On the demonstration of the normal polarity of remanent magnetization by volcanic rocks containing magnetite or hematite

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Abstract: Magnetic and paleomagnetic properties, and magnetic mineralogy of the Neogene andesitic rocks were previously studied. The author of the article has recently proposed a model of the sources of normal and reversed RM and tested it applying the results of the submarine volcanics (*Orlický, 2010*). The magnetites (cubic phase) and the titanium rich titanomagnetites (cubic phase) have been considered as the carriers of only normal remanent magnetization of the rocks. The low-temperature oxidized titanomagnetites and the Ilmenite-Hematites (Ilm-Hem; rhombohedral phase) carry either the reversed remanent magnetism (RM) of self-reversed origin, or normal RM, depending on the proportion of hematite in the Ilm-Hem solid solutions. I have enlarged the original model in the hematite bearing rocks which carry only normal RM. The paleomagnetic and magnetic results and the results of magnetic mineralogy of selected Neogene andesites and rhyolites from central, southern and eastern Slovakia of the Badenian to the Middle or Lower Sarmatian age (16.05–12.9 M.Y.) have been considered. The selected rocks with the magnetites and hematites have revealed only the normal RM. Normal partial thermoremanent magnetization (PTRM) was induced in many magnetites and hematites containing andesite and rhyolite samples in the laboratory. The occurrence of both these types of magnetic minerals is quite rare in volcanics. While the magnetite is more frequently present in the intrusive rocks, the hematite is frequently present in effusive, more acidic volcanics, e.g. in the rhyolites. Very important outcome is that both magnetite and hematite are the carriers of only normal polarity of RM in the rocks, regardless their age.

Key words: Neogene volcanics, magnetism and magnetic mineralogy, magnetite and hematite – the carriers of normal RM

1. Introduction

Magnetic and paleomagnetic properties, and magnetic mineralogy of the Neogene andesites and rhyolites were previously studied. In particular, the magnetite (Mt) has been considered as a carrier of normal remanent magnetization (*Orlický, 1986*). A correlation between opaque petrological parameters and the polarity of remanent magnetization (RM) were found previously by other authors. *Balsley and Buddington (1954)* revealed a correlation between the type of magnetic Fe-Ti minerals and that of polarity of RM of metamorphic rocks in the Adirondack Mountains. Rocks containing the magnetite (Mt) invariably showed normal polarity of RM, but the reversed polarity of RM was detected in the rocks containing the ilmenite-hematite (Ilm-Hem) solid solutions. The author of this article has proposed an enlarged model of the sources of normal and reversed RM of rocks (*Orlický, 2010*). The titanium rich (Ti-rich) titanomagnetite (Ti-Mt) and Mt have been considered as the carriers of normal RM and the low-temperature oxidized Ti-Mt (titanomaghemite, Ti-Mgh) and high-temperature oxidized Ti-Mt, Ilmenite-Hematites (Ilm-Hem) have been considered as the carriers of the reversed RM of the rocks of self-reversal origin. The results of submarine volcanics from limited number of sites and holes from the Mid-Atlantic and the Pacific Oceans have been compared to test a validity of the model (*Orlický, 2010*). The results were presented also at the 12^{th} Castle Meeting in Nové Hrady, Czech Republic, 29 August – 4 September 2010.

I have now complemented the previous model with the pure, or pseudobrookite intergrowth hematite (the higher and the final high-temperature oxidized Ti-Mt phase). From this model it has followed that the nearly pure magnetite bearing and the hematite bearing neovolcanics would be the carriers of normal polarity of RM. Generally, the pure magnetites and hematites have been detected very rarely in the volcanic fields of Slovakia (Štiavnicke vrchy, Vtáčnik, Kremnické vrchy, Javorie, Poľana, Vihorlat, Slánske vrchy, Zemplínske vrchy). The propylitized andesites of the 1^{st} stage, the diorites and granodiorites of the Hodruša-Štiavnica complex, andesite porphyry of the Tanád intrusive complex, the silica-diorite porphyry of the Banisko intrusive complex, Sihlanský diorite and the silica diorite and monzonodiorite of the Kalinka intrusive complex, both from Javorie area, have shown a dominant presence of magnetite (together only about 20 localities from a total number of 802 investigated localities). In most of localities the magnetites and hematites have occurred with the other Fe-Ti derivatives, or they have been accompanied by other mineral associations. The selected results from my previous works will be compiled to compare them with the model suggested above.

2. A selection of rocks with magnetite or hematite bearing rocks

Volcanics containing predominantly the magnetite as a carrier of RM

We see from Table 1 that the Q coefficient is relative low, which indicates that the magnetic and paleomagnetic stability of the andesites is very low. The inclinations of RM of the rocks of 10 localities are close to that of the probable geocentric dipole with respect to the geographical coordinates of localities, but the declinations of RM of rocks have shown a large dispersion. But the rocks from all localities show a normal polarity of RM. I have presented the results of the thermomagnetic measurements of 4 rock samples in which the magnetite was dominantly detected on the basis of T_C and T_V characteristic points (Fig. 1). There have been presented also the results of the nepheline basanite sample b2-1-4 from the Brehy locality, which is not a typical for the whole nepheline basanite lava flow. Whole basaltic lava flow contains predominantly the Ti-Mt-es with high portion of ulvöspinel. The sample b2-1-4 was collected from the boundary place of the lava flow, which was in close contact with the sedimentary rocks. The RM of this sample is very stable and it has reflected the probable direction of the field from the time of original cooling of the body.

Table 1. Magnetic characteristics of selected propylitized pyroxene andesites of the Lower Badenian age with magnetite as the main carrier of normal RM in the rocks. The rocks are located in the area defined by the coordinates $\varphi = 48.384 - 48.500°$ and $\lambda = 18.684 - 18.919°$

Locality, Sample No	$\kappa \times 10^6$ SI Units	NRM [nT]	Q	I°	D°	Locality, Sample No	$\kappa \times 10^6$ SI Units	NRM [nT]	Q	I°	D°
I-65-10	8566	320	0.75	49.3	269.4	I-104-7	7335	206	0.56	19.4	49.8
I-111-4	904	166	3.7	65.0	78.0	I-128-7	26740	501	0.4	68.0	330.0
I-129-8	4999	75	0.3	30.9	335.0	I-150-2	27582	620	0.44	75.2	90.3
I-167-5	9332	263	0.56	74.2	318.3	I-168-2	12459	222	0.36	55.6	1.2
I-171-4	18488	289	0.31	62.8	64.3	I-181-4	27582	620	0.45	75.2	152.5
I-234-2	7398	142	0.38	67.9	13.6	I-235-3	18199	428	0.47	78.0	322.0

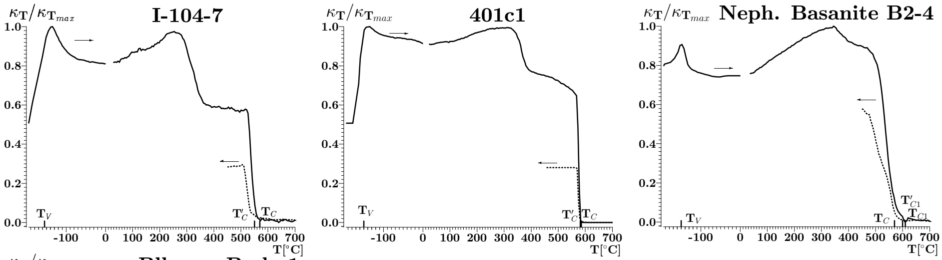
NRM – natural remanent magnetization; nT – nano Tesla; D° – declination; I° – inclination of stable remanent magnetization; Q – Koenigsberger's coefficient.

The representative thermomagnetic curve of the propylitized magnetite bearing andesites is shown in Fig. 1, sample I-104-7. The magnetite has been detected also by the Mössbauer spectroscopy results (Table 1). The Fe-sulphides were detected in the rocks of many localities with the propylitized andesites of the 1st phase. I assume that the magnetite was created from these Fe-sulphides during the propylitization process, and so the CRM magnetization was induced in the rocks. In other rocks of this first phase also the oxidized Ti-Mt-es and the Ilmenite-hematites have been detected. It can be pointed out that the direction of RM might be influenced by the RM of these secondary magnetic phases.

Magnetite alone is quite rare as the carrier of RM in volcanic rocks. It has mostly occurred either in intrusive rocks or in the rocks which have been intensely altered (*Orlický, 2001*). I present the results of propylitized andesites and the results of intrusive diorites or grano-diorites from the Slovak volcanic fields (Hodruša – Štiavnica intrusive complex – 4 samples, Tanad intrusive complex – 3 samples and intrusive complex Banisko – 6 samples). The propylitized pyroxene andesites from Central Slovakia come originally from 36 natural outcrops (*Orlický, 2001*). The andesites from 33 localities show the normal RM, but the rocks of 3 localities show the reversed RM. The samples of only 12 localities were selected for this study (the basic magnetic characteristics and the directions of stable RM are in Table 1.). The inclination of RM is only of normal polarity, but the declination of RM of the rocks showed a dispersion. An alteration of original Fe-Ti oxides, and Fe sulphides took place during the propylitization, and so the RM of these rocks is dominantly of chemical (CRM) origin, mostly of low paleomagnetic stability.

In Fig. 1 the typical thermomagnetic curves for the magnetite bearing rocks are depicted. The measurements were done in air in the interval of –193 to 700 °C. The curves have shown a Verwey transition temperature $T_V \approx -155\,^\circ C$ and the Curie temperature $T_C \approx 580\,^\circ C$. There has been detected also a transformation of magnetite to maghemite by conspicuous decrease of magnetic susceptibility (κ) at 300 °C on the curves (Fig. 1, samples I-104-7, 401c1). Some results of analyses are in Table 2. The magnetite in the sample I-104-7 was proven by the Mössbauer spectroscopy (*Orlický, 1988*). In the samples of further 11 localities (see Table 1) magnetite was detected by both $T_V \approx -155\,^\circ C$ and $T_C \approx 580\,^\circ C$ on the thermomagnetic

Volcanic rocks of the Štiavnica stratovolcano, Javorie volcano, basalt from Brehy locality and from southern Slovakia



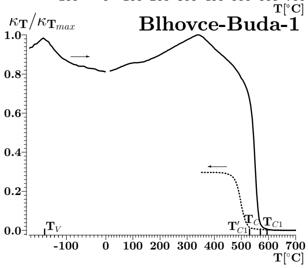


Fig. 1. Thermomagnetic curves of samples containing the magnetite. I-104-7 – propylitized pyroxene andesite, 401c1 – intrusive Sihlansky diorite and b1-33-1, b1-35-3 – hornblende pyroxene andesite). κ_T, κ_{Tmax} – magnetic susceptibility at temperature $T(\kappa_T)$; maximum susceptibility (κ_{Tmax}); T_C, T_C' – Curie temperatures; T_V – Verwey transition temperature.

curves. After heating to 700 °C and successive cooling of the sample, κ was reduced due to the maghemitization of the original magnetite.

The representative thermomagnetic curve of the intrusive rocks is in Fig. 1, sample 401c1, and the representative magnetic behaviour during inducing of PTRM is in Fig. 2, sample KON1-1259m. The intrusive rocks from the mentioned borehole from further 72 positions in the interval 844 to 1913 m show the normal polarity of RM and magnetic behaviour similar to that of the KON1-1259 sample (*Orlický, 1986*). In further above mentioned intrusive rocks, the magnetite is also the basic carrier of normal polarity of RM, but in some investigated samples from different localities also the Ti-Mt-es, exceptionally also the Ilm-Hem-tes are present, which carry the reversed RM. They influenced the resultant direction of RM of the rock. If there are only the magnetites present the normal RM of rocks has been proven.

The basaltic sample Blhovce-Buda-1 (Fig. 1, typical curve of the magnetic behaviour of the sample is in Fig. 2, smale BlhovBuda1-3) contains dominantly the magnetite. But the microprobe analyses detected also the small portion of ilmenite in the rock. According to *Orlický (2004)* the rocks

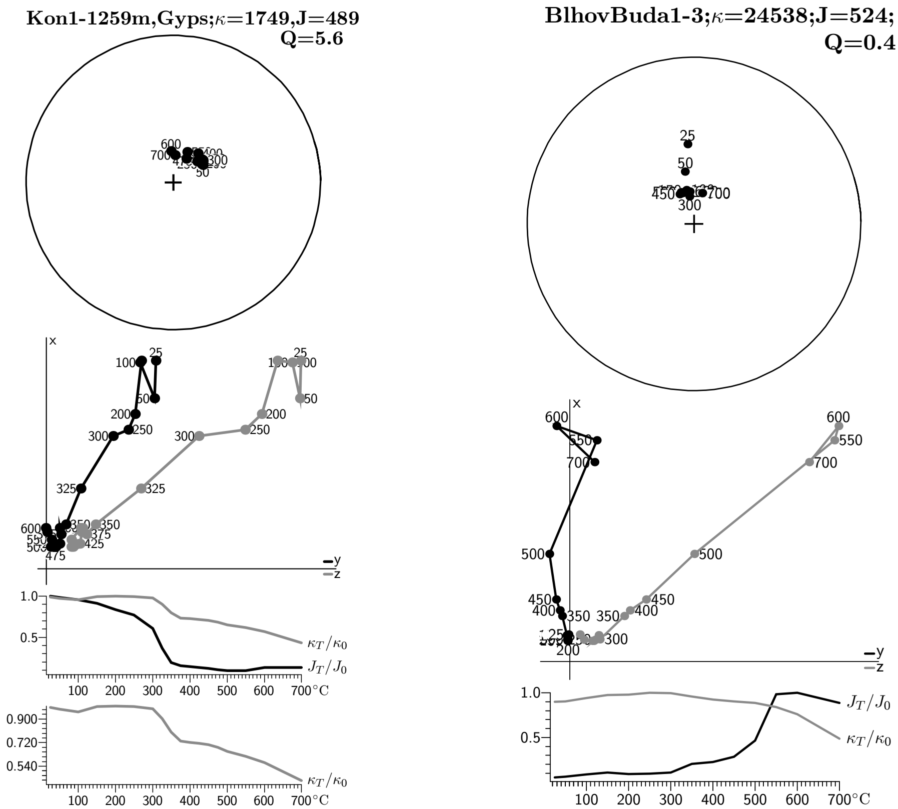


Fig. 2. Thermal inducing of PTRM and a change of magnetic susceptibility of the samples with temperature. Kon1-1259-monzonodiorite from the depth of 1259 m of the borehole Kon-1. Other 11 samples from the interval 1100 to 1350 m of the borehole Kon-1 have shown the same magnetic behaviour like the sample Kon1-1259. Blhov Buda1-3- olivine basalt from the southern Slovakia. J_T – remanent magnetization at temperature T, J_0 – natural remanent magnetization at laboratory temperature, κ_T – magnetic susceptibility at temperature T, κ_0 – magnetic susceptibility at laboratory temperature. The separated curve at the bottom for the respective samples represents the change of κ with temperature with overtopped relation.

of this locality belong to that of the basalts on the eastern part of Cerová vrchovina formations, which were influenced by the activity expanded beyond the limits of uplift of the area. Macroscopic image of most respective basalts has outlined that they were contaminated by either assimilated heterogeneous volcanic materials or some of them were thermally reworked.

Two magnetic carriers of RM in the rock: magnetite (Mt) and the ilmenite – hematite (samples b1-33-1, b1-35-3) and magnetite and the low-temperature oxidized titanomagnetite (Ti-Mt, Ti-Mgh)

The samples of the hornblende pyroxene andesite were collected from 50 individual sites of one large quarry near Bzenica village (*Orlický, 2002*). Dominantly the Ilm-Hem-es are the carriers of the stable RM of these rocks. But in the andesites also the magnetites from about 18 sites from the bottom of the quarry were detected (e.g. samples b1-33-1, b1-35-3, Fig. 3). The Curie temperature (T_C) of this magnetite is about 580 °C and the Verwey transition temperature (T_V) is about −155 °C. Magnetite and Ilmenite hematites were identified by ore microscopy. Dominantly the magnetite, hematite and maghemite were detected by Mössbauer spectroscopy and magnetite, hematite, titanomagnetite and Ilmenite-Hematites were detected by X-ray diffraction analyses (*Orlický, 1988*). The natural RM of magnetite containing andesites is only of normal polarity. But the stable RM after thermal demagnetization is of the reversed polarity, of the self-reversal origin.

I have proposed that the self-reversal CRM originated by the ionic re-

Table 2. The results of Mössbauer spectroscopy, X-ray diffraction analyses and electron microprobe analyses of magnetic minerals. Undivided rocks of the First Stage and hornblende pyroxene andesite of Bzenica locality

Number of sample	Type of rock	Mössbauer spectro-scopy	X-ray diffraction analyses	Microprobe analyses		
				Grain size (μ m)	FeO (%)	TiO_2 (%)
I-104-1	Propylitized pyroxene andesite	Mt(100%)	Mt, Rut	100 70 50 15	93.16 94.86 94.05 0.82	4.43 3.86 3.52 99.18
I-174-3	Propylitized pyroxene andesite		Mt, Rut	40 15 10 7	0.41 3.15 1.38 2.19	99.59 96.05 98.62 96.98
B1-35-3	Hornblende pyroxene andesite	Mt(52%) Hem(23%) Mgh(10%)	Mt, Hem, Mgh, Ti-Mt, Ilm-Hem			

Mt – magnetite; Hem – hematite; Rut – rutile; Ti-Mt – titanomagnetite; Mgh – maghemite; Ilm-Hem – Ilmenite-Hematite

Hornblende pyroxene andesites of the Bzenica locality from central Slovakia and olivine basalts of southern Slovakia

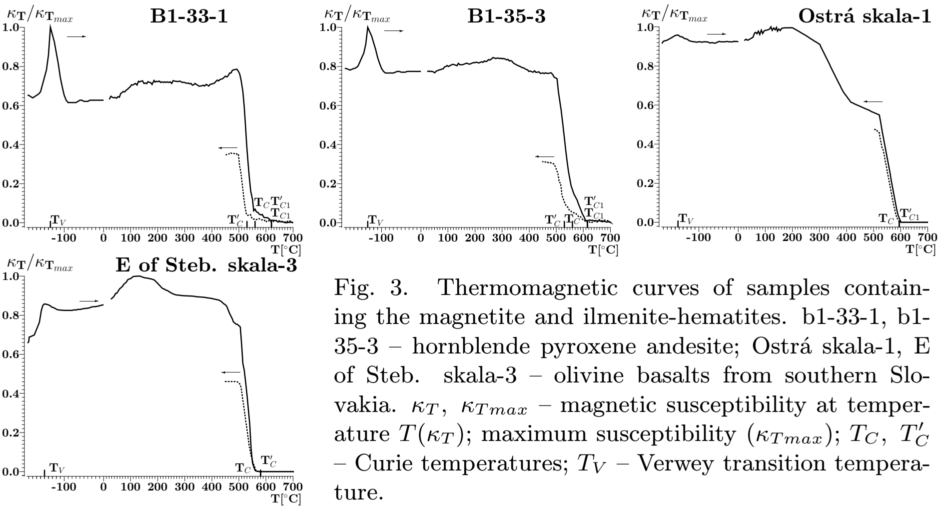


Fig. 3. Thermomagnetic curves of samples containing the magnetite and ilmenite-hematites. b1-33-1, b1-35-3 – hornblende pyroxene andesite; Ostrá skala-1, E of Steb. skala-3 – olivine basalts from southern Slovakia. κ_T, κ_{Tmax} – magnetic susceptibility at temperature $T(\kappa_T)$; maximum susceptibility (κ_{Tmax}); T_C, T'_C – Curie temperatures; T_V – Verwey transition temperature.

ordering of magnetic ions in A and B sublattices in the low-temperature oxidized Ti-Mt bearing rocks (*Orlický, 2009*). I will interpret the results of Ostrá skala-1, E of Steb. skala-3- olivine basalts with respect to this idea. The mentioned ionic reordering process and the self-reversal acquisition of PTRM is accompanied by an increase of magnetic susceptibility (κ) of sample in the interval between $250 - 450\,^\circ$C during inducing of partial thermoremanent magnetization (PTRM) and the stepwise measurement of κ of the rock. The results have shown that the magnetite was not present in the basaltic lava after an emplacement of hot magma on the surface, but it was created from the original Ti-Mt-es during low- and high-temperature oxidation on the earth's surface. During the low-temperature oxidation of these Ti-Mt-es, the reversed RM of chemical-CRM origin took place in these basalts. An increase of κ of about $350\,^\circ$ (Fig. 4) has evidenced that there is not only the magnetite alone, but also a small portion of low-temperature oxidized Fe-Ti phase in these basalt samples. So, we can see from the computed resultant vector, depicted in the stereographic projection in Fig. 4 that in the sample Ostrá skala-1 nearly a complete remagnetization of original CRM of basalt took place and normal polarity of RM was

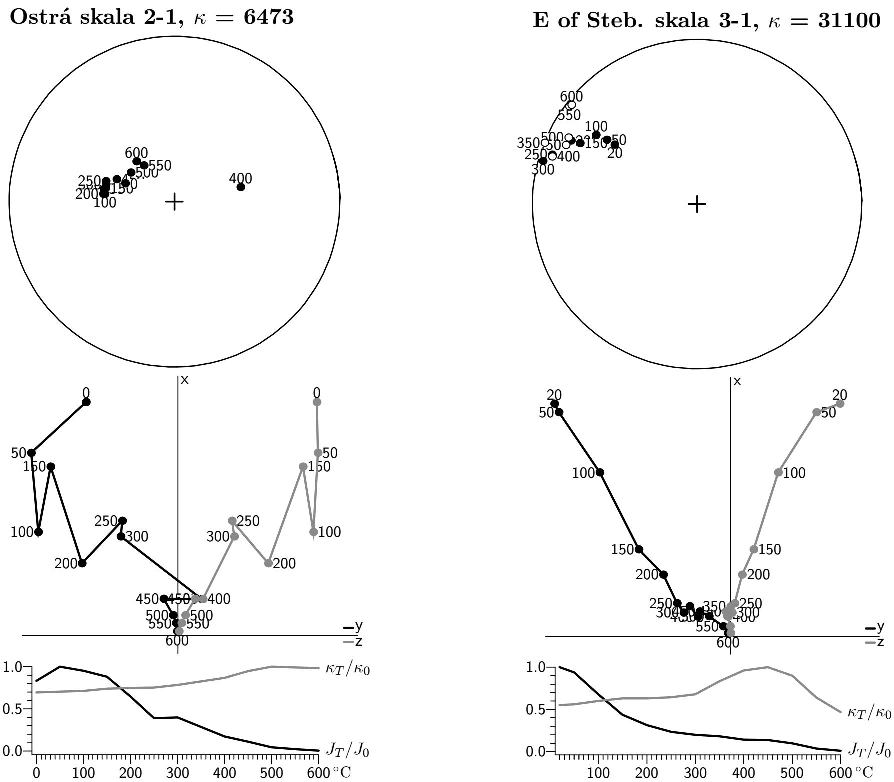


Fig. 4. Thermal inducing of PTRM and a change of magnetic susceptibility of the samples with temperature. Ostrá Skala 2-1, E of Steblová skala 3-1 – olivine basalts. Other explanations see in Fig. 2.

acquired by magnetite carrying basalt during its survival in the field. But in the sample E of Steb. skala-3, with a higher reminder of original low-temperature oxidized Fe-Ti phase, partly the normal, but also the reversed inclination of CRM and the remagnetized declination of CRM were detected ($I_{av} = 11°$, D= 290°) during the thermal demagnetization of the original samples in fully compensated external magnetic field (see in Fig. 4., a similar behaviour was detected in further 3 samples of Ostrá skala locality and 6 samples of E of Steblová skala locality). From the thermomagnetic curves in Fig. 3 it is evident that in both samples there is present the magnetite with $T_C \approx 580\,°C$ and with the $T_V \approx -155\,°C$. But the previous analyses have proven that there are present also the low-temperature oxidized Ti-Mt-es (*Orlický, 2009*) in these basalts. So, the direction of the resultant CRM (depicted in stereographic projection, Fig. 4) corresponds to the vector sum of the normal component and that of the self-reversed component (the magnetite is a carrier of normal component and the low-temperature oxidized Fe-Ti phase is a carrier of the reversed component of CRM). The direction of the RM of the rock containing only magnetite alone should correspond to that of the direction of the geomagnetic field with respect to the geographical coordinates (in our areas: inclination $I \approx 65°$ and the declination $D \approx 2°$; of course the direction of the field has been changed by the secular variations, and so it can make a change in the resultant direction of RM of the respective rock in the range 0 to 10° in inclination and in the range 0 to 35° in declination of RM, according to observatory data).

The hematite bearing volcanic rocks

I present short review about an oxidation of the titanomagnetite (Ti-Mt) solid solutions and the discrete ilmenite, before I deal with the hematite bearing volcanics. There have been presented 7 stages (C1 to C7) of oxidation of the Ti-Mt (cubic) and the basic 7 stages (R1 to R7) of the discrete ilmenite (Ilm; rhombohedral) by Haggerty, in *Lindsley (1991)*. C1 stage: homogeneous Usp-rich magnetite (Mt) solid solutions; C2 stage: Mt-enriched solid solutions with a small number of exsolved Ilm lamellae (the reaction for the C2: $6Fe_2TiO_4 + O_2 = 6FeTiO_3 + 2Fe_3O_4$); C3 stage: Ti-poor Mt with densely crowded exsolved Ilm lamellae (reaction for the C3: $4Fe_2TiO_4 + O_2 = 4FeTiO_3 + 2Fe_2O_3$). The Ti-Mt-ilmenite intergrowth occurred. C4 stage: mottling of the ilmenomagnetite (Ilm-Mt) intergrowth. The development Ilm-Mt at the exsolution interface, the development of minute exsolved transparent spinels in the Ti-Mt, and the development of ferri-rutile (metailmenite) in the Ilm. With increasing oxidation, the exsolved metailmenite becomes lighter in colour (Hem), and the Ti-Mt changes from tan to dark brown (Mt). Although the entire grain is subjected to the oxidation process, the most obvious changes are those within the metailmenite. Coarse and fine lamellae are equally affected, although grains near the edges of Ti-Mt grains are always more intensely oxidized than those towards the center. C5 stage: this stage of oxidation is characterized by the development of Ru + Ti-Mt. Ferri-rutile may persist in transitionally oxidized grains but is absent in the more advanced stages. Ru and titanohematite (Ti-Hem) develop extensively within the exsolved metailmenite lamellae; complete replacement of these lamellae may occur. With more intense oxidation, the lamellar rutile-titanohematite assemblage extends into and begins to develop within the Ti-Mt. Other contributory factors are the darker colour of the lamellar Ti-Hem. C6 stage: it is defined by the incipient formation of Psb (pseudobrookite) from Ru (rutile) + Ti-Hem. Psb is typically heterogeneous in colour, reflectivity, and degree of optical anisotropy. Some areas of relic Ti-Mt, especially near the center of grains, may persist. The development of Psb is indicative of more intense oxidation. The three phase assemblage Psb + Ti-Hem, with or without relic Ti-Mt, defines this stage of oxidation. C7 stage: C7 is the most advanced stage of oxidation of original spinels and is characterized by the assemblage Psb + Hem. Inclusions in lamellar Psb are dominantly Ru, whereas inclusions in intralamellar Psb are dominantly Ti-Hem. These inclusions may result in part, from decomposition of Psb upon slow cooling, but more likely are the result of incomplete reaction, respectively, of the original Ilm and Ti-Hem. C7 Ti-Hem is considerably whiter than that observed in either C5 or C6.

We cannot expect a presence of some pure stoichiometric hematites in the rocks, due to oxidation, but they would be mostly as intergrowth, assemblages or associations with other oxidation products in volcanics. It means that the magnetic characteristics would not be as discrete as for the synthetic hematite. E.g. the Curie temperature of pure hematite is $T_C = 675\,°C$. In natural samples we can find T_C mostly over 600° up to some maximum value of about 645 °C. The results of the Curie temperature measurements have been used in the most frequent way for the selection of the hematite bearing rocks. The results of the X-ray analyses, Mössbauer spectroscopy and the electron microprobe analyses have been applied as well.

I have reviewed the results of the Neogene rocks from about 850 localities from central, eastern and southern Slovakia volcanic fields (*Orlický, 2001, 2002, 2002a, 2002b, 2002c, 2003, 2003a, 2004*), and the volcanics from about 16 localities of the Bohemian Massif (*Orlický, 2002d*). E.g. the phonolites from Most locality of Bohemian Massif contain the separated Mt. The hematites are present in volcanics of some localities according to analyses of the Mössbauer spectroscopy, but only together with Ti-Mt-es, or Ilm-Hem-es.

The selected rocks of the Štiavnica stratovolcano are considered in Table 3. All hematite bearing volcanics have shown the normal RM, if they do not contain dominant portions of either low-temperature oxidized, or high-temperature oxidized Ti-Mt-es. The hematite is detected by Curie temperatures of over 600 °C on the thermomagnetic curves in Fig. 3. For the selected samples of rocks it has been detected also by the results of X-ray diffraction analyses, by the results of the Mössbauer spectroscopy and by the electron microprobe analyses (high content of FeO) in the Tab. 4. Similar thermomagnetic curves and Curie temperatures like for the samples in Fig. 3 have shown also other hematite bearing rocks. E.g. similar curve like the St-102-13 sample but with the $T_C = 645\,°C$ has shown the hornblende biotite andesite sample STR24-1 with high Q coefficient and normal RM (Table 3). We see that some samples contain also the maghemite and magnetite. E.g. sample I-174-3 (Table 2) has dominantly non-magnetic-simple oxides-rutiles (high TiO_2), the magnetite, but T_C and the magnetic behaviour of this sample have pointed out a presence of hematite with a highly maghemitized magnetite. The presence of maghemite and magnetite

Table 3. Magnetic characteristics of selected propylitized pyroxene andesites of the Lower Badenian age and the biotite hornblende andesites of the Upper Badenian age from the Štiavnica stratovolcano area. The selected samples dominantly contained the hematite and in most of samples also the magnetite is present. The rocks come from the area defined by the coordinates $\varphi = 48.4 - 48.7°$ and $\lambda = 18.6 - 19.0°$

Locality, Sample No	$\kappa \times 10^6$ SI Units	NRM [nT]	Q	I°	D°	Locality, Sample No	$\kappa \times 10^6$ SI Units	NRM [nT]	Q	I°	D°
STR20-2	13147	5252	8	42	205	STR21-2	2824	4348	30	68	60.7
STR24-1	2053	4805	28	64	23.6	STR22-1	21694	6760	6.2	56	17.2
St35-1	11744	222	0.4	25.0	322	I110-5	12874	516	0.8	67	330
I174-3	1754	140	1.6	75.8	81.4	I233-7	12020	736	1.2	89.0	19.6
St134-4	5996	711	2.4	75.7	8.4	St135-3	1153	4274	74.1	72	21
St155-5	2449	4116	33.6	55	6	St156-1	15888	3264	4.1	63	2
St201-4	8160	512	1.3	15	94	St214-1	7787	1703	4.4	4.6	277
St215-3	2612	1791	13.7	45	267	St217-6	4522	1805	8	44.5	282.4
St218-9	15562	2363	3	72.0	256	St219-7	19145	721	0.8	82	16.5
I228-5	7398	142	0.4	60.2	41	St263-1	24240	2018	1.7	71.5	50.8
St267-2	1868	3806	40.7	65	73	St268-1	21240	5727	5.4	58	36.3
St270-1	2381	4805	40	59	27.4	P70-2	7575	2855	7.5	47.2	355.4

NRM – natural remanent magnetization; nT – nano Tesla; D° – declination, I° – inclination of stable remanent magnetization, Q – Koenigsberger's coefficient.

Table 4. The results of Mössbauer spectroscopy, X-ray diffraction analyses and electron microprobe analyses of magnetic minerals of andesites.

Number of sample	Type of rock	Mössbauer spectro-scopy	X-ray diffraction analyses	Microprobe analyses		
				Grain size (μ m)	FeO (%)	TiO_2 (%)
St102-13	Biotite hornblende andesite	Mt(%) Hem(55%) Mgh(29%) Ilm	Mgh, Hem Usp, Ilm Brk	40 20 10 7	92.65 88.20 81.83 80.21	7.02 11.51 17.88 19.01
St156-1	Biotite hornblende andesite	Mt(13%) Hem(48%) Mgh(27%)	Mt, Hem	100 40 12 7	79.03 89.35 97.67 98.35	20.63 8.65 0.29 0.68
St263-2	Biotite hornblende andesite	Mt(49%) Ti-Mt(51%)	Mt, Hem	40 20 10 7	88.65 87.95 83.70 88.30	10.31 10.17 14.76 10.00
St267-2	Biotite hornblende andesite			100 100 30 6	92.72 63.50 93.17 93.44	5.64 35.86 5.20 5.14
St270-7	Hyperstene hornblende biotite andesite	Mt(16&) Hem(17%) Mgh(14%) Ilm	Mgh Hem	45 30 20 7	84.40 55.10 93.38 90.20	14.53 44.12 5.34 8.40

Mt – magnetite; Hem – hematite; Rut – rutile; Brk – brookite; Mgh – maghemite; Ti-Mt – titanomagnetite; Usp – ulvöspinel; Ilm – ilmenite.

together with hematite supports the acquisition of positive RM in the rocks. The most frequent occurrence of hematite (in some cases with magnetite and maghemite) are in the hornblende biotite andesites of the Studenec formation Table 4.

Except of Curie temperature measurements and the above mentioned analyses (see in Table 4), the induction of partial thermoremanent magnetization (PTRM) of samples was applied for andesites and rhyolites from Poľana and Javorie, Kremnické vrchy, Vihorlat, Slánske vrchy and Zemplínske vrchy Mts. This method was applied in the laboratory field of normal polarity and intensity H= 48μT, by the stepwise procedure, in a step of 20° in the interval from 700 °C to 520 °C. The results of this method have allowed to identify the type of magnetic mineral to which the acquired PTRM is linked. The results are directly inserted into a free space of the thermomag-

The hornblende biotite and pyroxene and hornblende pyroxene andesites, mostly of the Studenec formation of the Štiavnica volcanic field

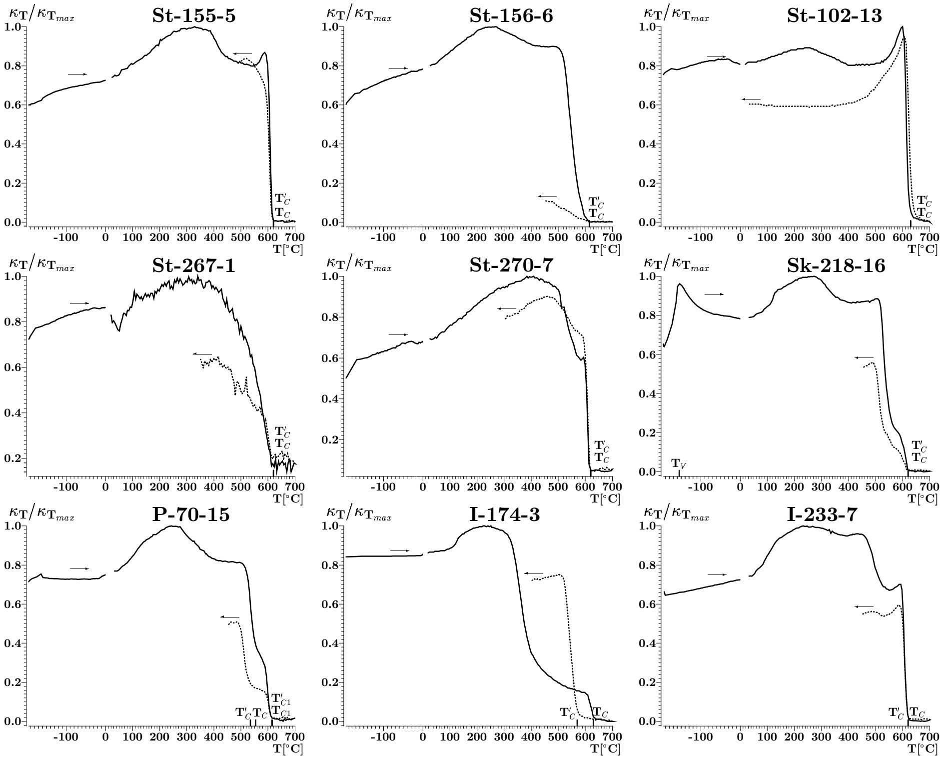


Fig. 6. Thermomagnetic curves of the samples. For symbols and other explanations, see Fig. 1.

netic curves of the respective samples. Acquired intensity of PTRM depends not only on the type of magnetic mineral, but also on its content, the grain size and so, on its coercivity. Generally, the hematite bearing rocks would acquire more intense TRM than the magnetite bearing rocks. But it can be valid only if we apply the total TRM, the magnetization of the sample during the whole interval from its Curie temperature to room temperature. I applied the magnetization of rocks only in the interval from 700 °C to 520 °C. In any case, both magnetite and hematite reflect the direction of the magnetizing field, in our case – in the positive – normal sense. It means

Table 5. Paleomagnetic characteristics of andesites from Javorie and Poľana volcanic fields

Loca-lity, Sample No	Geographical coordinates		$\kappa \times 10^6$ SI Units	NRM [nT]	Q	I°		Inducing of PTRM			Magn. mineral
	φ_L	λ_L					D°	PTRM [nT]	I°	D°	
317-1-1	48.661	19.447	30900	144	0.1	46	26.0	16.7	66	346	Hem
337a3	48.647	19.450	25360	908	0.7	64	352	15	60	3.3	Hem,Mt
338a1	48.646	19.473	1788	1066	12	8	28	417	57	23.6	Ilm-hem,Hem
340b1	48.645	19.472	3956	2119	11	62	350				Hem
343b3	48.640	19.444	2286	216	1.9	61	320	307	66	2	Hem
345a1	48.633	19.440	5677	1944	6.8	5	278	3110	68	6	Ilm-hem,Hem
349-1-1	48.626	19.477	16113	1473	1.8	57	32	67	63	16	Hem+Mt
356-2-2	48.624	19.398	6900	3781	11	56	192	104	72	347	Ilm-hem,Hem
399a3	48.583	19.373	4731	6737	28	-15	244	628	68	10	Ilm-hem,Hem
403-1-3	48.579	19.342	11725	7938	14	36	7	222	63	8	Hem
452a1	48.470	19.350	13838	1362	2	33	3368	36	61	14	Ti-Mt,Hem
456c1	48.457	19.353	7575	1847	5	53	6	228	64	9	Hem

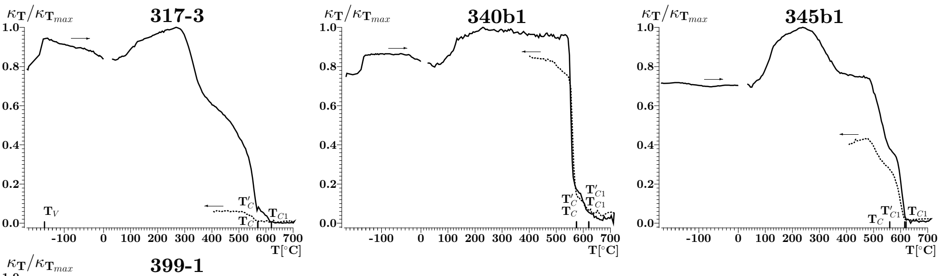
PTRM – partial thermoremanent magnetization in nano Tesla (nT). For other symbols see Fig. 3 and Table 4. Most of samples contain also pseudobrookite (Psb), except for minerals specified in Table.

that the PTRM of the samples will acquire the inclination (I) near 64 ° and the declination (D) would be near 5 °, corresponding to the direction of the magnetizing field in the laboratory (with some deviations due to non-precise position of the sample with respect to the field).

The andesites of the Poľana and Javorie Mts. contain the hematites only in the samples from 12 outcrops (Table 5) from the total amount of 102 ones. Dominant number of andesite lava flows or extrusive bodies contain also the Ti-Mt-es or Ilm-Hem-es. They were detected on the basis of their Curie temperatures, in several cases by the Mössbauer spectroscopy and X-ray diffraction analysis. From Table 5 it is evident that the selected samples show normal polarity of RM (except one) and acquire normal PTRM after their magnetization in the normally-oriented field. The PTRM direction of rocks corresponds mostly to that of the inducing magnetic field. The Curie temperatures and the Verwey transition temperature of samples point out a presence of magnetites in several samples, except for hematite. The analyses mentioned above revealed also for maghemites in some samples.

From the total number of 100 natural outcrops of Kremnické vrchy Mts., only hornblende pyroxene andesites from 3 outcrops of the Krahule forma-

Andesites from Poľana and Javorie volcanic fields of central Slovakia



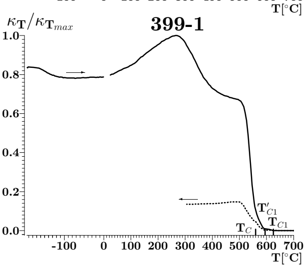


Fig. 7. Thermomagnetic curves of samples 317-3, 340b1, 345b1, 399-1, containing dominantly the hematite, but the magnetite and ilmenite-hematites are present as well. κ_T, κ_{Tmax} – magnetic susceptibility at temperature $T(\kappa_T)$; maximum susceptibility (κ_{Tmax}); T_C, T_C' – Curie temperatures; T_V – Verwey transition temperature.

tion, but the rhyolites from 14 localities of the Jastrabá formation have shown the hematites, except for magnetite in several investigated rocks (Figs. 8, 9). These rhyolites have the normal RM and they acquired normal PTRM after their magnetization in the normally oriented laboratory field. The direction of PTRM of rocks corresponds mostly to that of the inducing magnetic field.

The andesites of Vihorlat, Slánske vrchy and Zemplínske vrchy Mts. have only rarely been detected with a presence of hematites (Fig. 8). In some rhyolites they were detected (Figs. 8, 9). Similar to the previous rocks, these andesites and rhyolites had normal polarity of RM and they acquired normal PTRM after their inducing in the laboratory field.

3. Discussion and conclusions

Magnetic and paleomagnetic properties, and magnetic mineralogy of the Neogene andesitic rocks were previously studied (*Orlický, 1993, 1998*). The

Samples of andesites and rhyolites dominantly with the hematites, and in some samples with the magnetite from Kremnické vrchy Mts., Vihorlat Mts. and Slánske vrchy Mts.

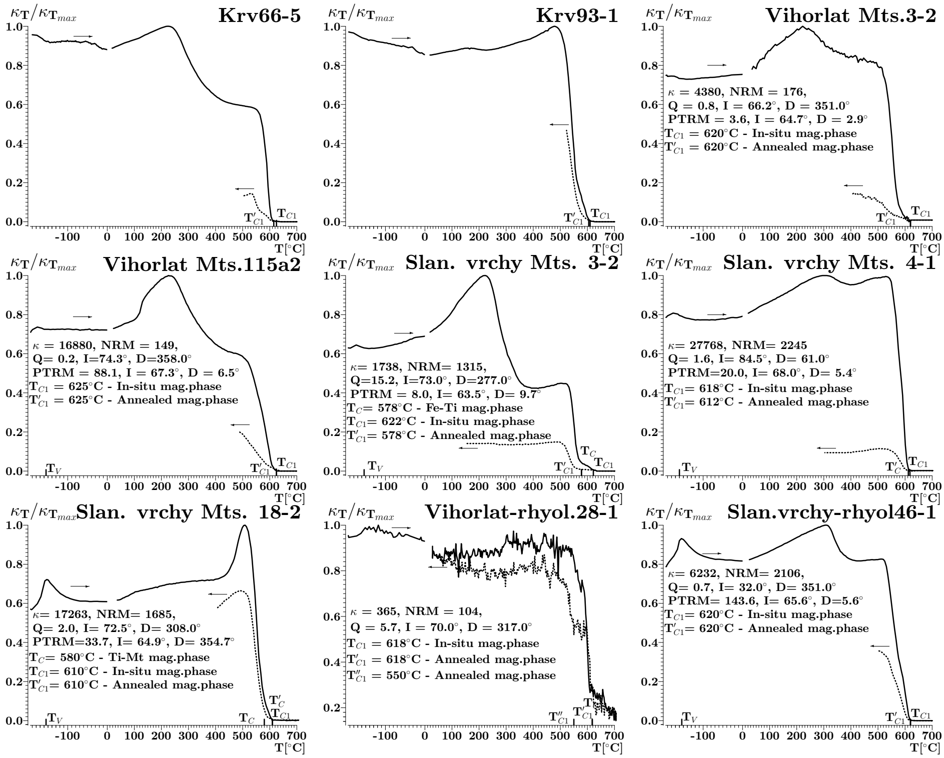


Fig. 8. Thermomagnetic curves of samples from Kremnické vrchy (Krv66-5, Krv93-1), Vihorlat (Vihorlat Mts.3-2, Vihorlat Mts.115a2, Vihorlat-rhyol.28-1) and Zemplínske vrchy Mts. (Slán.vrchy Mts.3-2, Slán.vrchy Mts.4-1, Slán.vrchy Mts. 18-2, Slán.vrchy-rhyol46-1). PTRM – partial thermoremanent magnetization induced by the normally oriented magnetic field of intensity H= 48μT in the interval of 700 to 520 °C. Other symbols and explanations are given in Fig. 1.

author of the article has recently proposed a model of the sources of normal and reversed RM and tested it applying the results of the submarine volcanics (*Orlický, 2010*). The magnetites (cubic phase) and the titanium rich titanomagnetites (cubic phase) have been considered as the carriers of only normal remanent magnetization of the rocks. The low-temperature oxidized titanomagnetites and the Ilmenite-Hematites (Ilm-Hem; rhombohe-

Samples of rhyolites dominantly with the hematites, and in some samples with the magnetite

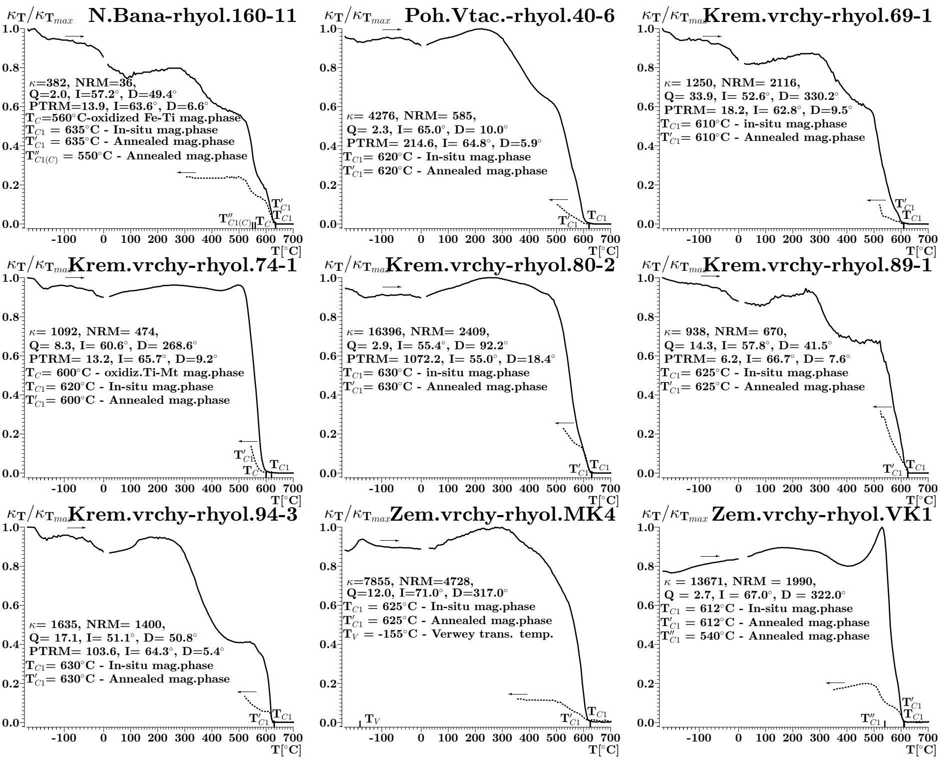


Fig. 9. Thermomagnetic curves of samples of rhyolites from Vtáčnik Mts., Nová Baňa area, Kremnické vrchy Mts. (Krv69-1 – Krv94-3) and Zemplínske vrchy Mts. (Malý Kam4, Vel.Kam1). The hematites were detected also in rhyolites of further 7 localities (25, 70, 71, 75, 76, 81, 84) of the Jastrabá formation from Kremnické vrchy Mts. Other symbols and explanations are given in Fig. 1.

dral phase) carry either reversed remanent magnetism (RM) of self-reversed origin, or normal RM, depending on the proportion of hematite in the Ilm-Hem solid solutions. I have enlarged the original model with the hematite bearing rocks which carry also normal RM. The paleomagnetic and magnetic results and the results of magnetic mineralogy of selected Neogene andesites and rhyolites from central, southern and eastern Slovakia of the Badenian to the Middle or Lower Sarmatian age (16.05–12.9 M.Y.) have been evaluated. The selected rocks with the magnetites and hematites have shown only the normal RM. Normal partial thermoremanent magnetization (PTRM) was induced in many magnetite and hematite bearing andesite and rhyolite samples in the laboratory field of normal orientation and the intensity of H= 48μT.

The occurrence of both these types of magnetic minerals is quite rare in volcanics. While the magnetite is more frequently present in the intrusive rocks, the hematite is frequently present in effusive, more acidic volcanics, e.g. in the rhyolites. The hematites are mostly not of primary origin, but have been created from the titanomagnetites or the ilmenites during their oxidation. They are the last members of oxidation and frequently are present together with non-magnetic simple oxides of Ti, e.g. with rutile, brookite, pseudobrookite, pseudorutile etc. Very important outcome is that both magnetite and hematite are the carriers of only normal polarity of RM in the rocks, regardless their age. This phenomenon has significantly contributed to the explanation of the validity or invalidity of the field-reversal hypothesis.

The hematites are of course frequently present in the rocks containing the ilmenite-hematites, often along with the associations of the titanomagnetites. Such types of Ilm-Hem-es will acquire the self-reversed PTRM. So, we must be very careful with a selection of such types of hematite bearing rocks.

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