Ti AFM cubic inversion spinel phase is supposed to be in a metastable state. It can be either partly or completely desintegrated, or it can be trans-

formed for tetragonal symmetry Fe-Ti oxide, due to alteration-transition mechanism, during heating of a previous material to temperatures about 600–700 °C in the field. I have revealed the Fe-Ti FriM-AFM ChPs of a tetragonal symmetry, or a combined cubic-tetragonal spinel, in the rocks. One could detect a less striking κ curve versus temperature (mostly only some remnant of previous phase has been preseved), frequently with a higher T_N than the previous a cubic symmetry Fe-Ti FriM-AFM ChPs. The physical and chemical features of this Fe-Ti FriM-AFM ChPs have shown that this type has arisen due to a transition of the previous Fe-Ti FriM-AFM ChPs of the spinel cubic phase. There are the examples of magnetic behaviour during magnetization versus temperature of samples (Figs. 3–5). The results have shown that the reversed RM has been inparted from the respective Fe-Ti FriM-AFM cubic spinel ChPs to the Fe-Ti FriM-AFM tetragonal spinel ChPs.

The results of the sample Pohanský vrch in Fig. 4 A, sample Trebelovce1-5 in Fig. 5 A and the sample Lošonec 4m in Fig. 6 have shown a very complex behaviour of the PTRM and the κ versus temperature. The samples in Figs. 4, 5 belong to the grouping involving 9 localities in Cerová vrchovina of southern Slovakia. About 76 samples of the olivine basalts were studied. All these samples have shown the physico chemical features similar to that like the Pohanský vrch and Trebelovce1-5 samples. In all these samples the AFM behaviour and the reversed RM was either partially or totally preserved during magnetization of the sample by normally oriented geomagnetic field of intensity H = 47.5 μT in the laboratory (in sample Pohanský vrch up to 300 °C, Fig. 4). The κ curve has shown also the AFM behaviour up to the Néel temperature T_N = 500 °C. The samples of rocks with these Fe-Ti FriM-AFM ChPs have shown the presence of T_N and T_{N1} different points. The peaks of the T_{N1} and T_N are suppose to be a rather less conspicuous than that in the Fe-Ti FriM-AFM cubis spinel ChPs. These types have more Ti-Hem containing composition. The rocks containing this type of the Fe-Ti FriM-AFM ChPs do have the reversed polarity of RM, more consistent direction of RM and a higher magnetic stability than those of the previous cubic spinel phases. A very low κ and a relatively high RM are the dominant chracteristics for the older rocks. Some of them do possess only one AFM phase with only one T_N temperature, others do have the two AFM phases and the two T_N (see in Fig. 6).

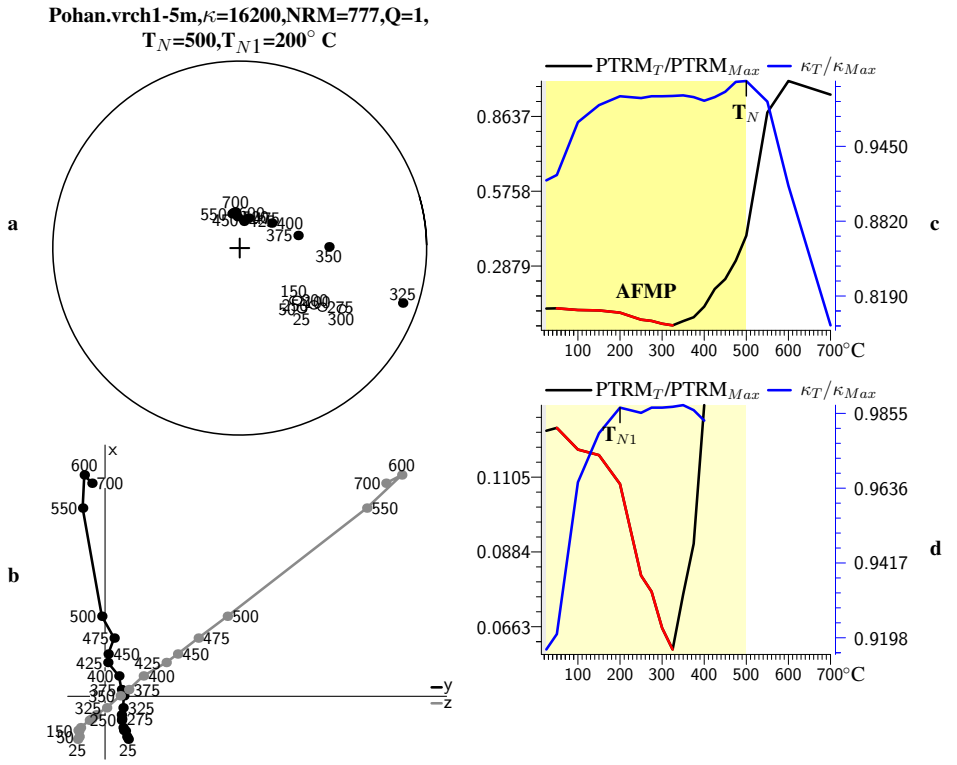

Fig. 4. PTRM and κ versus temperature of olivine basalt, sample Pohanský vrch, locality Pohanský vrch; Coordinates: 48.200 N, 19.922 E, Southern Slovakia; **d** – a magnification of the behaviour of a limited part of the PTRM and κ versus temperature of the sample.

The Fe-Ti FriM-AFM tetragonal spinels are dominantly characterized by the T_N near to 500 °C, but in many cases also with the intermediate T_N between 450 to 500 °C. I present the example of the combined, the Fe-Ti FriM-AFM tetragonal spinel and the Fe-Ti FriM-AFM cubic spinels, which are there in the olivine basalt from the Trebelovce locality, belonging to the grouping of 9 localities (a description see above).

The Eq. (7) is valid also for this type. But we need to respect some influence of the RM on the κ behaviour of the sample (the κ versus temperature is lagging behind the RM behaviour versus temperature). This effect is probably the reflection of the extreme high hysteresis of the RM of these rocks. I have selected only three examples in the Figs. 4–6, but

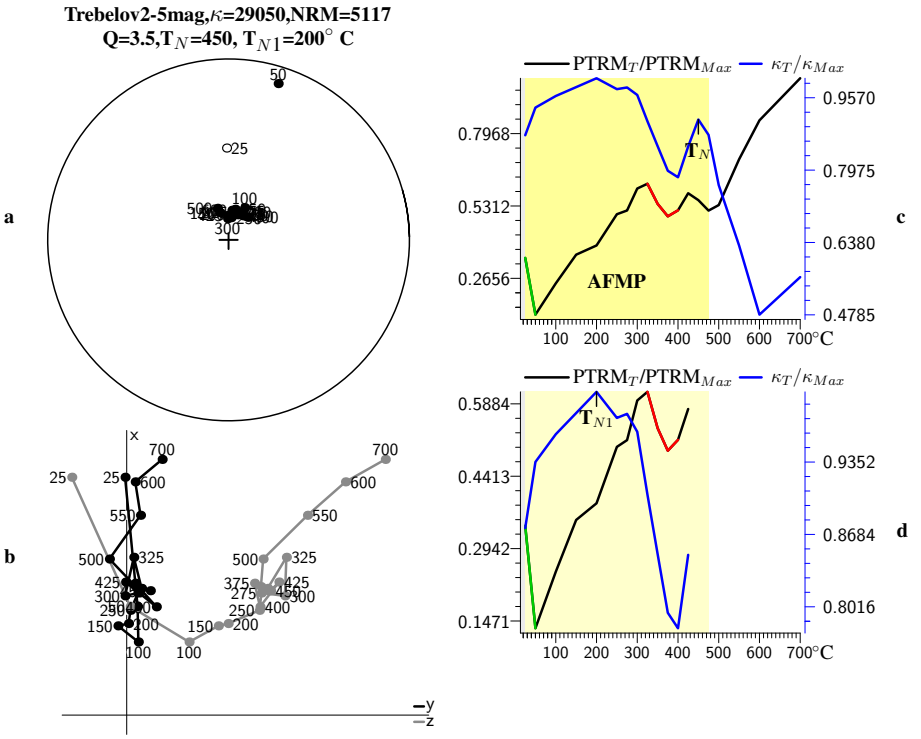

Fig. 5. PTRM and κ versus temperature of olivine basalt, sample Trebelovce2-5, locality Trebelovce; Coordinates: 48.287 N, 19.716 E, Southern Slovakia; **d** – a magnification of the behaviour of a limited part of the PTRM and κ versus temperature of the sample.

I have identified many such types of rocks so far. We see that the stable RM is linked with the AFM phases of the rock. The hysteresis of the RM is evident on nearly unchangeable values of the vector projections onto the $x-y$ and $x-z$ plains versus temperature, in the interval from 25 to 500 °C, (see on the Zijderveld diagrams in Figs. 4–6). The high stability and the reversed direction of the RM of the sample has been preserved up to 500 °C (see in Fig. 6). The reversed RM of the high Fe-Ti FriM-AFM tetragonal spinel ChPs in the rocks have been imparted from the Fe-Ti FriM-AFM cubic spinel ChPs containing rocks during the alteration transition processes in nature.

Many laboratory tests have shown that the oxidation and partial decomposition of minerals in the rocks take place rather regularly in the field. The

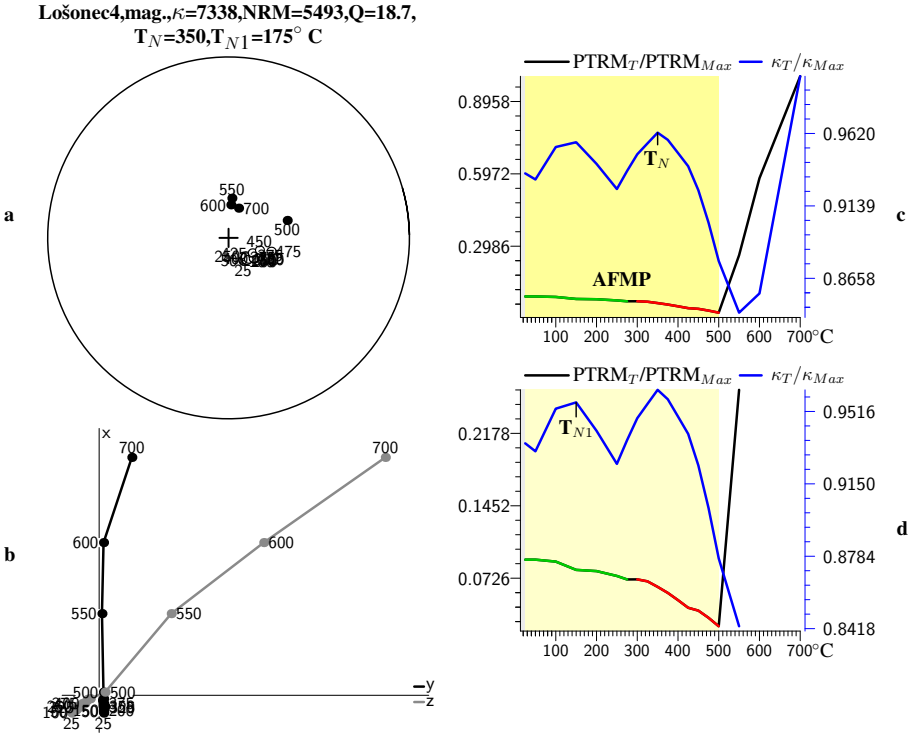

Fig. 6. PTRM and κ versus temperature of the melaphyre (the age about 270 My, the Upper Permian, the sample Lošonec 4m, the locality Lošonec; Coordinates: 48.438 N, 17.302 E, Low Carpathian Mts., Westhern Slovakia; **d** – a magnification of the behaviour of a limited part of the PTRM and κ versus temperature of the sample; green and red part of the PTRM curve differ the individual AFM phases.

decomposition of the Fe-Ti FriM-AFM cubic spinel phases has taken place at the temperatures close to T_N, or over 450 °C to 500 °C in the field (the temperature about 475 °C was derived as a typical for the decomposition of the AFM phase).

6. The summarized results of laboratory magnetization of rocks

The results were previously published, but not complete explanation of all characteristics was done. Generally, the pure ferromagnetic and the pure

ferrimagnetic Fe and Fe-Ti minerals of rocks should acquire a normally oriented RM under normally oriented magnetizing field. But if there are the Fe-Ti FriM-AFN ChPs in the rocks, the acquirement of the reversed sponataneous magnetization can be expected during their magnetization in laboratory. The reversed magnetization was only seen in the rocks having the Fe-Ti AFMP, according to *Orlický (2014)*. Generally, the chemicophysical features and the characteristic behaviour of κ versus temperature described above can be effectively applied for the interpretation of the results.

I studied the rocks from Kremnické vrchy Mts., Poľana-Javorie Mts., Zemplínske vrchy Mts., Vihorlat Mts., and Bohemian massif (*Orlický, 2001; 2002a; 2002b; 2002c; 2002d; 2002e; 2003a; 2003b; 2003c; 2003d; 2003e*). I applied the laboratory induction of PTRM in the rocks by normally oriented geomagnetic field. The samples were heated to 670 °C in a non-magnetic furnace under a fully compensated field and they were kept there for 30 minutes at this temperature. The PTRM was induced during the cooling of samples from 640 °C to 580 °C; the external field was fully compensated in the interval from 580 °C to laboratory temperature; later it was modified; the geomagnetic field was compensated from 520° C during the cooling of the samples (the description of procedures is in the literature cited above). The magnetization of samples by the external magnetic field should be active only within the delineated interval of 640 to 580 °C, temperatures the geomagnetic field, but it has taken place also at lower temperatures. Together 210 samples were magnetized (194 basaltic andesites and other types of andesites and 16 samples of rhyolites, all of them aged 9 to 15 My). Together 119 samples were of reversed polarity and 91 were of normal polarity of RM before laboratory magnetization. The results after the magnetization of the samples were the following: 102 samples acquired reversed magnetization (63 samples were originally of reversed polarity, 39 were of normal polarity of RM). Other 108 samples acquired normal PTRM (91 samples were originally of normal polarity and 17 of reversed polarity of RM). It is evident from a review that 39 samples acquired reversed magnetization which were originally of normal RM before laboratory magnetization. Many other samples of rocks were magnetized as well, but I have analysed only the results described in papers cited above. Why some samples of rocks, originally of reversed magnetization have not been magnetized reversally again,

and why some samples, originally of normal polarity acquired reversed magnetization by a normally oriented magnetic field in the laboratory? I have dominantly applied the results of the temperature dependent measurements of the magnetic susceptibility of a powdered sample and the compact sample versus temperature (Figs. 4–9) to explain the answers above. I presented many such evidences and the thermomagetic curves of selected rocks in the papers cited above.

I present now a short background to explain a more complex magnetic behaviour of the magnetic susceptibility versus temperature for the two sublattice systems, for the Fe-Ti FriM-AFM cubic spinel ChPs.

The Fe-Ti FriM-AFM cubic spinel ChPs probably contains the titanomagnetite, Ti-Mt, partly oxidized, of a ferrimagnetic alignment, and the titanomaghemite, Ti-Mgh, of the antiferromagnetic alignment. A partial oxidation and partial decomposition of minerals in the rocks took place rather regularly in the field. The results have shown that the state of the Fe-Ti FriM-AFM phases in the rocks has been influenced by the level of the thermal heating and its time duration. The decomposition of the Fe-Ti FriM-AFM phases has taken place at the temperatures close to T_N, or over 450 °C to 500 °C in the field (the temperature about 475 °C was derived as typical for the decomposition of the AFM phase. The specific measurements of a change of the κ of powdered sample at a constant temperature during 100 minutes, at different selected temperature intervals were done to derive a critical temperature of the probable decomposition of the AFM phase in the rock. The instrument and the procedure according to *Orlický (1990)* were used for these measurements. Most of rocks have been found in the field with a partly decayed AFM phase. This state of the AFM phase is then reflected in the intensity and the non-consistent directions (I and D) of RM of the magnetite and hematite containing rocks and of M_s containing dominantly the AFM titanomaghemite. The results have shown that there are present in the rock the individual constituents, as magnetite, hematite, pseudobrookite and ilmenite, after an alteration and a complete desintegration of the Fe-Ti AFM phase. Such rocks have possessed dominantly normal RM. There exists a second type of alteration and a transition of the Fe-Ti spinel AFM phase to the tetragonal spinel phase in the rocks of our interest. These effects have appeared on the deformed shapes of κ and PTRM curves versus temperature.

I have selected five groupings of rocks, respecting their different magnetic behaviour. The results for two samples from the different volcanic fields are presented in the respective figurere. There are considered the results of the polarity of magnetization (M) in the "in situ state" and the M′ "after the laboratory magnetization" of sample: 1) Normal, normal, Fig. 7; 2) Reversed, reversed, Fig. 8; 3) Normal, reversed, Fig. 9; 4) Reversed, normal, Fig. 10; 5) Anomalous directions and intensities of M of the autometamorphed rocks, Fig. 11.

6.1. Curie temperature measurements, a detection of the magnetic phases

The results of measurements of a change of κ of a powdered sample during a continual heating and a successive cooling of the sample have detected the Ti-Mt and the Ti-Mgh, which are the constituents of the Ti-Mt/Ti-Mgh AFM phase. The mentioned constituents were also detected by the X-Ray diffraction analysis. This is a completely new knowledge. The individual inversion spinel-cubic constituents Ti-Mt and Ti-Mgh have been coupled into the Ti-Mt/Ti-Mgh AFM (the Fe-Ti FriM-AFM phase during their existence in nature. This has allowed to establish a completely new category in rock magnetism, which has been based on the existence of antiferromagnetically aligned chemical compounds in nature.

6.2. The self-reversed origin of RM of rocks was proven by the results of the Curie temperature measurements of rocks

I firstly start with the characteristic features of the thermomagnetic curves. The presented thermomagnetic curves have concerned the natural sister samples of the respective rock. The results concern the measurements of a change of κ of a powdered sample of rock. These curves are combined from a low-temperature interval (– 190 to 0 °C) and a hihg-temperature interval (25–700 °C). Characteristic features: (heating curve, red colour), Low-temperature interval: an increase of κ from −190° C) to a peak T_V (Verwey transition temperature) detects the magnetite (Fe_3O_4); a gradual increase of κ from −190° C to laboratory temperature detects the titanomagnetite; a gradual decrease of κ from −190° C, mostly to laboratory temperature detects ilmenite. The ilmenite is an antiferromagnetic mineral with T_N about

$-205°$ C (maximum κ at an ordering temperature). It does not contribute to the RM of rocks. During heating over T_N a κ of the samples decreases. High temperature interval: The Curie temperatures: T_C = 120–230 °C – Ti-rich titanomagnetites; $T_C \approx 560°$ C – magnetite (mostly non-stoichiometric), with the same or very near T'_C and a reversible or, nearly reversible cooling curve, after heating of the sample to 700 °C and successive cooling; the Fe-Ti antiferromagnetic phase is characterized on the curves with the Néel temperatures T_N for an original state, and T'_N after heating of the sample to 700 °C and a successive cooling of the sample; $T_{C''}$ and T''_C correspond to the Curie temperatures of these Fe-Ti AFM phases, respectively; T_{C1}, T'_{C1} correspond to the Curie temperatures of the most oxidized magnetic phase, dominantly of the hematite enriched by maghemite. A rapid decrease of κ within the interval 300 to 450 °C, sometimes more (hump) in many samples corresponds to a transition and alteration of magnetite to maghemite (in some rocks it is a natural state, in some of them it is due to heating of samples in the laboratory; also a combined effect).

The interpretation of the results of magnetized rocks call for a detailed study of each respective sample. We need to pay an attention for the basic features and magnetic properties of the Fe-Ti FriM-AFM cubic and and the tetragonal spinels. If they are the stable enough ad they have not been decomposed during heating and cooling of the sample, the reversed RM should be preserved. If it has been either partly or a fully decomposed, the FriM-AFM alignment was disturbed and it was desintegrated in favour of individual constituents. The shape of the κ curve versus temperaure should be deformed in such cases (it is actual near to 475 °C).

The Fe-Ti FriM-AFM tetragonal spinels are dominantly characterized by the T_N near to 500 °C, but in many cases also with the intermediate T_N between 450 to 500 °C and there exist the combined, the Fe-Ti FriM-AFM tetragonal spinels and the Fe-Ti FriM-AFM cubic spinels in some rocks. These types of rocks contain two critical temperatures, the T_{N1}, haracterizing the tetragonal spinel and the T_N, characterizing the cubic spinel (see in Fig. 6). The curves of the κ and $1/\kappa$ versus temperature and the respective N éel temperatures are readable from the figures. A very characteristic feature is the very stable reversed RM (surviving to about 300 °C, in many types of rocks to about 500° C, during heating and the magnetizing of samples in the laboratory. This reversed RM is so stable, that it was

not removed, or remagnetized totally during cooling of the samples in the laboratory. The repeated heating of rocks to 670 °C did not destroy the previous RM of the rocks. Some rocks have shown a soft differences in the inclination (I) and the declination (D) values after heating to 670 °C and cooling to room temperature (see above), but the reversed polarity of the sample was preserved due to high hysteresis (high coercivity) of the Fe-Ti FriM-AFM tetragonal spinel ChPs in the rock. This is the basic explanation for the rocks which possessed the reversed RM before the laboratory magnetization and the reversed RM was preserved also after its magnetization by the normally oriented geomagnetic field in the laboratory.

These characteristics have been used to differ the cubic spinel types of Fe-Ti FriM-AFM phase carrying rocks from those of the tetragonal types of the Fe-Ti FriM-AFM phase carying rocks. in general.

As it was mentioned above, the temperature dependent measurements of κ of the two sublattice Fe-Ti FriM-AFM phase systems are governed by their Curie constants C_A and C_B, proportions of their quantities, and also with the forces of three types $n_{AA}J_A$, $n_{AB}J_AJ_B$ and $n_{BB}J_B$ exchange interactions. The most intense is the $A-B$ interaction. The actual Eqs. (6) (7) are above. The isolated ferrimagnetic Fe-Ti oxides are dominantly the products of both, the oxidation-alteration process of the Ti-Mt containing rocks, or the products of the decomposition of the Fe-Ti FriM-AFM ChPs in the rocks. There are present magnetite, hematite as the dominant minerals, except of the Ti-Mt and the non magnetic ilmenite and pseudobrookite in the rocks. If the isolated ferrimagnetic products are as dominant magnetic phases there in the rock, they carry dominantly normal RM. We can detect them at about 565–570 °C for magnetite, and at about 600–640 °C for hematite on the thermomagnetic curves during heating to 700 °C. If they have survived after heating, under duration of about 30 minutes. they are able to acquire the normal RM again.

6.3. Normal before, normal after magnetization (Fig. 7)

I took into account the polarity of the inclination of the RM of rocks. A similar behaviour concerns the 91 studied samples. All samples of rocks of this grouping have possessed the more oxidized Fe-Ti magnetic phases, the hematites, in some of them with magnetites. These hematites are of

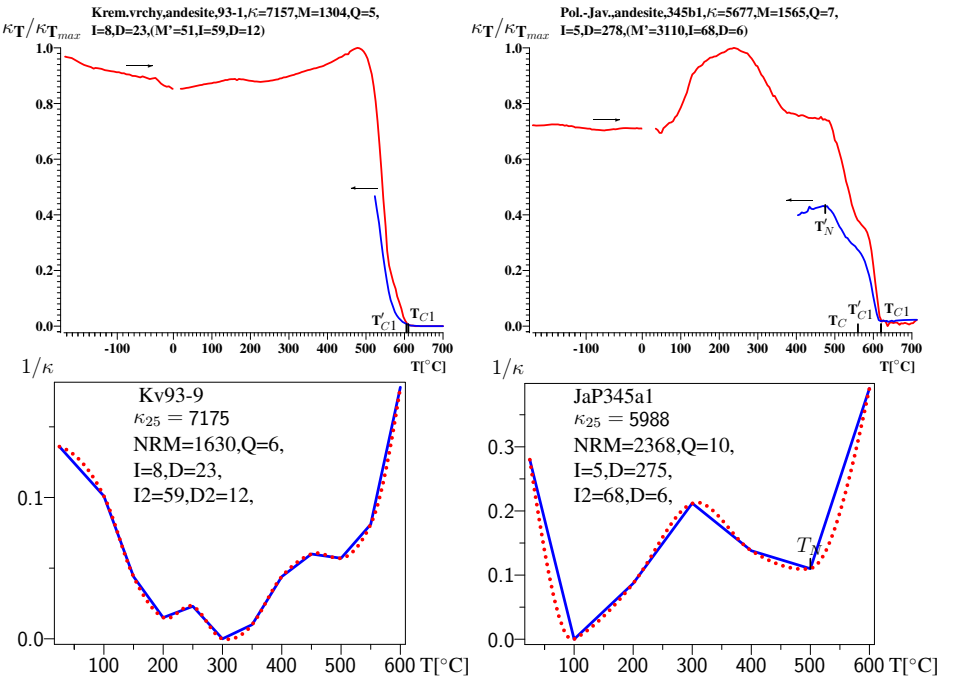

Fig. 7. **Normal before, normal after magnetization:** The temperature dependence of κ of sotfly powdered sample during heating to 700 °C and cooling to lower temperatures. Samples: krv93-1 (93-6, $1/\kappa$ curve) – andesite, Sielnica Formation, Kremnické vrchy Mts.; poj345b1, (jap345a1, $1/\kappa$ curve) – andesite Detva Formation, Poľana-Javorie Mts.; data in a picture: κ – magnetic susceptibility $\times 10^{-6}$ in SI Units; M – magnetization (remanent magnetization for the rocks of normal polarity and spontaneous for the rocks of reversed polarity) in mA/m – milli Ampere over meter; Q – Koenigsberger coefficient; I – inclination, D – declination of magnetization, respectively in a °; data in a round bracket – data after laboratory magnetization of the samples; M′ – a value of magnetization in mA/m, I, D – inclination and declination of RM of sample respectively after magnetization of sample in thelaboratory; T_C, T'_C – Curie temperatures after heating and cooling, respectively after magnetization of sample; T_V – Verwey transition temperature of the magnetite; T_N, T'_N – Néel temperatures of the Fe-Ti antiferromagnetic phase after heating and cooling of sample respectively; T''_C – Curie temperature of the Fe-Ti antiferromagnetic phase after cooling of the sample.

secondary origin and they originated due to the decay of the Fe-Ti AFMP, the titanomaghemite during its heating over T_N in the field. The magnetite, or the Ti-Mt are the products of the decay of the Fe-Ti AFMP. A successive alteration of the magnetite, through the maghemite occurs and the hematite

is the resulting and final product of this alteration. The magnetization is mostly of chemical (CRM) origin, only in the rare cases could be acquired as the thermoremanent (TRM) origin in the basaltic and the andesitic rocks. It means, that if there are present these hematite and the magnetite as the dominant minerals in the rocks, only the normal magnetization can be induced in the field and also in the laboratory, during magnetization by a normally oriented magnetic field. There are 17 samples which possessed reversed magnetization before laboratory magnetization. We see from Fig. 9 that the Fe-Ti AFM phase has not been preserved during heating to 700 °C and a successive cooling of the samples. So, the Fe-Ti AFM phase was decayed in the field and the secondary magnetite through maghemite to hematite were transformed. So the only normal magnetization was induced in these rocks in the laboratory.

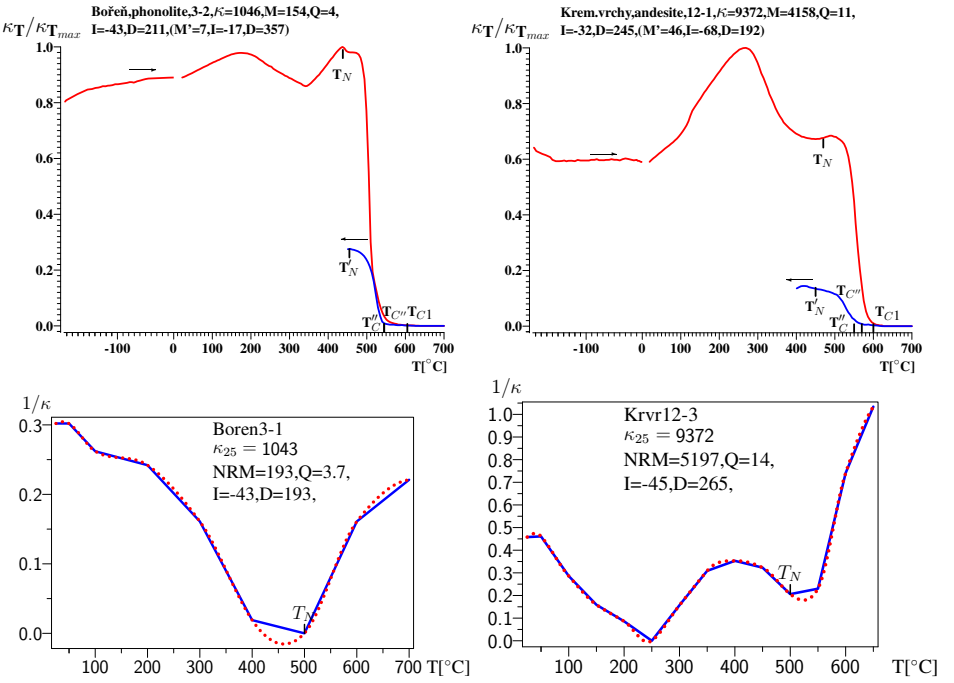

Fig. 8. **Reversed before, reversed after magnetization:** The samples: (Bořen3-2, Bořen3-1, $1/\kappa$ curve) – nepheline phonolite, North Bohemia; (krv12-1, krv12-3, $1/\kappa$ curve) – andesite, Turčok Formation, Kremnické vrchy Mts. For further descriptions and explanations see in Fig. 7.

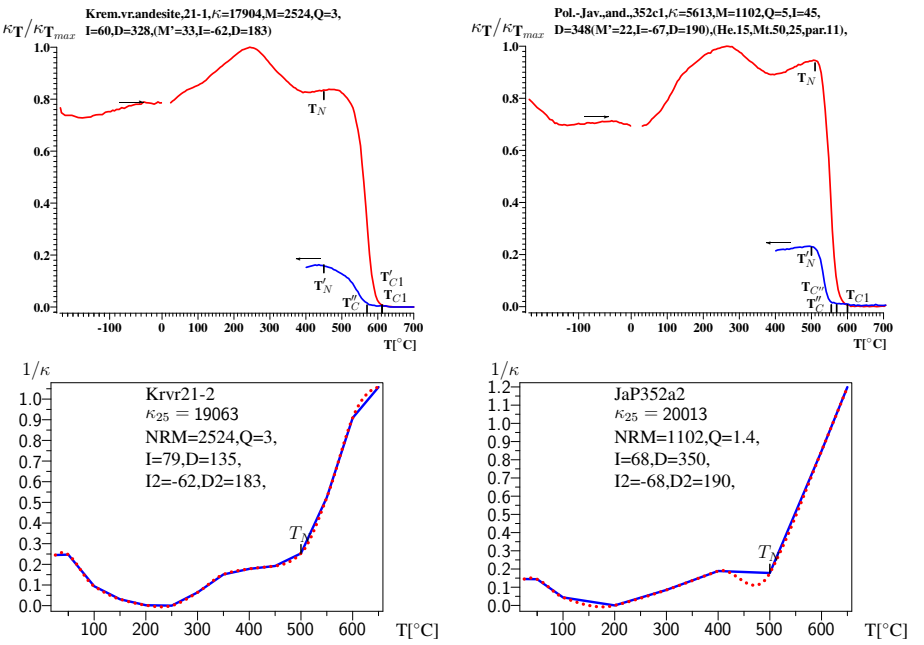

Fig. 9. **Normal before, reversed after magnetization:** The samples: (krv21-1, Krvr21-2, $1/\kappa$ curve) – andesite, Turčok Formation Kremnické vrchy Mts.; poj352c1, Jap252a2, $1/\kappa$ curve) – andesite, Veľká Detva Formation, Poľana-Javorie Mts. For further descriptions and explanations see in Fig. 7.

6.4. Reversed before, reversed after magnetization (Fig. 8)

A role in these samples plays the Fe-Ti AFM phase with its magnetic behaviour. The Fe-Ti FriM-AFM phase was there in the sample before laboratory magnetization and it has been preserved also after the laboratory magnetization in the sample. A similar behaviour have shown 63 samples having the reversed magnetization. In 39 samples of rocks, having a normal RM before magnetization possessed also a more oxidized phase, mostly magnetite. This was partially transformed to hematite before the magnetization of the sample. But during its heating to 700 °C and cooling this portion was reduced and dominantly the Fe-Ti AFM phase was preserved in the sample. During repeated heating of the sample a transition of the Fe-Ti FriM-AFM cubic spinel phase to the Fe-Ti FriM-AFM tetragonal spinel phase took place in the system. Such behaviour was seen in 39 samples (an example see in Fig. 9). From Fig. 8 we see that the shape of the $1/\kappa$ curve

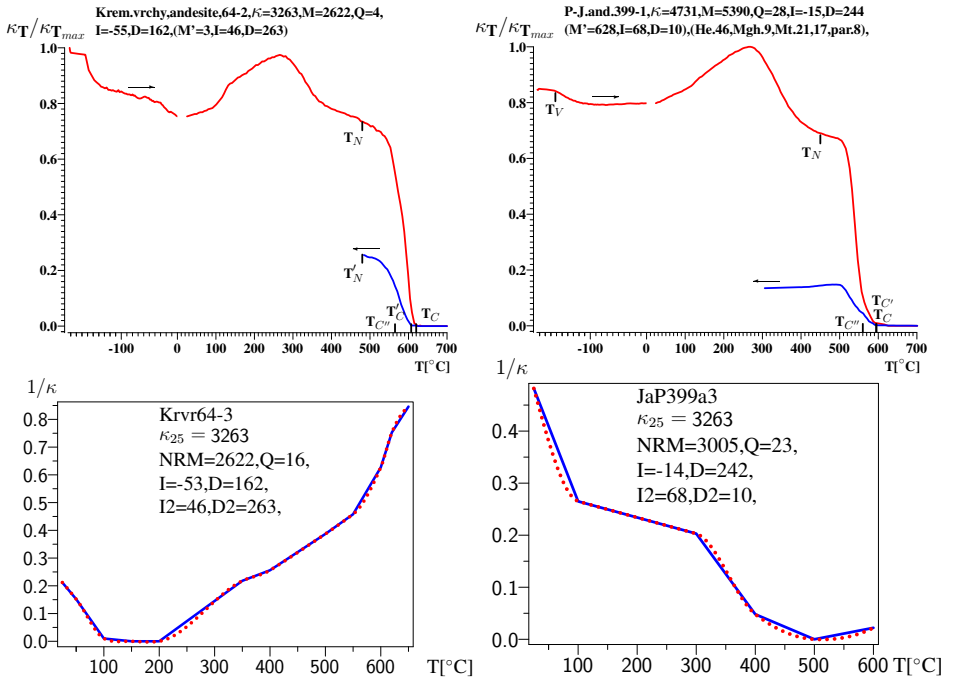

Fig. 10. **Reversed before, normal after magnetization:** The samples: (krv64-2, Krvr64-3, $1/\kappa$ curve) – andesite, Zlatá Studňa Formation, Kremnické vrchy Mts.; poj399-1, JaP399a3, $1/\kappa$ curve) – andesite, Rohy Formation, Poľana-Javorie Mts. For further descriptions and explanations see in Fig. 7.

of sample Boren3-1 is very near to that of a parabola like shape, characteristic for the reversed RM of samples. These more oxidized minerals are of a secondary origin. There are frequently present some combined Fe-Ti FriM-AFM phases in these chemical compounds, having partially the Fe-Ti cubic spinels and those of the Fe-Ti FriM-AFM phase tetragonal spinels. This feature is indicated by an enhanced T_N point from about 450 to about 500 °C and by a missing of domain structure in such samples of rocks. But the preservation of the reversed RM in these types of the Fe-Ti tetragonal spinel containing rocks is the most characteristic feature (see in Figs. 4–6).

6.5. Normal before, revered after magnetization

There were originally present both, the cubic spinel and the tetragonal spinel ChPs in these rocks. A partial destroying of these antiferromagnetic phases

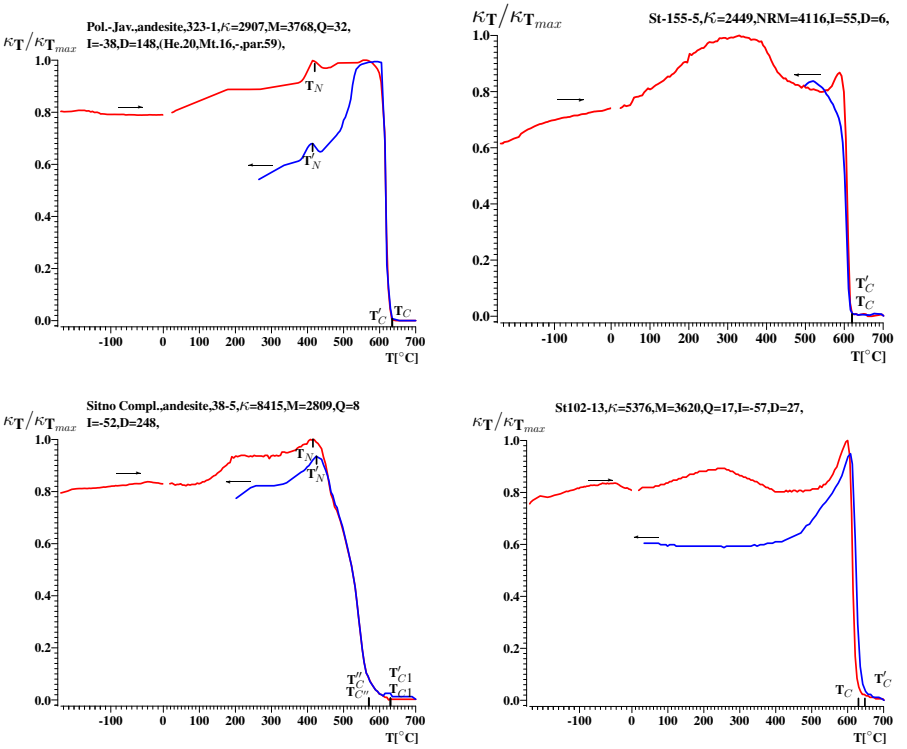

Fig. 11. **An anomalous magnetic behaviour:** The samples: PoJ323-1, autometamorphed andesite, Abčina Formation, Poľana-Javorie Mts.; Stf155-5, biotite-hornblrnde andesite of Studenec Formation; Sk38-5, autometamorphed andesite, Sitno effusive Complex, Štiavnické vrchy Mts.; St-102-13, biotite-hornblrnde andesite of Studenec Formation, Štiavnické vrchy Mts.; For further descriptions and explanations see in Fig. 7.

produced the individual Fe-Ti oxides which were remagnetized in the field. The directions (I, D) of the RM are mostly anomalous ones. A high stability of a previous reversed RM is a main characteristic which remagnetized the secondary components and the resultant RM has becommed to be as the reversed RM of the rocks, after heating in the laboratory. The thermomagnetic curves detected the T_C of over 600 °C and the T_N temperatures at about 450° and 500°, respectively during heating (red curve), and of about T'$_C$ about 550 to 570 °C during cooling of sample (blue curves). The T_N temperatures were detected at about 450°, 500 °C, respectively during cooling of samples. The $1/\kappa$ versus temperature curves have shown the anti-

ferromagetic Fe-Ti FriM-AFM behaviour with a T_N temperatures at about 599 °C.

6.6. Reversed before, normal after magnetization

There were originally present both, the cubic spinel and the tetragonal spinel ChPs, differing the T_N temperatures in these rocks. A partial destroying of these antiferromagnetic phases produced the individual Fe-Ti oxides which were remagnetized in the field in favour of normal directions of the RM (the directions are close to the direction of the geomagnetic field in the laboratory). The thermomagnetic curves detected the T_C of over 600 °C during heating (red curve), and during cooling of sample (blue curves). The $1/\kappa$ versus temperature curves have not detected the antiferromagetic Fe-Ti FriM-AFM behaviour, no T_N temperatures were detected. The X-ray diffraction analysis identified the tetragonal γ-Fe_2O_3 spinel, rhombohedral α-Fe_2O_3 in the samples of autometamorphed andesites PoJ323-1, Sk38-5, and in the biotite-hornblende andesite St-102-13. Low portion of magnetite (in the A sublattice) was also detected by the Mössbauer spectroscopy. The high portion of FeO and mostly low portion of TiO_2 were identified by the electron microprobe analysis in these samples. We can deduce that the rocks, as that represented by the samples in Fig. 11 survived the alteration-transition process in nature. They had originally the reversed RM, which was dominantly preserved also after the alteration-transition process.

7. Discussion and conslusions

So far, nearly all authors in a study of the magnetism and the paleomagnetism of rocks have accepted an explanation that the reversed RM of the rocks originated due to reversally oriented geomagnetic field in the time the rocks originated. An attractivity of this hypothesis was enhanced after the publication of geophysical measurements under the seas and oceans and the interpretation of marine magnetic anomalies. Many variable Geomagnetic Polarity Time Scales (GPTS) have been constructed, e.g. *Heirtzler et al., 1968; Kent and Grantstein, 1986; Berggren et al., 1995; Candl and Kent, 1995; Kent and Olsen, 1999; Huestis and Acton, 1997;* and others. The Pleistocene to Early Miocene Time Scale (*Berggren et al., 1995*)

is a very complex one. It is based on the RM polarity intervals of rocks, complemented by the Planctonic foraminifera and Calcareous nanoplancton data, ranging in the age from present time to 24.6 My. The GPTS of *Kent and Olsen (1999)* was constructed using the stratigraphic and magnetostratigraphic analyses from approximately 5000 m thick composite section obtained by scientific coring in the Newark rift basin of eastern North America. Only normal polarity was found in approximately 1000 m of interbedded volcanics and continental sediment of earliest Jurassic age but a total of 59 normal and reverse polarity magnetozones are delineated underlying 4000 m of the Late Triassic continental sediments. Generally the polarity timescale intervals are very irregular, reflecting also a very irregular dynamics of the geomagnetic field in the past. The GPTS have been frequently applied by specialists for the magnetostratigraphic interpretations. As we have known, the field-reversal theory was applied as a dominant in the paleomagnetism and in the study of magnetism of the rocks. The geomagnetic polarity timescales have provided one of the few lines of the empirical evidence of the geodynamo dynamics (*Kent and Olsen, 1999*). We do exactly know only today's orientation of the field with its short period and long period variations, applying the observatory measurements. Some known model see in *Olsen and Mandea (2007*).

There are presented above the complete new, original approaches for the explanation of the origin of the reversed remanent magnetization of rocks on Earth. The explanation is based on the existence of the Fe-Ti ferrimegnetic-antiferromagnetic chemical phases of the two sublattice systems in the rocks. There exist the interactions of these Fe-Ti FriM-AFM ChPs with the Weiss molecular field-Heinsenberg forces, generating the reversally oriented internal magnetic field. A production of the reversed spontaneous magnetization is a consequence of these processess. So, the Fe-Ti FriM-AFM ChPs in the rock, the local molecular fields with so called Weiss-Heisenberg forces (*Néel, 1971*) are decisive for the acquirement of the reversed magnetization in the rock. The basic ChPs in the rocks is supposed to be the Fe-Ti FriM-AFM cubic spinel. But it has a tendency to be altered and transitioned in favour of the tetragonal spinel. A very important knowledge is that the reversed magnetization is supposed to be imparted from the cubic spinel to the tetragonal spinel during this alteration-transitopn process in the rock. As a result, more stable RM has been preserved in these tetragonal spinels

(this part of my new idea call for more complex evaluation of knowledge about this problem). The central point of the above mentioned processess is the internal field, which is generated by the Weiss molecular field in the system.

More complex explanation of the reversed magnetization of rocks will be complemented in a future by analyzing the magnetizing processes applying the available knowledge (*Brož, 1962; Hajko et al., 1982; Vonsovskij, 1971*). From the results we see that there have been generated two different types of mechanisms during magnetizing of samples versus temperature. The shifting of the domain walls and the magnetizing vector of spontaneous magnetization rotation. If it is so, the magnetizing vector of spontaneous magnetization rotation is exclusively actual only for Fe-Ti FriM- AFM ChPs in reck.

The effective laboratory methods for the detection of the magnetic behaviour of the Fe-Ti FriM-AFM ChPs containing in the rocks are described as well. I need to empasize that the application of the magnetic methods and procedures has played the very important role to reveal the presented new phenomena. A very favourable knowledge is that we are able to study the Fe-Ti FriM-AFM ChPs containing rocks also by the Curie and the T_N temperature measurements of powdered rocks (see above).

The presented results have allowed to establish a complte new model:

1) Only the normal RM can be find in the rocks, containing the isolated Ti-rich titanomagnetite, the isolated non-stoichiometric, or pure magnetite, the isolated non-stoichiometric, or pure hematite.
2) Only the reversed RM can be find in the rocks, containing the Fe-Ti FriM-AFM ChPs, either of the cubic, or the tetragonal symmetry. The complementary are the results of the self-reversal origin presented in a review above.

My final statement: the above presented results have shown that we do not need to apply the field reversal theory, because I have revealed the realistic mechanism which is able to generate the reversed RM of rocks under a presence of the normal geomagnetic field. The presented results have shown that we do not need to apply the field reversal theory, because I have revealed the realistic mechanism which is able to generate the reversed RM of rocks under a presence of the normal geomagnetic field.

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