A realistic interpretation of magnetic and paleomagnetic data: A study of basalts from Southern Slovakia

O. Orlický
Geophysical Institute of the Slovak Academy of Sciences[1]

Abstract: Basaltic rocks of the Pleistocene to Quaternary age from 38 localities from volcanic fields of southern Slovakia were studied. Except of the Curie temperature measurements of Fe-Ti oxides and the thermal demagnetization tests, also the hysteresis properties of selected samples of basalts were investigated. The basalts from 33 localities (87 %) were reversely magnetized, basalts from only 5 localities acquired originally normal remanent magnetic polarization (RMP). A very soft selection of magnetic phases has allowed to categorize the basalts into 6 groups with different magnetic properties and direction of RMP. The results have lead to the suggestion that the reversed RMP of basalts is a consequence of the self-reversal process acting during the magnetization of cooling rocks in the normal polarity geomagnetic field. Some basalts of originally reversed RM were re-heated during repeated volcanic activity, and they were remagnetized. They acquired either normal polarity of the RMP, or they attained extremely anomalous directions of the RMP.

Key words: softly differentiated Fe-Ti magnetic phases, self-reversal RMP, remagnetized basalts

1. Introduction

In classical paleomagnetism the field-reversal hypothesis is commonly applied to interpret the results in favour of some geological solutions, e.g. for the magnetostratigraphy, or a support of sea spreading hypothesis. In the earlier times this idea was largely applied in the study of basalts (*Orlický et al., (1982, 1996), Konečný et al., (2001)*.

Most paleomagnetists tend to have an optimistic attitude towards paleomagnetic results. They rely dominantly on the results of undisputed geophysical observations like the marine magnetic anomalies, polarity scales

[1] Dúbravská cesta 9, 845 28 Bratislava, Slovak Republic; e-mail: geoforky@savba.sk

and reconstruction of continental drift with the polar wander paths. Some of them are persuaded about the validity of the field-reversal hypothesis, and they are sometimes willing to support even exaggerated interpretations with respect to global geological point of view. *Larson and Olson (1991)* e.g. studied a correlation between the volume production rate of oceanic plateaus, seamount chains, and continental flood basalts and the magnetic reversal frequency. They suggested that the magnetic reversal frequency correlates inversely with mantle plume activity and that the mantle plumes control magnetic reversal frequency.

There are also authors who consider the results in a very realistic way. *Soffel (1978)* studied the Oligocene basalts from the Monti Lessini of the Southern Alps. He studied not only the paleomagnetic characteristics, but also the domain structure of magnetic Fe-Ti oxides of these rocks. He did not use the results for any paleomagnetic interpretation, because the correlation between age of remanence and age of rock was uncertain. Huge amount of paleomagnetic and magneto-mineralogical studies from the whole globe have resulted in an idea that the major problem are the alterations of magnetic minerals, the change of magnetic state, and the remagnetization of rocks. Many authors studied the remagnetized components of natural remanent magnetization (NRM) of rocks. *Gautam (1989)* studied trachytes and trachyandesites from the Aulis volcanics of the Tansen of the Lesser Himalaya, Nepal. He revealed that the remanent magnetization of rocks is of complex multicomponent origin composed of at least four components. Such or similar studies can contribute to a realistic view about the origin of the stable component of the NRM of rocks. In a global conception we follow to study not only some paleomagnetic relations of the rocks, but the most interesting phenomenon is the dynamics of the geomagnetic field, namely the existence or non-existence of a change of polarity of the geomagnetic field in the past. I suggested in my previous works, that the dynamics of the geomagnetic field has corresponded only to that, which has been registered at the world's observatories since about 1540 to the present (in *Orlický, 2002a*). According to the mentioned world's observatories data the changes of inclinations of the field have ranged about 10° and the declinations about 34°. I have assumed that no excursions, no changes of polarity of the geomagnetic field have existed in the past, nor in the present.

I have been aware of a dilemma that the field-reversal hypothesis is too deep-rooted in the mind of the specialists and largely accepted. It is not an easy way to persuade the paleomagnetists about its non-validity. Today, one can be very surprised that the pioneers of paleomagnetism *Brunhes (1906), Mercanton (1926) and Matuyama (1929)* had very high level of courage to initiate and support an idea about a change of polarity of the geomagnetic field (the field-reversal hypothesis), because in that time there was very little knowledge about the dominant carriers of magnetism, their complicated properties, including a possibility of self-reversal behaviour in some types of rocks. Moreover the basic theory about the magnetism of solid matter was only in an initial level.

Today, there is experimental evidence which has proven the direct laboratory reproducible self-reversal reversed remanent magnetization (RM), or partial thermoremanent magnetization (PTRM) in large amount of volcanic rocks *Orlický et al., (2000); Orlický and Funaki (2000, 2001, 2002); Orlický (2001, 2002, 2002a, 2002b, 2002c, 2002d, 2003, 2003a)*, except of works cited by other authors. These results are the most powerful arguments to persuade the specialists about the self-reversal origin of the reversed RM of rocks. But in many types of rocks intense alterations of original magnetic minerals developed, and only a small or no portion of the original Fe-Ti oxides was preserved, so an inducing of the reversed RM by the self-reversal process in the laboratory was impossible. For this reason the other effective way is necessary to be applied. Lately, I realized the laboratory works on the artificially prepared samples to support an idea about the self-reversal origin of RM of rocks *(Orlický, 2006, 2006a)*.

In this article I will contribute to the knowledge using a correlation of different Fe-Ti magnetic phases with some specific magnetic behaviour and the different directions of stable components of RM in large collections of basaltic rocks, which is the dominant task of this work.

2. Methodical setting, geological predispositions and evaluation of experimental data

The subject of this work is a study of basalts from the Lučenec basin and the Cerová vrchovina Highlands, from southern Slovakia (Fig. 1). From a global point of view the magnetic characteristics, the directions of RM of

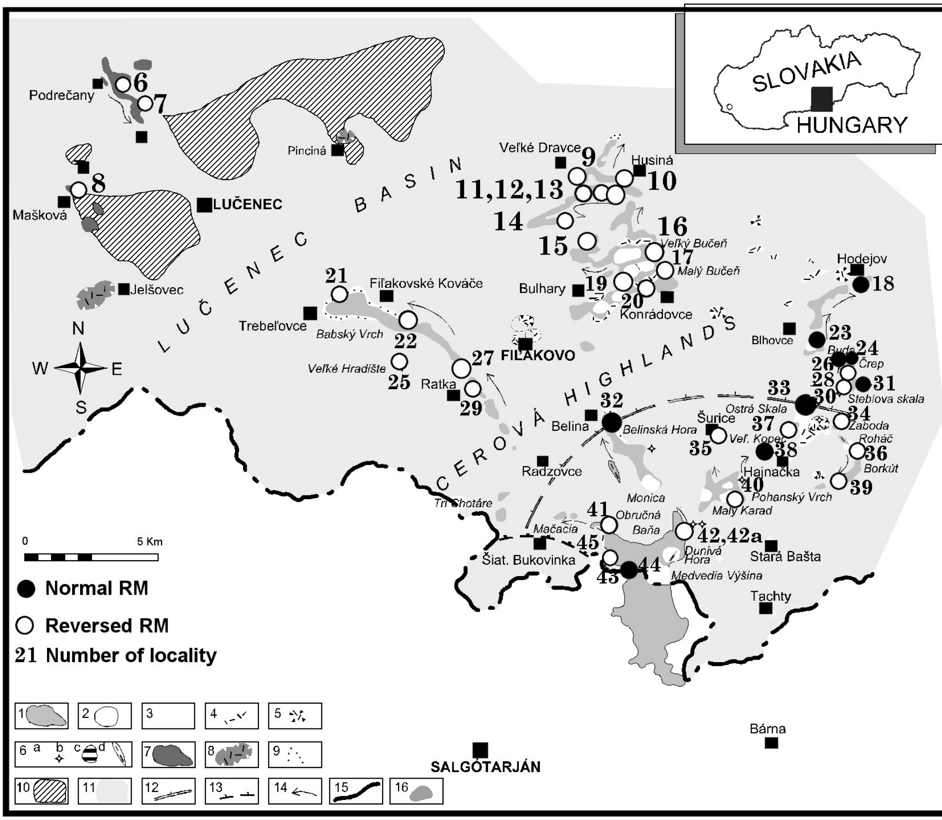

Fig. 1. A sketch map (according to *Konečný et al., (2001)*; modified by author of this article) - the distribution and forms of the Late Miocene to Early Quaternary alkaline volcanics, including the investigated localities (Mašková-8 to Šomoška-45) in southern Slovakia. Cerová basalt formation (Middle Pliocene - Pleistocene): 1– lava flows; 2 – scoria cone; 3– agglomerates; 4– lapilli tuffs; 5– maar; 6– eruptive centres (6a- diatreme; 6b- neck; 6c- extrusion; 6d- dyke). Podrečany basalt Formation (early Pliocene): 7 – lava flows; 8– maar. Belina Member (Romanian?): 9– gravels, clays, sands. Poltár Formation (Pliocene): 10– clays, sands, gravels, rare lignite lenses. 11– Early Miocene sediments, other signs; 12– updomed area; 13– local scale elevation; 14– direction of lava flows; 15– state boundary; 16– undifferentiated basaltic rocks.

basaltic bodies, the Curie temperatures of magnetic phases, some petrological aspects, and radiometric ages of basalts were used to make a categorization of basalts into some time-space arrangements in the area in question. It will be shown that the basalts of the same or similar petrological development and the same or similar magnetic phases posses the same or similar magnetic characteristics including the stability and the polarity of RM.

In the previous work it has been outlined that some basaltic bodies have shown mostly anomalous directions of RM *(Orlický, 2004)*. The causes of this behaviour were anticipated, but it has not been so far explained in detail. The results of the Curie temperature measurements and thermal demagnetization of samples of rocks are dominantly used to contribute to the solution of the problem of a realistic interpretation of paleomagnetic results of basaltic bodies. The magnetic hysteresis measurements of four samples were realized to consider the differences in magnetic stability of the the Ti-rich Ti-Mt bearing and magnetite-bearing basalts.

Alkali basalt volcanism in southern Slovakia had been active since the Late Miocene to Quaternary time, according to *Konečný et al. (2001)*. The development of basaltic volcanism was described in some abridged form also in *Orlický (2006)*. The basaltic volcanism started with the first phase in central Slovakia during 8.00 - 6.59 Ma (*Konečný et al., 2001*). Slightly younger are the products of the Podrečany basalt formation, including the two maars and lava flows dated on 7.2 – 6.4 Ma. It followed in the southern part of the Cerová vrchovina Highland and/or northern Hungary, in close relation with gradual uplift of this area (2nd volcanic phase). In the 3rd volcanic phase the eruptive centres migrated to the margins of the uplifted area. Afterwards the main volcanic activity expanded beyond the limits of the uplift, but still continued in a restricted extent in its centre (4th and 5th volcanic phase). The volcanic activity finished with phreatomagmatic explosions giving rise to several maars situated on the periphery of the uplifted area (Fiľakovo, Hodejov, 6th volcanic phase). The local updoming in southern Slovakia is contemporaneous with alkali basalts in the Cerová vrchovina Highland may indicate the presence of spatially limited mantle plume responsible for generation of basalt magmas. According to *Huraiová and Konečný (1994)* the estimate of equilibrium in pressure and temperature for mantle xenoliths indicates adiabatic uprise of mantle material. The outlined geological volcanic formations including the localities under study are in Fig. 1.

Differentiation of basalts using magnetic characteristics

The magnetic characteristics of basalts are not uniform in the area under study. Moreover with respect to a very large heterogeneity of mineralogical development within the individual volcanic bodies, it is not statistically possible to generalize the results, because many of basaltic bodies are covered by the surface layer, so they are not accessible, and that only limited number of samples could be collected for a study.

General knowledge about the magnetic minerals

The dominant magnetism carriers in basaltic rocks are the titanomagnetites (Ti-Mt-es), less frequently ilmenite-hematites (Ilm-Hem-es) and the Fe-Ti derivates of both types of minerals. We determined the composition and magnetic state of the Fe-Ti oxides in the natural basalts, but their predisposition was initiated during formation of hot magma, depending on the partial oxygen pressure in a magmatic state, during the ascent and cooling of magma on the earth's surface. The petrological conditions and oxidation of Ti-Mt and Ilm-Hem solid solutions have been described by Haggerty (in *Lindsley, 1991*). The primary source of Ti-Mt-es is not known exactly. They probably originated in the nascent state in basaltic magma from Fe and Ti components of more basic mantle (*Orlický, 2004a*). From the works about a synthesis of Fe-Ti oxides it is known that except of initial components TiO_2 and Fe_2O_3 a high temperature about 1200°C and the high level of vacuum are needed to prepare the Ti-rich Ti-Mt solid solutions (*Petersen and Bleil, 1973*). In magmatic conditions there is commonly a lack of oxygen. We can deduce that the Fe_2O_3 will be only rarely there in magma. We only assess from what level the basaltic magma has come from. The Cerová vrchovina Highland may indicate the presence of spatially limited mantle plume responsible for generation of basalt magmas. According to *Huraiová and Konečný (1994)* the estimate of equilibrium in pressure and temperature for mantle xenoliths indicates an adiabatic uprise of mantle material. *Larson and Olson (1991)* suggested that the mantle plumes rise from the *D* seismic layer just above the core/mantle boundary, about 2 900 km below the earth's surface.

The Ilm-Hem solid solutions are mostly transformed from the Ti-Mt-es, either during an ascent of magma to the earth's surface, or during hydrothermal alterations of original Fe-Ti oxides of basalts in post-burial conditions, according to *Lindsley (1991)*.

Thermal demagnetization and Curie temperature measurements

The magnetic and directional stability of RM of individual rock sample was tested using the stepwise thermal demagnetization of the rock sample. The paleomagnetic stability of the whole rock in question is considered using the Fisher's statistical coefficients - α_{95} (1/2 angle of cone of confidence for probability 0.95) and the so called precision coefficient k. Selected examples of the thermal demagnetization of samples are presented in Figs. 2–5. In these figures also the representative thermomagnetic curves of the Fe-Ti oxides of samples in question are included.

Basalts with primary Ti-rich Ti-Mt-es.

The results of measurements of the change of κ with temperature (Curie temperature measurements) and those of thermal demagnetization tests of samples are in Fig. 2. As the representatives of one large group the basalts from Mašková locality can be selected. The age of basalts is about 7 Ma. In Mašková-2 (Mašková-2-2) sample the dominant magnetism carrier is the Ti-Mt of $T_C \approx 120°C$. Two other magnetic Fe-Ti phases with $T_C \approx 220$ (very negligible portion) and 520°C are also present. The most important is the Ti-rich Ti-Mt with $T_C \approx 120°C$ (this phase corresponds probably to the composition of Ti-Mt in its primary state in magmatic conditions). This magnetic phase is not characterized by thermodynamically stable domain structure. It is probably in superparamagnetic-like (SP) behaviour magnetic state. Commonly in SP magnetic minerals no RMP could be predicted. In contrast with high portion of softly magnetic (non-magnetic) ulvöspinel in Ti-Mt solid solution, its $\kappa \approx 63553 \times 10^{-6}$ SI Units is relatively very high. Non changeable κ during heating of the sample in air (Fig. 2, Ma2-2, κ_T/κ_0 curve) has pointed out that this Ti-Mt is a relatively stable magnetic mineral. We see that there is a rapid decrease of RMP (demagnetizing curve J_T/J_0) of the sample Mašková 2-2 at about 200°C (Fig. 2). A residuum of RMP of the sample is linked to the secondary magnetic phases with the Curie temperature of up to 520°C. The basalts with such types of Ti-rich Ti-Mt-es acquired originally relatively low reversed intensity of RMP, so they have also low value of Q ratio. The RMP is not of the thermoremanent origin but it is supposed to be of thermo-viscous origin. I have proposed that this reversed RMP is of the self-reversed origin. In *Orlický (2006)* the results of partly self-reversed laboratory induced TRM of Ti-rich Ti-Mt of the natural basalts from Mašková locality and corresponding artificially prepared samples were demonstrated. *Petersen and Bleil (1973)* presented the results of self-reversed RMP of synthesized Ti-rich Ti-Mt-es. The partly reversed or totally reversed TRMP were induced in the geomagnetic field of

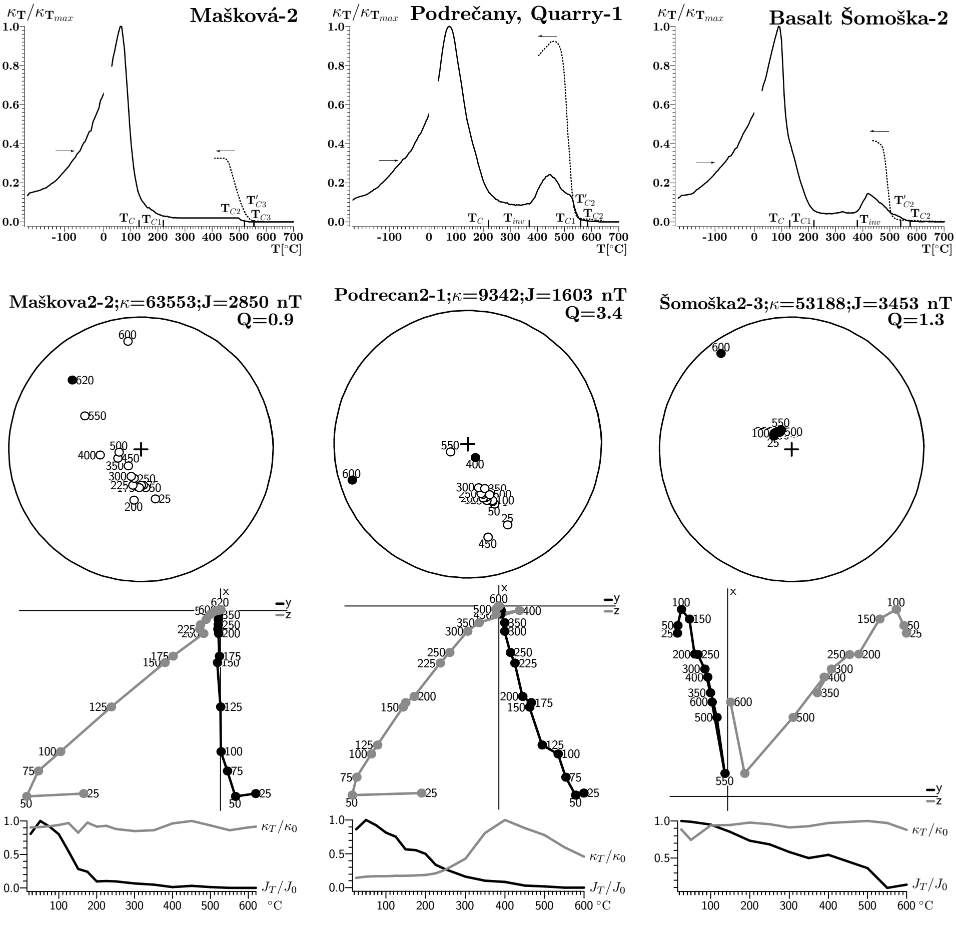

Fig. 2. Thermomagnetic curves (Mašková-2, Podrečany1, Šomoška2, $T_{C,C1}$,-Curie temperatures) and thermal demagnetization of samples (stepwise heating to 600°C); Zijderveld diagrams and stereographic projections; • (○)-positive (negative) polarity of RM;κ- magnetic susceptibility: κ_T at T, κ_0- at 25°C; values of κ in pictures are x 10^6 in SI units; J_T (J_0)- remanent magnetization at T and at 25°C; T_C' – Curie temperature during cooling of the sample; T_inv – inversion temperature.

normal polarity. I can deduce that the acquisition of the self-reversed RMP of basalts with the Ti-rich Ti-Mt-es is supposed to be a quite common process in nature.

The hot basaltic magma had probably some predispositions to be cooled on the earth's surface with the Ti-Mt composition, magnetic state and magnetic properties similar to basaltic sample of the Mašková-2 (see a thermomagnetic curve in Fig. 2). The dominant proportion of such magma was widely displaced and cooled in the investigated area (also around of updomed area, see in Fig. 1), at the beginning of the basaltic activity.

Basalts with low-temperature oxidized Ti-Mt phases

In some basalts the low-temperature oxidation of Ti-Mt-es (e.g. Podrečany, Quarry-1, Fig. 2, and Basalt Šomoška 3a, Fig. 3) is evident and in other samples from different positions of Mašková locality, Trebeľovce, Fiľakovské Kováče, NE of Ratka, SE of Ratka and Dunivá hora (Fig. 1, loc. 42). The oxidation of the original Ti-Mt of the sample probably passed out at the atmospheric condition during the post-volcanic time. The samples with the developed secondary oxidized phases have regularly a lower, sometimes extremely lower values of κ compared to the unoxidized samples. The cause of the lower κ in these basalts may be the following: According to *Stacey and Banerjee (1974)*: According to the Néel-Chevallier model for cation distribution in Ti-Mt-es the Fe^{3+}, ions always have a preference for the A-sites in the lattice. It is probable that oxidation results first in a decrease in the spontaneous magnetization (I_S), followed by an increase as exsolution occurs. Thus the low-temperature oxidation can result in a chemical remanence in basalts. Since the oxidation also causes a decrease in the number of magnetically anisotropic Fe^{2+} ions in the lattice, coercive force H_C is expected to be lowered, and hence, the new CRM is expected to be relatively unstable. In all these samples κ increased several times after thermal stepwise demagnetization during heating to 600°C and cooling to room temperature of the sample in air. There is evident dependence on the value of bulk κ of sample before heating. The lower the κ the more intense increase of κ during heating. It means that the secondary phases were developed very heterogeneously in different basalts or different parts of basaltic bodies (different values of bulk κ, see in Tables 1,2). Despite this peculiar properties and behaviour of the Fe-Ti magnetic phases of the sample, the stability and reversed directions of RMP are similar to that of unoxidized rock sample from Mašková quarry. There is gradual decreasing of RMP with the temperature, e.g., of the sample Podrečany 2-1 (Fig. 2), the sample Šomoška3A2-2 (Fig. 3), also the samples of other not documented localities. The decreasing of NRMP with the temperature (the demagnetizing curve J_T/J_0) is about 0.1 at 400°C of its original value at 25°C and then

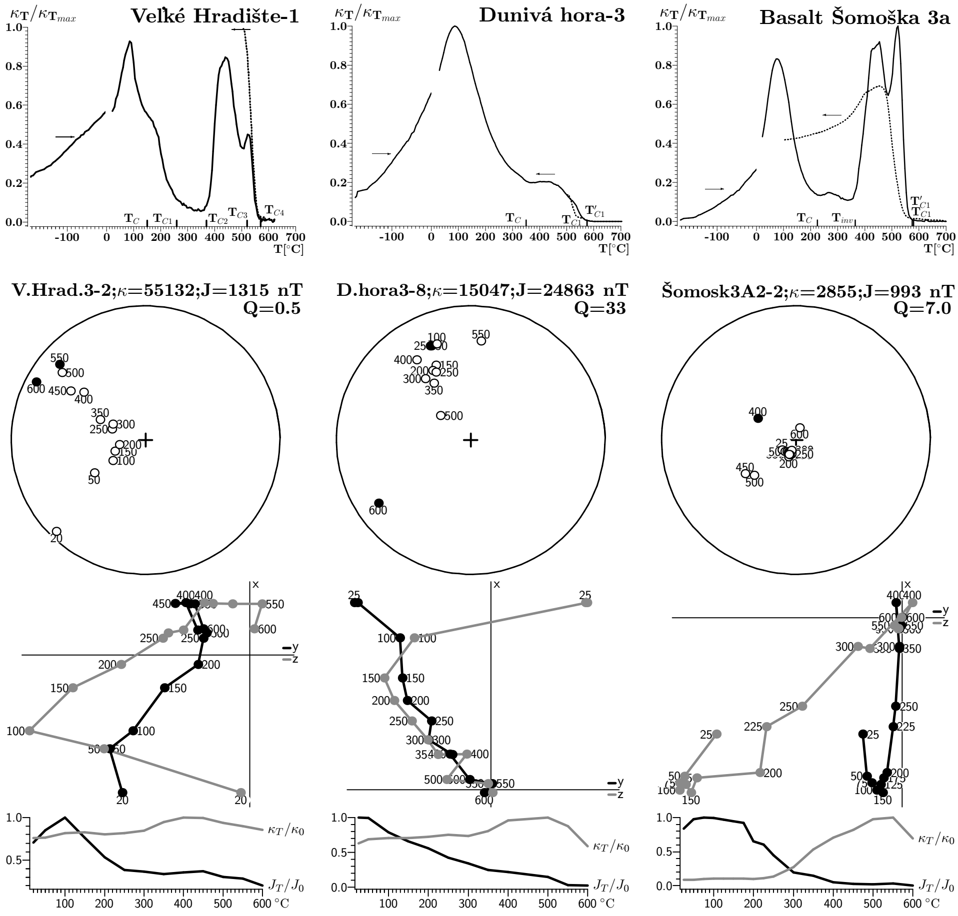

Fig. 3. Thermomagnetic curves (Veľké Hradište1, Dunivá hora3, Basalt Šomoška3a; $T_{C,C1}$,-Curie temperatures); Thermal demagnetization of samples: V. Hrad.3-2, D.Hora 3-8, Šomoška3A2-2 (stepwise heating to 600°C); Zijderveld diagrams and stereographic projections (explanations see in Fig. 2).

rather completely disappeared. One can assume that there was no developed classical domain structure in the rocks under the limit of about 150°C during low-temperature oxidation. In such types of basalts the direction of original reversed RMP changed only partly, or it has not changed at all.

Basalts containing high-temperature oxidized Ti-Mt phases

In many places a hot basaltic magma ascended and cooled below and on the earth's surface in the form of the neck and dyke bodies. One may suppose that the conditions during cooling of magma and creation of such forms were unlike those creating the basalt lava flows. A duration of hot magma in case of necks and dykes may take longer time below the surface. It may result in the high-temperature oxidation of a part of the Ti-Mt-es. As the examples the results of the neck and dyke forms of basalts Veľké Hradište-1, Dunivá hora-3 (Fig. 3) can be shown. The original Ti-Mt-es were partly oxidized, which has the influence on their magnetic properties. The original Ti-Mt-es were partly oxidized also by the low-oxidation process (up to about 350°C) after cooling of basalts during post-volcanic time. We see from Figs. 2,3 that the thermomagnetic curves have assigned more magnetic phases with the different Curie temperatures of the samples Veľké Hradište-1, Dunivá hora-3 (Fig. 3). These secondary phases have evident influence on the direction and stability of RMP. We see from Fig. 3 (V.Hrad.3-2 and D.hora3-8) that the RMP was nearly completely destroyed at about 600°C and at 560°C respectively (Fig. 3, demagnetizing curve J_T/J_0). Relative high resistance of RMP of the samples to thermal treatment resulted mainly in the presence of secondary high-temperature oxidized magnetic phases that carry the normal RMP. A very large deviation of declination of RMP for both samples is evident. Similar behaviour to the basalts of Veľké Hradište is shown also by several samples from Maar (28) and Steblová skala (30) localities (Table 2).

I have paid a special attention to the samples from large basaltic neck of Šomoška locality (Fig. 1, loc. 43, 44); the samples from both these places of one body differ in the declination of RMP. There are two dominant magnetic phases in these basaltic rocks. The first one with $T_C \approx 120$°C, which corresponds to the primary Ti-rich Ti-Mt. This phase is a source of high values of bulk κ of basalts and is of SP like behaviour. The second one with $T_C \approx 230$°C (250 °C), which originated due to high-temperature oxidation and the 3rd phase with $T_C \approx 560°C$ (570°C), corresponding to Ti-Mghemite. In all studied samples of this neck body all three mentioned phases developed, but not of the same portion and intensity. So the direction of RMP of all samples has shown some deviations. We see that in the sample Šomoška2-3 (Fig. 2) the RMP decreases only very softly up to 560°C (the demagnetizing curve J_T/J_0), NRMP and RMP after thermal demagnetization are of positive direction and they are very stable. Many samples from this locality have shown intense values of NRMP, which is a typical property for additionally highly-thermally oxidized primary Fe-Ti oxides. Very important phenomenon is, that the thermodynamically stable domain structure has developed in the dominant part of the Fe-Ti high-thermally oxidized phase. Owing to its high stability, only normal RMP in the basaltic body was induced by geomagnetic field during cooling. The basalts with such type of behaviour have not been found in other places of the area under study.

Basalts with the remagnetized Ti-Mt magnetic phases

There are basaltic bodies of the properties similar to those as in Fig. 4 (Ostrá skala-1, E of Steb. skala-3, Zaboda-2, or other localities, Fig. 1, Belinská skala, Veľký kopec) with normal or anomalous direction of RMP, that are situated on the eastern part of Cerová vrchovina Highland. They form some non-continual belt of NE-SW direction. These basaltic bodies originated probably during a stage, coinciding with that of Steblová skala. They had originally exclusively reversed RM which was linked to the primary Ti-rich Ti-Mt-es (a presence of small portion of Ti-rich Ti-Mt phase is evidenced by the measurements of Curie temperatures in nearly all of samples of the mentioned localities). During the reheating (or long time survival) of basaltic bodies, at the temperatures over about 300°C, a dominant portion of Ti-rich Ti-Mt of basalts of this group underwent high temperature transformation and more oxidized Ti-Mt-es originated (the high Curie temperature magnetic phases were established, Fig. 4).

This process of transformation can be simulated as follows: from the results of thermal demagnetization of samples with a presence of secondary - low-temperature oxidized Ti-Mt phases (Podreč.2-1, Fig. 2, Šom3A2-2, Fig. 3), or with small portion of preserved low-temperature oxidized Ti-Mt phase (E St.sk3-1, Fig. 4), there is evident an intense increase of κ_T/κ_0

curve over cca 300°C, with a maximum about 400°C or more (e.g. sample Podreč.2-1 κ_{Max} is 6 times more, the sample Šom3A2-2 is 9 times more than the κ before a heating of the sample). Such or similar behaviour is supposed to be a characteristic feature in the Ti-rich Ti-Mt-es with the low-temperature oxidized phases. This behaviour is a reflection of the creation of highly-temperature oxidized Ti-Mt phase. An initiation of nucleation and

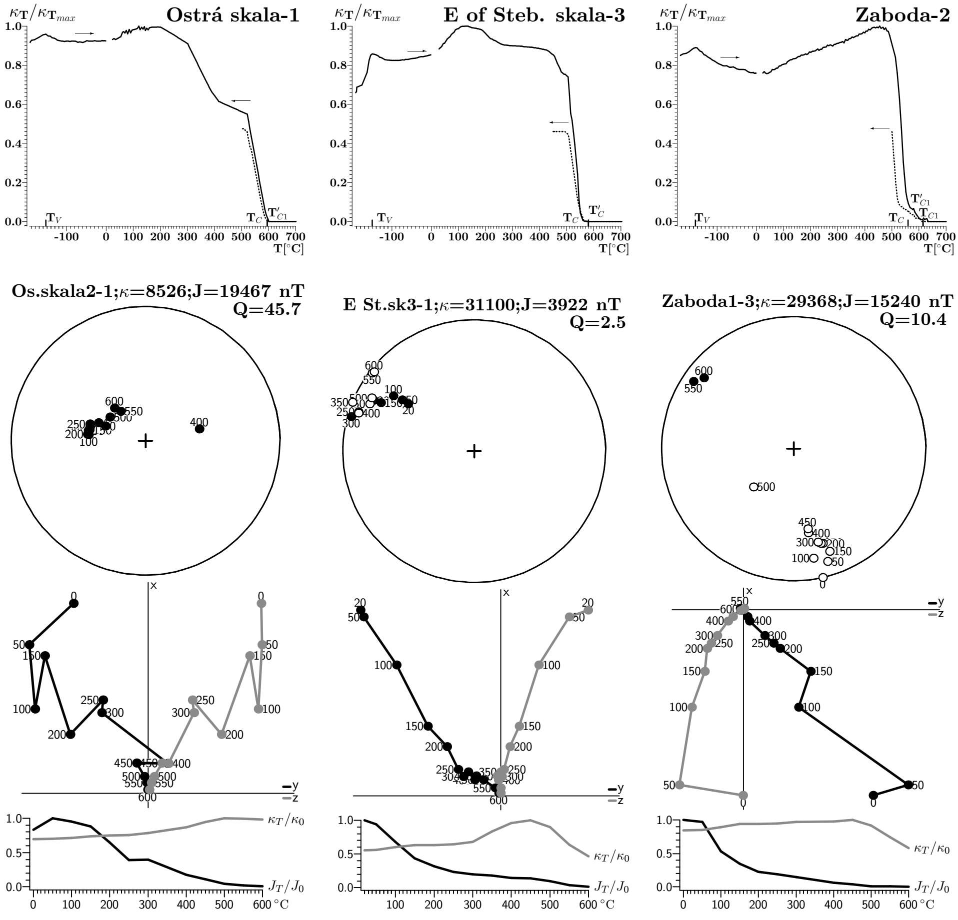

Fig. 4. Thermomagnetic curves of samples: Ostrá skala-1, E of Steblová skala-3, Zaboda-2; Thermal demagnetization of samples: Ostrá skala2-1, E St.Sk3-1, Zaboda1-3; (stepwise heating to 600°C); Zijderveld diagrams and stereographic projections. T_V - Verwey transition temperature. Other explanations see in Fig. 2.

the thermodynamically stable domain structures developed. We see from Figs. 2,3,4, that the remanent magnetization J_T/J_T curve of samples has gradually decreased and finally was nearly destroyed during stepwise thermal demagnetization in a fully compensated ambient magnetic field. We can expect a very similar transformation of original Ti-Mt-es also during the reheating of basaltic bodies in the field. But the final magnetic characteristics of basalts will be determined by two very important factors. There is a permanent presence of the geomagnetic field in nature and the process of reheating of original basalts by repeated volcanism (or survival of basaltic bodies under the additional high temperatures) took much longer time in the field than in the laboratory, during thermal demagnetization of samples. Because the transformation of the low-temperature Fe-Ti oxidized phases to high-temperature Fe-Ti oxidized phases depends on the time duration, it is possible to expect more intense increase of κ of basalts in the field than in the laboratory. While the complete thermal demagnetization of samples within the actual intervals from about 250° C to 650°C (9 temperature steps) took only about 15 hours in the laboratory, very long exposure of basalts under the heating can take at least months, years or tens of years in the field. Due to high κ of magnetic Fe-Ti oxides with the thermodynamically stable domain structures and the presence of the geomagnetic field the most portion of the viscous remanent magnetic polarization (VRMP) will be created in the rock. This will be linked dominantly to the multi-domain Fe-Ti particles. According to *Néel (1955)* viscosity can occur in multidomain grains, when thermal activation supplies the necessary energy for domain wall translation, meaning that the viscous effect arises from thermal activation of domains (*Stacey and Banerjee, 1974*). The VRMP will be accompanied also by the TRMP and CRMP in the new highly Curie temperature magnetic phase. This magnetic phase will be magnetized in the direction of the actual geomagnetic field (in positive sense and commonly of very high intensity). Magnetic stability of RMP of these rocks against the thermal demagnetization is mostly quite good, but there are some rocks with an unexpected dispersion in direction of the RMP. According to data in Table 2 (the numbers of localities are according to Fig. 1 and Table 2) the average directions of the RMP of basalts from lava flows of 3 further localities are: Črep(26:I=-2.0°, D=47.3°), E of Steblová skala(31: I=13.6°, D=285.7°) and Zaboda(34: I=-32.3°, D=162.0°). These directions are anomalous ones. In 3 samples of locality Črep 2 magnetic phases were detected one with $T_C \approx 220°C$, 2nd with $T_{C1} \approx 550°C$ (the 2nd phase is dominant).

The radiometric ages of basalts from these localities are (from 1.43 Ma for E of Steb. skala to 4.76 Ma for Belinská skala). Macroscopic image of most basalts from mentioned localities has outlined the presence of vesicles. The basalts are frequently either contaminated by assimilated heterogeneous volcanic material (inclusions and so), or some of them were thermally reworked. These results have proven the idea that the original basaltic bodies underwent additional volcanic activity expanded beyond the limits of the uplifted area. This activity was probably linked with the updoming of the eastern part of the Cerová vrchovina Highlands. Very important effect of additional volcanic activity was a reheating of the original volcanic material and that the original reversed RMP was remagnetized. Because there were created the thermodynamically stable domain structures in the reheated magnetic Fe-Ti minerals the remagnetized portion of Fe-Ti oxides acquired the normal RMP of the direction corresponding to the direction of the normal polarity of geomagnetic field (I$\approx$ +65°, D$\approx$ 1°). But the resultant direction of the RMP of mentioned basalts is the vector sum of this newly magnetized part of Fe-Ti oxides and that of original reversed RMP in the basalts. Depending on the direction and intensity of both components the resultant vector of basalts may be of positive or negative inclination and a very variable declination.

Basalts containing dominantly the Ilm-Hem solid solutions

The presence of the Ilm-Hem associations in basalts was detected by the results of Curie temperature measurements of the samples (see examples in Fig. 5, Husina3-2, Poličko1-1, Konrádovce - 1; similar thermomagnetic curves and other characteristics was shown also by samples of localities Veľ. Dravce, NE of Šavoľ, Bulhary and N of Šíd - Fig. 1 and Table 1), applying the knowledge presented in *Orlický (2004a)*. Dominantly the ilmenite-hematite solid solutions with the $T_C \approx 560°C$ (with Ilm content of about 15%) are present in these basalts. There is present also a small remnant of Ti-rich Ti-Mt in most of samples. The basalts belong to the relatively large lava flow with the radiometric age of about 1.16 to 1.6 Ma. The youngest basalts from the mentioned lava flow are supposed to be those from the

Čirinč (11, 12, 13 - Table 1) localities. Their Fe-Ti oxides are dominantly of Ti-Mt composition, containing also the secondary low-temperature oxidized phases. According to Dr. Vass (personal communication) they might initiate the reheating process of the whole lava flow in question, but a large lava flow was probably formed from the hot more oxidized magma. The Ilm-Hem-es originated from the original Ti-Mt-es during ascending of hot

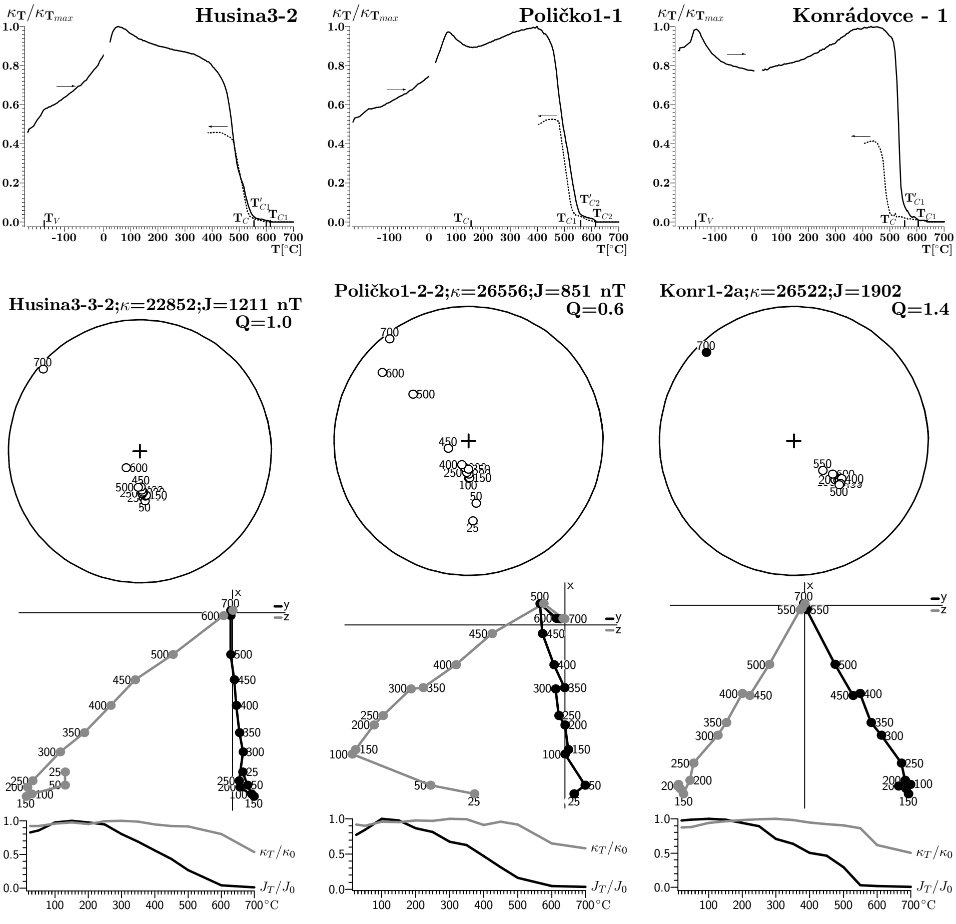

Fig. 5. Thermomagnetic curves (Husina3-2, Poličko1-1 and Konrádovce 1); Thermal demagnetization of samples: Husina3-3-2, Poličko1-2-2, Konr.1-2a (stepwise heating to 600°C); Zijderveld diagrams and stereographic projections. T_V - Verwey transition temperature (explanations in Fig. 2).

magma onto the Earth's surface. The Fe-Ti oxides in the intrusive conditions tend to re-equilibrate readily during cooling. This behaviour leads to a complex series of re-equilibration reactions. At high temperatures these reactions involve inter-grain exchange of ferric iron and Ti between Ti-Mt-es and ilmenite (Ilm) with the consequent enrichment of Fe_3O_4 in spinel and $FeTiO_3$ in rhombohedral phase. At intermediate temperatures Ti-Mt re-equilibrates by the process of oxyexsolution in which the Fe_2TiO_4 component of the Ti-Mt oxidizes to form granules of Ilm within or around the spinel. At lower temperatures the process produces lamellae of Ilm of the host spinel in *Lindsley (1991)*.
Ordinarily there is a better magnetic and directional stability of RMP of basalts with the Ilm-Hem associations, compared to Ti-Mt bearing rocks. We see from Table 1 quite low values of κ, low intensity of reversed NRMP, and relative high k and low values of α_{95} for samples of all localities in question. The RMP of samples decreases very softly. It was destroyed at the temperatures in the interval 560-600°C (Fig. 5, J_T/J_0 curve), and there is relatively low dispersion of directions of the reversed RMP in stereographic projections during thermal demagnetization of samples (Fig. 5, the samples Husina3-3-2, Poličko1-2-2, Konr1-2a). The causes of the reversed RMP of basalts with the Ilm-Hem carriers of magnetism were analysed and described in *Orlický (2006)*.

The magnetic hysteresis characteristics

There are depicted the results of hysteresis measurements of four selected basalts in Figs. 6,7. The measurements were realized with a very kind assistance of Dr. M. Funaki, in the National Institute of Polar Research in Tokyo.

From the measured hysteresis data the coercive force (H_C), remanent coercive force (H_{RC}), saturation magnetization (I_s) and saturation remanent magnetization (I_r) parameters were derived. The sample Blhovce Buda 1 of normal RM, containing nearly stoichiometric magnetite, with the H_C=333.7 Oe, and H_{RC}=605.8 Oe, is the most stable basalt among of all four tested samples. The samples Fiľakovské Kováče 2 (H_C=58.1 Oe, H_{RC}=105.0 Oe), Veľké Hradište 4 (H_C=56.9 Oe, H_{RC}=145.8 Oe) and Steblová skala 1 (H_C=39.7 Oe, H_{RC}=87.5 Oe), all of the reversed RM, dominantly with a high portion of Ti-rich Ti-Mt-es, are of very low mag-

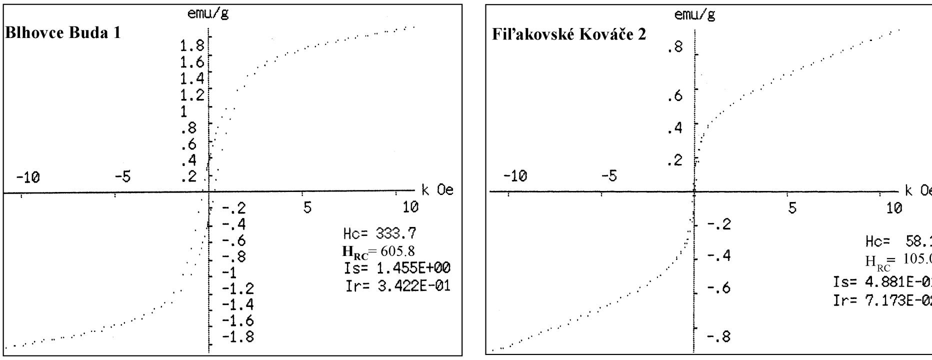

Fig. 6. Magnetic hysteresis loops of basalt's samples Blhovce Buda 1, and Fiľakovské Kováče 2. Explanations: emu–electromagnetic units; g–gramme; k Oe–kilo Oerstedt; H_C(Oe), H_{RC}(Oe)–coercive force (in Oe), remanent coercive force (in Oe), respectively; I_s–saturation magnetization; I_r–remanent magnetization.

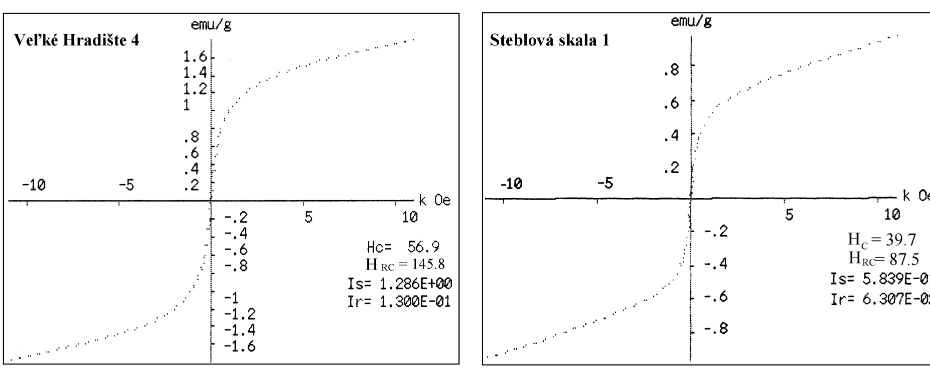

Fig. 7. Magnetic hysteresis loops of basalt's samples Veľké Hradište 4, and Steblová skala 1. Explanations see in Fig. 6.

netic stability. The results have very closely corresponded with the derived stability parameters k and α_{95} (in Tables 1,2) for the respective samples and localities. If there is present the intense developed secondary oxidized phase in the sample, the H_{RC} increases (e.g. the sample Veľké Hradište 4, H_{RC}=145.8 Oe), comparing it to the samples without/or with very low portion of the secondary phase.

Table 1. Magnetic characteristics and magnetic phases of basaltic rocks from southern Slovakia

Number, name of locality, age of basalts	n	$\kappa \times 10^6$ SI Un.	NRMP [nT]	Q	I°	D°	k	α_{95}	ΔI°	ΔD°	Mag. phases T_{C1}-T_{C3}(°C)
18-Hodejov	13	15432	853	1.2	51.0	19.0	18	14.6	-	-	480,595
23-Blhovce,1.73	11	36613	7249	4.0	88.0	11.0	115	5.2	-	-	570,610
24-Buda,1.73	6	18095	3045	3.4	61.0	3.7	4327	1.0	-	-	570,610
32-Belin.skala,4.76	7	35419	4132	2	60.8	358.7	407	3.8	-	-	210,560,605
38Hajnačka C.,2.58	15	32448	2620	1.6	63	31	19	5.2	-	-	160,500,570
43-Šomoška,4.06	18	54523	16733	6.2	66.5	349.6	115	3	-	-	120,230,560
44-Šomoška,4.06	3	62123	17710	5.7	74.2	327	231	8.1	-	-	120,250,570
Lava flows:											
8-Mašková,7.17	14	41750	3050	1.5	-66.6	178.5	115	4.0	8.5	2.2	140,560
6-Podrečany,6.44	18	13320	3046	4.6	-53.8	175.9	111	5.0	4.3	-0.4	220,560
7-Podrečany,6.44	5	21612	9617	8.9	-50.8	178.3	359	4.0	7.3	2.0	220,560
21-Trebeľovce.	4	12500	14690	23.5	-55.1	161.0	2003	2.1	3.0	-15.3	130,570,605
22-Fi.Kováče,2.15	4	19050	8610	9.0	-53.4	168.0	1165	2.6	4.7	-8.3	170,570,605
9-Veľ.Dravce,1.28	6	25895	749	0.6	-63.4	172.3	1171	2.2	5.3	-4.0	150,550
10-Husina	17	28309	613	0.4	-64.2	187.5	69	4.3	-6.1	11.2	140,560,605
11-13Čirinč	26	16172	1798	2.2	-68.3	237.7	28.3	25.1	-10.2	61.4	140,370,570
14-Poličko	10	28409	860	0.6	-63.0	177.1	273.7	2.9	-4.9	0.8	140,570,605
15-NE of Šavoľ,1.16	18	19413	848	0.9	-68.5	175.4	596	1.6	-10.4	-0.9	560,580
16-Konrádovce,1.5	8	11069	942	1.7	-68.6	171.8	892	3.2	-10.5	-4.5	150,575
17-Konrádovce,1.5	11	11313	924	1.7	-64.4	160.9	280	3.3	-6.3	-15.4	150,575
19-Bulhary, 1.6	14	27220	943	0.7	-34.3	166.6	31	12.2	23.8	-9.7	220,560
20-N of Šíd	7	12400	1729	2.8	-63.5	158.2	541	3.0	-5.4	-18.1	140,595

n – number of samples; K/Ag ages are in million of years; κ – bulk magnetic susceptibility; NRMP – natural remanent magnetic polarization; nT – nano Tesla; Q – Koenigsberger ratio; I°, D° – inclination, declination of stable component of RMP of basalts; k – precision parameter; α_{95} – semi-angle of cone confidence for P = 0.95; ΔI° – deviation of inclination; ΔD° – deviation of declination; mean directions of reversed stable components of RM derived from the data of lava flows of Podrečany and Cerová basalt formations (except of localities No. 11–13, and 21 and 22): I_{mean} = -58.1° – mean inclination of RMP; D_{mean} = 176.3° – mean declination of RMP; Mag. phases – magnetic phases of sample with Curie temperatures T_{C1}, T_{C2} – T_{C5}. The explanations are valid also for Table 2.

Magnetic characteristics, the deviations of directions of I and D of RM of basalts

Very interesting phenomenon is the reversed RM of dominant number of basaltic bodies. Basalts of only 6 from 37 localities acquired originally the normal polarity of RMP and basalts of 31 localities were originally of

Table 2. Magnetic characteristics and magnetic phases of basaltic rocks from southern Slovakia (explanations in Table 1)

Number, name of locality, age of basalts	n	$\kappa\times10^6$ SI Un.	NRMP [nT]	Q	I°	D°	k	α_{95}	ΔI°	ΔD°	Mag. phases T_{C1}-T_{C5}(°C)
Necks and dykes:											
25-V.Hradište,5.43	9	47887	2028	1	-53.0	282.6	41.7	8.1	5.1	106.3	150,260,370, 520, 570
28-Maar	7	35395	1406	1	-67.0	161.1	75	7.0	-8.9	-15.2	260,550
30-St.skala,4.63	7	33775	6180	4	-78.0	261.5	108	5.8	-19.9	85.2	140,570
33-Os.skala,2.6	4	25118	25863	21	22.5	11.2	90	26.6	80.6	-165.1	150,570,605
36-Ragáč	2	21051	1970	2	-70	255	96	8	-11.9	78.7	240,560
42-Dun.hora,1.3	3	23800	1260	1	-62.8	170.2	67	15.2	-4.7	-6.1	280,350,560
42a-Dun.hora,1.3	4	16725	24780	10	-42.7	345.6	3	61.5	15.4	169.1	520,570
Lava flows:											
26-Črep,4.1	7	34917	19262	11	-2.0	47.3	11.6	18.5	56.1	-129	220,550
27-NE of Ratka,1.94	9	33705	2430	1	-60.0	230.0	18	14.6	-1.9	53.7	120,560
29-SE of Ratka,1.94	10	35473	2509	1	-43.2	132.3	25	12.4	14.9	-44	120,560
31-E of St.skala,1.4	8	28915	3285	2	13.6	285	25	52	71.7	108.7	150,350,560
34-Zaboda,2.03	6	26601	19172	14	-32.3	162	18	16.3	25.8	-14.3	150,560,605
37-V.kopec,1.92	6	21057	3602	3	-41.1	155.1	30	12.5	17.0	-21.2	240,570
39-E of Hajnačka	6	24557	843	1	-76	195	315	5.2	-17.9	18.7	150,340,570
40-Pohan.vrch,5.03	11	29750	1415	1	-55.8	143.9	726	1.7	2.3	-32.4	570,610
41-Mačacia,2.61	6	34138	1607	1	-42.7	115.4	19	21.8	15.4	-60.9	160,570
45-Šomoška	4	8282	1157	3	-73.5	231.6	103	9.1	-15.4	55.3	230,360,560

reversed polarity of RMP. From the results of laboratory works an influence of secondary Fe-Ti magnetic phases on magnetic characteristics including the directions of RMP of rocks is evident. The mean direction of the reversed RMP of basalts (I_{mean} = -58.1°, D_{mean} = 176.3°) was derived from the results of 11 outcrops (6–10, 14–17 and 21–22) that have shown the closest directions to each other. The deviation of inclination ΔI and deviation of declination ΔD (+ in clockwise direction, - in counterclockwise direction) of the stable component of the RMP for the rocks of individual outcrops were derived (Tables 1,2). The largest ΔI, or ΔD have been detected for basalts of necks and dykes (Table 2), and basalts of lava flows which underwent repeated heating and successive remagnetization (Table 2). I can propose that the directions of RM of basalts of the localities with a large deviations of ΔI and ΔD (Table 1, loc. 11-13- Cirinc; Table 2 - all localities) do not correspond to the actual direction of the geomagnetic field from the time of the origin of the RMP of rocks, but they are a consequence of remagnetization of the original RMP.

3. Discussion and conclusions

Basaltic rocks from 38 localities were studied. It is interesting that basalts from 33 localities (87%) were originally magnetized reversely and only rocks from 5 localities were magnetized in the sense of the normal field. *Orlický (2004a)* presented the results on the anomalous and unusual properties of titanomagnetites with high portion of ulvöspinel (with low $T_C \approx$ 120-130°C and compositional parameter x $\approx$ 0.68-0.70). I have applied this knowledge to the explanation of the reversed RM of basalts as well as to a more detailed description of Fe-Ti magnetic phases. I have presented an idea that in basalts with the Ti-Mt-es of well developed domain structure the normal RMP of TRMP origin is acquired during cooling of magma. But when there are the Ti-Mt-es of SP-like state in basalts, there is a chance to acquire the thermo-viscous RM of a reversed sense during cooling of basaltic magma.

In this article it is shown that the basalts with a different Fe-Ti compositions (different Curie temperatures) and magnetic state have different magnetic properties including the stability and the direction of the RMP.

- The basalts with dominantly nearly-stoichiometric magnetites have high magnetic, directional stability and only normal polarity of RMP. The basalts of only 4 localities belong into this group (18-Hodejov, 23-Blhovce, 24-Blhovce Buda and 38-Hajnačka Castle)

- The basalts with primary Ti-rich Ti-Mt-es. This magnetic phase is not characterized by thermodynamically stable domain structure. It is probably of a superparamagnetic-like behaviour (SP) state. In contrast with high portion of softly magnetic ulvöspinel in Ti-Mt solid solution, its κ is relatively very high. The basalts with such types of Ti-rich Ti-Mt-es acquired originally relatively low self-reversed intensity of RMP, which is not of the thermoremanent origin, but it is supposed to be of thermo-viscous origin, of low magnetic and directional stability.

The hot basaltic magma had probably some predispositions to be cooled on the earth's surface with the T-rich Ti-Mt composition, SP magnetic like state and magnetic properties that have an ability to acquire the self-reversal remanent magnetization. Dominant proportion of such magma was widely displaced and cooled in the investigated area (also around the updomed area), at the beginning of the basaltic activity.

- The basalts with low-temperature oxidized Ti-Mt phases. These types of the secondary phases were developed very heterogeneously in different basalts or different parts of basaltic bodies. The samples with the developed secondary low-temperature oxidized phases have regularly a lower, sometimes extremely lower values of κ compared to the unoxidized samples. The stability and reversed directions of the RMP are similar to that of unoxidized rock samples. We can assume that there has not developed the classical domain structure in the rocks under the limit of about 150°C during low-temperature oxidation. In such types of basalts the direction of original reversed RMP changed only partly, or it has not changed at all.

- The basalts containing high-temperature oxidized Ti-Mt phases. In the neck, dyke forms and large domatic volcanic bodies the cooling of magma might have taken longer time. It may result in the high-temperature oxidation of part of the Ti-Mt-es. The original Ti-Mt-es were partly oxidized, part of them were preserved in their original form. It has the influence on their magnetic properties. In such types of basalts the original Ti-Mt-es were partly oxidized also by the low-oxidation process after cooling of basalts during post-volcanic time. These high-temperature oxidized phases have evident influence on the direction and stability of the RMP. The magnetic component with the high-temperature oxidized magnetic phases carries the normal RM. There is evidence of very large deviation of the direction of the RMP in the basalts with both the original and the high-temperature oxidized magnetic phases.

A special case of large basaltic neck of Šomoška locality has been presented. In this body the two dominant magnetic phases are present. One phase with a primary Ti-rich Ti-Mt is a source of high values of bulk κ of basalts and is of the SP like behaviour magnetic state. The second phase originated due to high-temperature oxidation of the original Ti-rich Ti-Mt-es. It can be supposed that the thermodynamically stable domain structure has developed in the dominant part of the Fe-Ti high-temperature oxidized Fe-Ti phase and the thermo-remanent magnetization (TRM) of normal polarity was acquired during cooling of the basaltic magma in the geomagnetic field. Also a third titano-maghemite phase has developed which has acquired also only the normal polarity RMP. Many samples from Šomoška locality have shown intense values of the NRMP. This behaviour is a typical property for the highly-temperature oxidized primary Ti-Mt-es with a presence of low-temperature oxidized phases.

- The basalts with the remagnetized Ti-Mt magnetic phases. There are basaltic bodies which form a non-continual belt of NE-SW direction in the eastern part, near the updomed area of the Cerová vrchovina Highland (the respective localities have been described above). They have normal or anomalous direction of the RMP. These basaltic bodies had originally exclusively reversed polarity of the RMP, and were linked with the presence of Ti-rich Ti-Mt-es. The secondary Fe-Ti magnetic phases of high Curie temperatures (nearly to stoichiometric magnetite) with the stable domain structure developed during re-heating of original volcanic material in the field. A new remagnetized component with the normal polarity and direction of RMP corresponding to normal polarity geomagnetic field was created during this reheating process. The resultant direction of the RMP of the mentioned basalts is the vector sum of this newly magnetized part of the Fe-Ti oxides and that of original reversed RMP in the basalts. Depending on the direction and intensity of both components the resultant vector of basalts may be of positive or negative inclination and very variable declination (the results see in Tables 1,2). Very important aspect of this reheating process is the creation of a new, frequently very high intense RMP. This magnetization is dominantly of a viscous origin (VRMP), or a combination of a chemical VRMP CRMP and TRMP, in major portion of normal polarity.

Because there is no direct geological evidence for repeated volcanism in the respective area, I present some geophysical and petrological aspects. In *Šefara et al. (1996)* an idea was presented, that the mantle xenoliths which were transported to the surface by the youngest alkaline basalts give petrological evidence about the uplift of the local partially molten masses. There have been presented geotherms for the thick continental crust as well as for the provinces with alkaline-basaltic volcanism. In analogy to South Australia, characterized by the high heat flow, the above authors expect similar geotherm courses in Southern Slovakia. However, the geotherm reminds rather an adiabatic uplift of the upper mantle masses, which also confirms the upper mantle situation. The updoming of the upper mantle is also indicated by the paleorelief change and by basaltic volcanism (*Konečný et. al., 1996*). Simultaneously with updoming the volcanic activity first broke out in the central part and gradually moved outwards, while that in the centre continued only to a limited extent. The updoming is documented by radial distribution of the lava flows and by intense erosion in the updoming centre. With respect to the global point of view there was a process of thinning of the lithosphere, which was associated with an uplift of asthenospheric, partially molten masses, accompanied by local asthenoliths. Geophysical and petrological evidence has shown that the uplift of the local partially molten masses nearly reached the Moho discontinuity (*Šefara et al., 1996*). The results of the study of the magnetic and paleomagnetic properties of basalts have confirmed the remagnetization of the original RMP, and so the repeated thermal effects on some original volcanic bodies took part in some places of the area.

- The basalts containing dominantly the Ilm-Hem solid solutions. The basalts of 11 localities belong into the relatively large lava flow with the radiometric age of about 1.16 to 1.6 Ma. The large lava flow was probably formed from the hot more oxidized magma. The Ilm-Hem-es (of the composition about 15% of Ilm) originated from the original titanomagnetites during ascending of hot magma onto the Earth's surface. The rocks of all localities have exclusively the reversed RM. The causes of the reversed RMP of basalts with the Ilm-Hem carriers of magnetism were analysed and described in *Orlický (2006)*. Moreover, according to *O'Reilly and Banerjee (1966)* the self-reversal may be linked with the production of a highly oxidized cation deficient spinel at high temperatures. Under these conditions there might be expected the stabilizing effect of suitable magmatic gases, where then the A sublattice moment will result. Subsequent decomposition to the magnetite-ilmenite intergrowth will then produce a reversal moment. This would provide the physical model for explaining the correlation between reversed lavas and the signs of a high degree of oxidation. Ordinarily there is a better magnetic and directional stability of the RMP of basalts with the Ilm-Hem associations, comparing it with Ti-Mt bearing rocks.

There are radiometric ages available for some basalts, but because the correlation between age of remanence and age of rock is uncertain their application is supposed to be problematic. A strict application of this attitude to all previously published paleomagnetic results would mean that many if not most of them are unreliable and have to be interpreted in a different way.

From the presented results it is evident that the presence of different composition and magnetic state of Fe-Ti phases results in different magnetic properties, including the polarity and direction of the RMP of basalts. It could be deduced that the reversed RMP of the studied basalts can be explained on the basis of the self-reversal hypothesis and the is not necessary to apply so far a non exactly verified field-reversal hypothesis.

Acknowledgments. The author is very grateful to Dr.M. Funaki from the National Institute of Polar Research, Tokyo for his help with the hysteresis measurements of samples, to Prof. Dr. D. Vass for his fruitful consultation, and to the Slovak Scientific Grant Agency (grant No. 4042) for the partial support of this work.

References

Brunhes B., 1906: Recherches sur la direction d'aimantation des roches volcaniques. Journal Phys. **5**, 705–724.

Gautam P., 1989: Multi-Component Remanent Magnetization in the Aulis Volcanics, the Lesser Himalaya, Nepal. J. Geomag. Geoelectr., **41**, 101–117.

Huraiová M., Konečný P., 1994: Pressure-temperature conditions and oxidation state of upper mantle in the Southern Slovakia. Acta Geol. Hung., **37** (1-2), 33–44.

Konečný V., Lexa J., Balogh K., Konečný P., 1996: Alkali basalt volcanism in southern Slovakia volcanic forms and time evolution. Spacial Issue of Acta Volcanologica.

Konečný V., Balogh K., Orlický O., Lexa J., Vass D., 2001: The evolution of Neogene-Quaternary alkali basalt volcanism in Western Carpathians (Slovakia). Session Carpathians, Poster. Pancardi 2001, II. Abstracts, CP-11.

Larson R. L., Olson P., 1991: Mantle plumes control magnetic reversal frequency. Earth and Planetary Science Letters, **107**, 437–447.

Lewis M., 1968: Some Experiments on Synthetic Titanomagnetites. Geophys. J. R. astr. Soc., **16**, 295–310.

Lindsley D. H., 1991: Oxide Minerals: Petrologic and Magnetic Significance. Reviews in Mineralogy, **25**. Series Editor: Ribbe P. H., Mineralogical Society of America, 698 p.

Matuyama M., 1929: On the direction of magnetization of basalt in Japan, Tyôsen and Manchuria. Proc. Imp. Acad. Japan, **5**, 203–205.

Mercanton P. L., 1926: Inversion de l'inclinaison magnétique terrestre aux ages geologiques. Terr. Magn. Atmos. Elec., **31**, 187–190.

O'Reilly W., Banerjee S. K., 1966: Oxidation of titanomagnetites and self-reversal. Nature, **211**, 26–28.

Orlický O., Kropáček V., Vass D., 1982: Paleomagnetism and radiometric ages of alkaline basalts from the Central and Southern Slovakia. Miner. slovaca, **14**, 2, 97–116 (in Slovak).

Orlický O., Balogh K., Konečný V., Lexa J., Túnyi I., Vass D., 1996: Paleomagnetism and radiometric ages of basalts of the Central and Southern Slovakia. Geol. Carpathica, **47**, 21–30.

Orlický O., Funaki M., Pagáč P., 2000: Study of the self-reversal thermoremanent and partial thermoremanent magnetization of the Haruna dacite from central Japan. Contr. Geophys. Geod., **30**, 4, 323–342.

Orlický O., Funaki M., 2000: An origin and mechanism of the self-reversal TRM or PTRM of rocks. A Study of the Rhyodacite from the Haruna Locality (Japan). Geol. Carpathica, **51**, 203–204.

Orlický O., Funaki M., 2001: Magnetic study of individual Fe-Ti oxides separated from the rhyodacite of the Haruna Volcano (Japan) and the dacite ash of Mount Pinatubo (Philippines). Contr. GeophYS. Geod., **31**, 3, 537–556.

Orlický O., Funaki M., 2002: Study of laboratory induced self-reversed thermoremanent magnetization and the Fe-Ti oxides of the dacite ash from the 1991 Pinatubo eruption (Philippines). Stud. Geoph. Geod., **46**, 527–544.

Orlický O., 2001: Field-reversal versus self-reversal hypothesis: Paleomagnetic properties and magnetic mineralogy of the Neogene andesites of central Slovakia (Part I). Contr. Geophys. Geod., **31**, 4, 653–681.

Orlický O., 2002: Field-reversal versus self-reversal hypothesis: Paleomagnetic properties and magnetic mineralogy of the Neogene andesites of central Slovakia (Part II). Contr. Geophys. Geod., **32**, 1, 1–40.

Orlický O., 2002a: Field-reversal versus self-reversal hypothesis: Paleomagnetic properties, magnetic mineralogy and the reproducible self-reversal RM of the Neogene andesites from the Javorie and Poľana mountain range (Part III). Contr. Geophys. Geod., **32**, 2, 91–128.

Orlický O., 2002b: Field-reversal versus self-reversal hypothesis: Paleomagnetic properties, magnetic mineralogy and the reproducible self-reversal RM of the Eocene to Miocene age volcanic rocks from České Stredohorí Mts.-North Bohemia (Part IV). Contr. Geophys. Geod., **32**, 2, 129–149.

Orlický O., 2002c: Field-reversal versus self-reversal hypothesis: Paleomagnetic properties, magnetic mineralogy and the reproducible self-reversal PTRM of the Neogene andesites from the Kremnické vrchy mountain range (Part V). Contr. Geophys. Geod., **32**, 4, 309–333.

Orlický O., 2002d: Field-reversal versus self-reversal hypothesis: Paleomagnetic properties, magnetic mineralogy and the reproducible self-reversal PTRM of the Neogene andesites from the East-Slovak Lowlands, Zemplínske vrchy Mts., and the Slanské vrchy Mts., (Part VI). Contr. Geophys. Geod., **32**, 4, 359–373.

Orlický O., 2003: Field-reversal versus self-reversal hypothesis: Paleomagnetic properties, magnetic mineralogy and the reproducible self-reversal PTRM of the Neogene andesites from the Vihorlat Mts. (Part VII). Contr. Geophys. Geod., **33**, 1, 57–76.

Orlický O., 2003a: Field-reversal versus self-reversal hypothesis: Paleomagnetic properties, magnetic mineralogy and an origin of the reversed RM of the Neogene rhyolites from central and eastern parts of Slovakia (Part VIII). Contr. Geophys. Geod., **33**, 2, 77–97.

Orlický O., 2004: Field-reversal versus self-reversal hypothesis: Magnetic and paleomagnetic properties of basalts from central and southern Slovakia (Part XIII). Contr. Geophys. Geod., **34**, 3, 251–274.

Orlický O., 2004a: Magnetic mineralogy and anomalous magnetic susceptibilities of basalts from Central and Southern Slovakia, Contr. Geophys. Geod. **34**, 3, 227–249.

Orlický O., 2006: Field-reversal versus self-reversal hypothesis: Different intensities of TRM of the reversely magnetized natural basalts and those of the same origin of artificial samples magnetized in laboratory. Contr. Geophys. Geod., **36**, 1, 35–48.

Orlický O., 2006a: Field-reversal versus self-reversal hypothesis: The Ti-rich titanomagnetite bearing basalts and their partly self-reversed thermoremanent magnetization induced in the laboratory field. Contr. Geophys. Geod., **36**, 2, 1–18.

Petersen N., Bleil U., 1973: Self Reversal of Remanent Magnetization in Synthetic Titanomagnetites. Zeitschrift für Geophysik, Band **39**, Physica - Verlag, 965–977.

Soffel H. C., 1978: The Reliability of Paleomagnetic Data from Basalts with Low Curie Temperatures ($T_C \leq 90°C$). Phys. of the Earth and Planet. Interiors, **16**, 38–44.

Stacey F. D., Banerjee S. K., 1974: The physical principles of rock magnetism. Amsterdam - London new York, 195 p.

Šefara J., Bielik M., Konečný P., Bezák V., Hurai V., 1996: The latest stage of development of the lithosphere and its interaction with the asthenosphere. Geol. Carpathica, **47**, 6, 339–347.