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MAGNETIC AND MINERALOGICAL INVESTIGATION OF REMANENT MAGNETIZATION CARRIERS IN SELECTED ANDESITES AND OLIVINE BASANITES FROM GREECE

(Figs. 10, Tabs. 2)

Abstract: Biotite-hornblende andesite (to andesitodacite) from the Kammeno-Chorio locality (250 years B. C.) and biotite-hornblende pyroxene andesite, both from the Methana peninsula, as well as olivine basanites from Achilleion (age: 3.0 m. y.), Microthebe and Porphyrion (age: 1.5 m. y.) localities have been studied. Nonstoichiometric magnetites and titanomagnetites of composition (1-x) $Fe_3O_4 \times Fe_2TiO^4$, with $x \approx 0.1$ are carriers of magnetism in andesitic rocks. Titanomagnetites were carriers of magnetism in olivine basanites in their original state however, they have been altered since their origin. According to the results of transmitted and relfected — light microscopy, Mössbauer and X-ray microscopy, microprobe analyses and results of Curie temperature measurements ilmenite-haematite solid solutions, haematites and rare magnetite and maghemite are carriers of magnetism in these rocks now.

Резюме: Изучены были биотитово-амфиболовый андезит (до андезито-дацита) из области Каммено-Хорио (250 лет до н. э.), биотитово-амфиболово-пироксеновый андезит — оба из полуострова Метана, оливиновые базаниты из областей Ахиллеион (возраст: 3 млн. лет), Микротебе и Порфирион (возраст: 1,5 млн лет). Носителями магнетизма в изученых андезитовых горных породах являются нестехиометрические титаномагнетиты и магнетиты состава (1 — x) Fe_3O_4 x Fe_2TiO_2 ($x \approx 0{,}1$). Носителями магнетизма в оливиновых базанитах были в начальной стадии вероятно титаномагнетиты. В течение времени они уже изменились. Теперь в них находятся гематитово-ильменитовые твердые растворы, гематиты, малые количества магнетита и маггемита. Это кажется правильным по результатам микроскопических, рентгенометрических, мессбауэровских анализов, анализов по микрозонде и измерений точек кюры.

Paleomagnetic investigation of the Pliocene to Quaternary volcanic rocks from the Methana peninsula and small volcanic centers in NW Aegean Arc in Greece has been carried out by Orlický (1986). Investigated localities are shown in the Fig. 1. Obtained results can be summarized as follows:

- essential magnetic characteristics of the rocks are given in the Tab. 1;
- laboratory tests confirmed the directional stability of RMP for the rocks from the extrusive domatic body of the loc. 1., lava flows of the loc. 2 and

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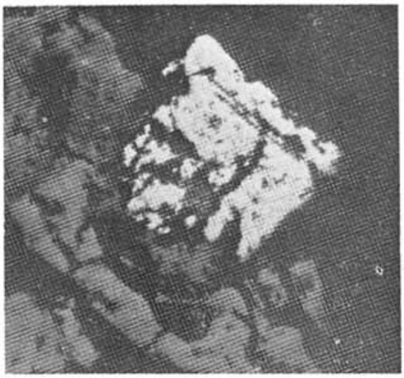
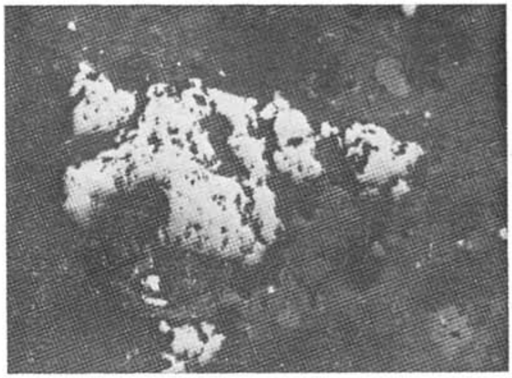
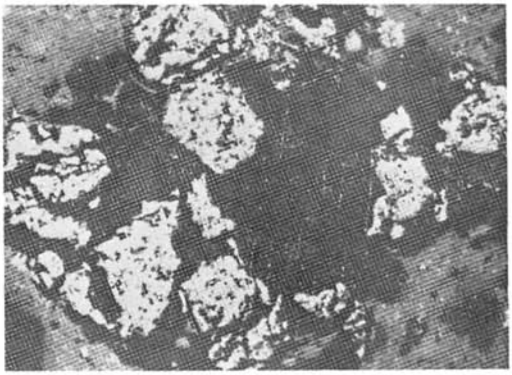


K-M-1c/1; 240; II

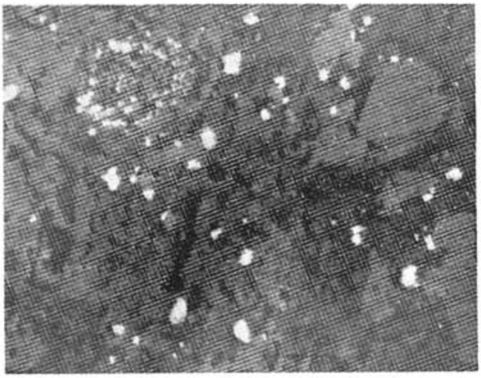


K-M-2c/4; 150; II

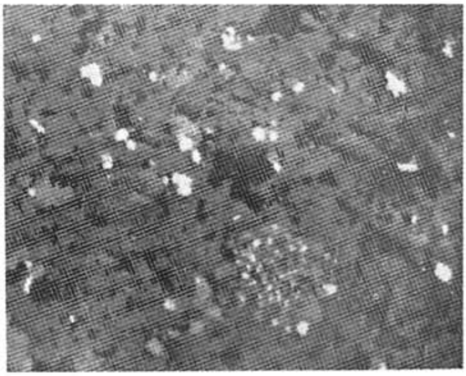
K-M-3c/3; 150; II



K-M-5c/2; 75; II

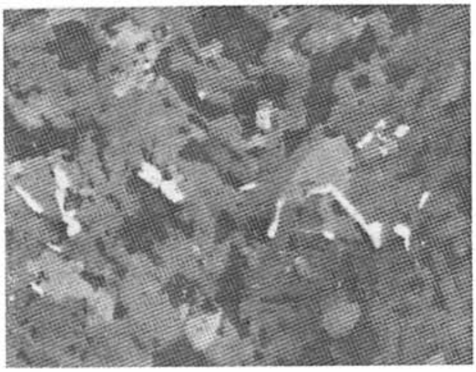


Ach. 1/1; 240; II

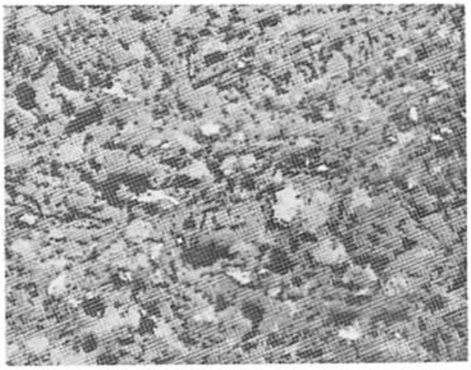


Ach. 4/3; 240; II

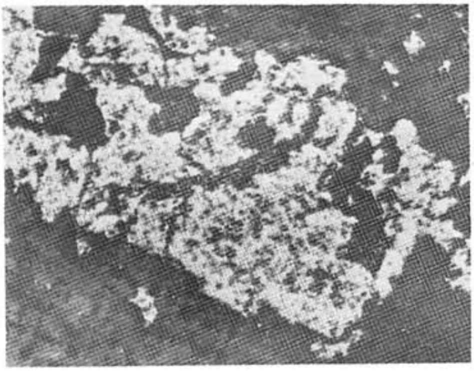
Fig. 3. Photomicrographs of magnetite and haematite grains (and intergrowths) in andesitic rocks of the loc. 2 (along the road from Kammeno-Chorio to Methana); K-M-1c/1 — K-M-2c/4 sample numbers 2; Ach-1/4 — Ach-4/3 samples of olivine basanites from the locality Achilleion (loc. 3) — dispersed grains of haematites and magnetites. Other data see the explanation of the Fig. 2.



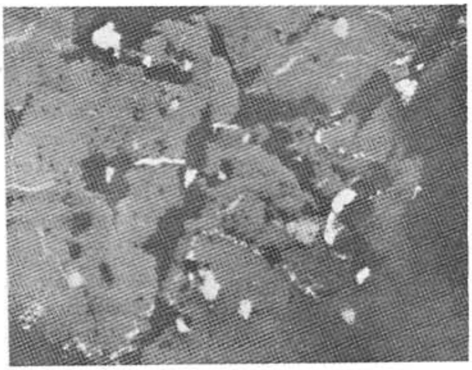
Micr. 1/3; 300; II



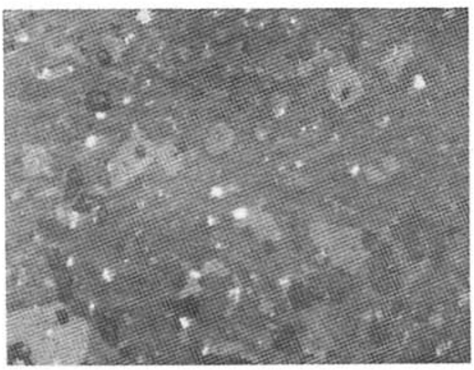
Micr. 2/2; 240; II



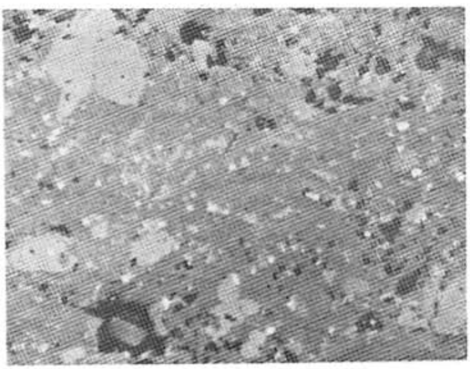
Micr. 3/2; 240; II



Micr. 4/1; 300; II



Porph. 2/4; 300; II



Porph. 3/5; 190; II

Fig. 4. Photomicrographs of haematite grains in olivine basanites of the localities Microthebe (Micr. 1/3 — Micr. 1/4) and Porphyron (Porph. 2/4, 3/5). Other data see the explanation of the Fig. 2.

According to reflected light microscopy the most common magnetic mineral in olivine basanite from the Achilleion locality (loc. 3) is magnetite. Grains of magnetite have the size mostly from 5×10^{-3} to 1×10^{-2} mm. In olivine basanites from Microthebe and Porphyrion magnetic particles are usually composed of haematite and magnetite with prevailing haematite. Their size is from 5×10^{-3} to $2.5 \times 10^{2-}$ mm. These minerals are dispersed in very fine form in the rock samples (see Fig. 4). Limonite and iddingsite as secondary minerals have been detected in olivine basanites of all three localities.

A thorough study of magnetic fraction by means of X-ray diffraction measurements and Mössbauer spectroscopy have confirmed the content of following Fe and Fe-Ti oxides.

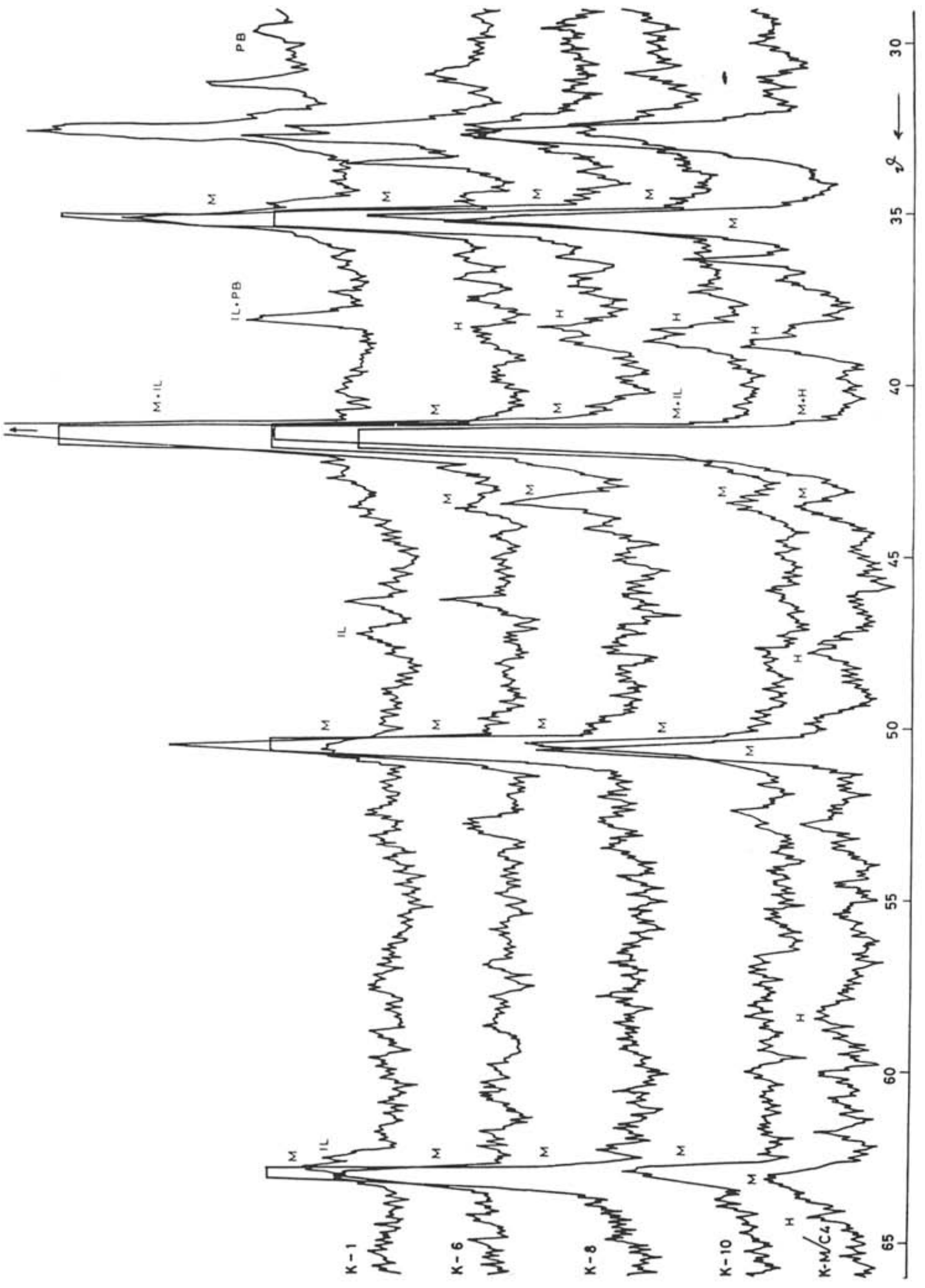
Biotite-hornblende andesite to dacite, of the loc. 1: Fe_3O_4 — as the dominant component, very small amount of α-Fe_2O_3 (Fig. 5, samples K-6, K-8, K-10) and small amount of ilmenite (Fig. 5, sample K-1). Fe_3O_4 as the dominant component was identified also by Mössbauer spectroscopy (Fig. 7, samples K-1, K-6, K-8, K-10) and from 4, to 20 % Fe^{2+} and Fe^{3+} is in paramagnetic fraction. Magnetite is in a different stage of unstoichiometry.

Biotite-hornblende-pyroxene andesite of the loc. 2: Fe_3O_4 and a small amount of α-Fe_2O_3 have been detected by X-ray spectroscopy (Fig. 6, sample K-M/4c). According to the results of Mössbauer spectroscopy Fe_3O_4 in the sample K-M/4c (Fig. 7) has been detected also in the high-substituted stage. (Fe^{3+} substituted in the crystalline lattice of Fe_3O_4 probably by Ti^{3+}).

Olivine basanite of localities Achilleion (loc. 3), Microthebe (loc. 4) and Porphyrion (loc. 5):
Haematite as the dominant component, Fe_2TiO_4, ilmenite and brookite has been identified by X-ray spectroscopy measurement in olivine basanites of the Microthebe and Porphyrion localities (Fig. 6), Fe_3O_4, brookite and $FeTiO_3$ in olivine basanite of the Achilleion locality. A mixture of haematite, maghemite and high-substituted magnetite have been identified by Mössbauer spectroscopy in olivine basanites of all three localities (Achilleion, Microthebe and Porphyrion) (Fig. 7). Part of Fe^{2+} and Fe^{3+} have been found also in paramagnetic fraction of rock samples.

A precise identification of Fe and Fe-Ti oxides can be carried out by determining the Curie temperatures of magnetic constituents. We have applied measurements of change of $\varkappa$ during heating of powdered sample. The results are illustrated in the Figs. 9 and 10. 9 samples of biotite-hornblende-andesite from the loc. Kammeno-Chorio and two samples of biotite-hornblende-pyroxene andesite from the loc. No. 2 show Curie temperatures (T_C) very near to that of T_C of magnetite (around 585 °C). In the samples No. K-3/6, K-5/7 and especially No. K-4 also haematite has been identified. In the samples K-M/4c and K-M-5c/1 (loc. 2) titanomagnetites with T_C around 500—520 °C have been confirmed. There is present also titanomagnetite with low $T_c \approx 400$ °C in the samples K-M-4c and K-M-5c/1.

Fig. 5. Result of X-ray spectroscopy; K-1-K-10, K-M/4c — see the explanations of the Fig. 2, and Fig. 3; M — magnetite, H — haematite, IL — ilmenite, PB — pseudobrookite.


K-1
K-6
K-8
K-10
K-M/C4
30
35
40
45
50
55
60
65
PB
IL·PB
M·IL
M·H
IL
M
H

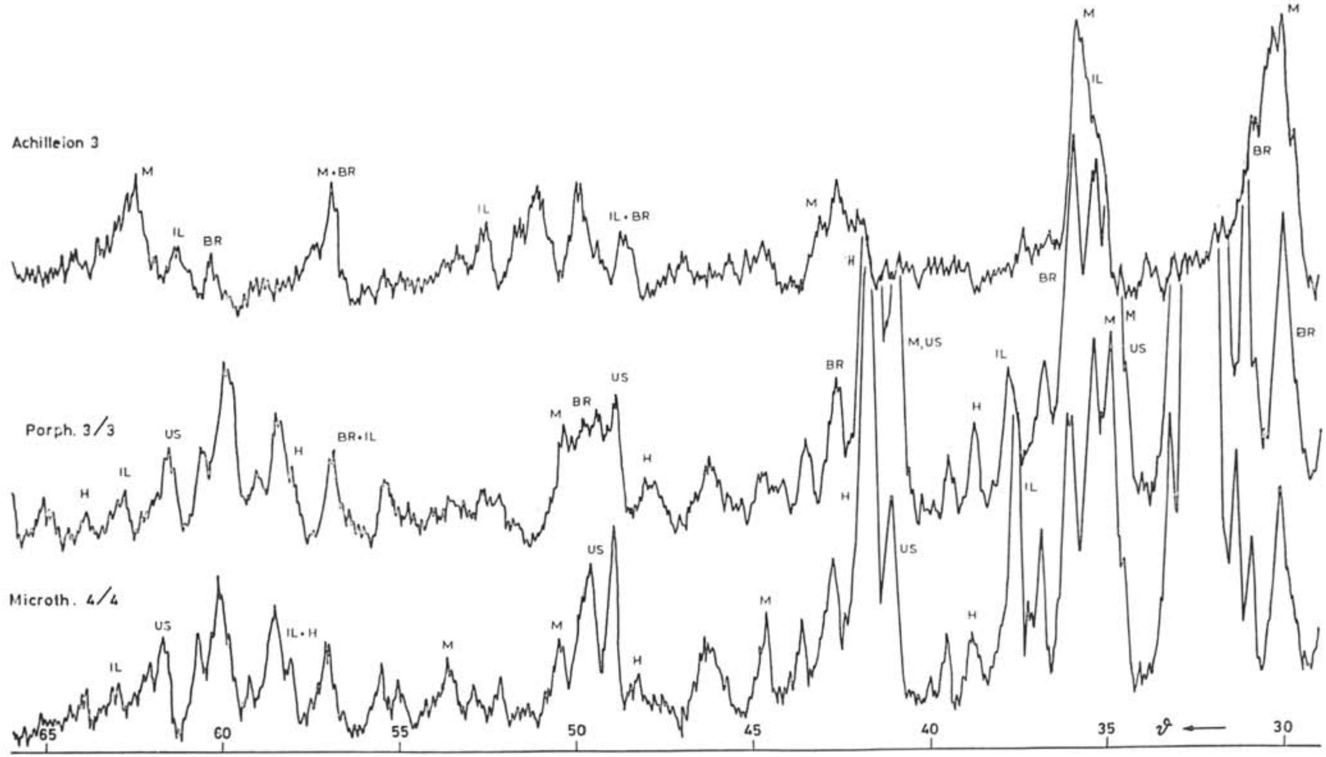


Fig. 6. Results of X-ray spectroscopy; Achilleion 3, Porph. 3/3, Microth. 4/4 — magnetic fraction from olivine-basanites of the Achilleion, Porphyrion and Microthebe localities respectively; M — magnetite, H — haematite, IL — ilmenite, US — ulvospinel, BR — brookite.

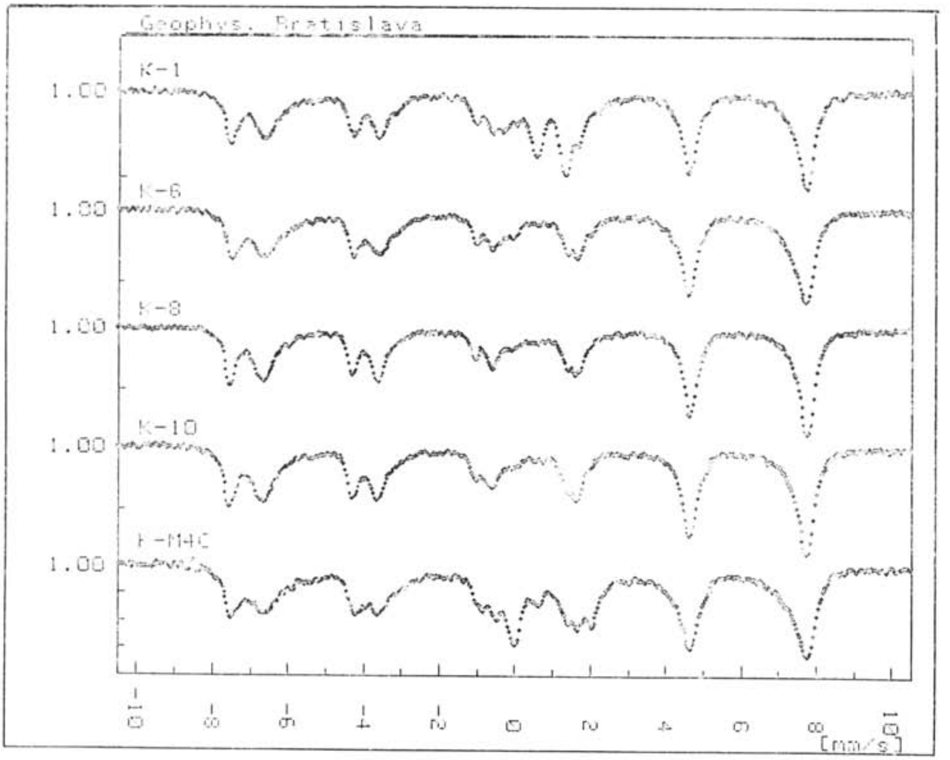


Fig. 7. Mössbauer spectra of magnetic fraction from the rocks of extrusive domatic body near by the Kammeno-Chorio village (K-1-K-10) and andesites of the loc. 2 (K-M 4c).

Haematite as the dominant magnetic component has been detected in powdered rock samples of Achilleion, Microthebe and Porphyrion ($T_c \approx 700$ °C, Fig. 10). Evident decreasing of T_C and increasing of $\varkappa$ magnetic minerals have been identified in powdered olivine basanites of the Microthebe and Porphyrion locality using results from continual heating up to the 750 °C and cooling from 750 °C to the laboratory temperature.

Conclusions and discussion

Magnetic minerals of investigated rocks with measured magnetic properties have been studied using transmitted and reflected – light microscopy, Mössbauer and X-ray spectroscopy, microprobe analyses and the method of Curie temperature measurements.

Obtained results confirm that the carriers of remanent magnetizations are as follows:

– Titanomagnetites (1-X) $Fe_3O_4 \times Fe_2TiO_4$, with $X \approx 0.1$ are present in biotite-hornblende-andesite to dacite of the loc. Kammeno-Chorio and in biotite-horn-

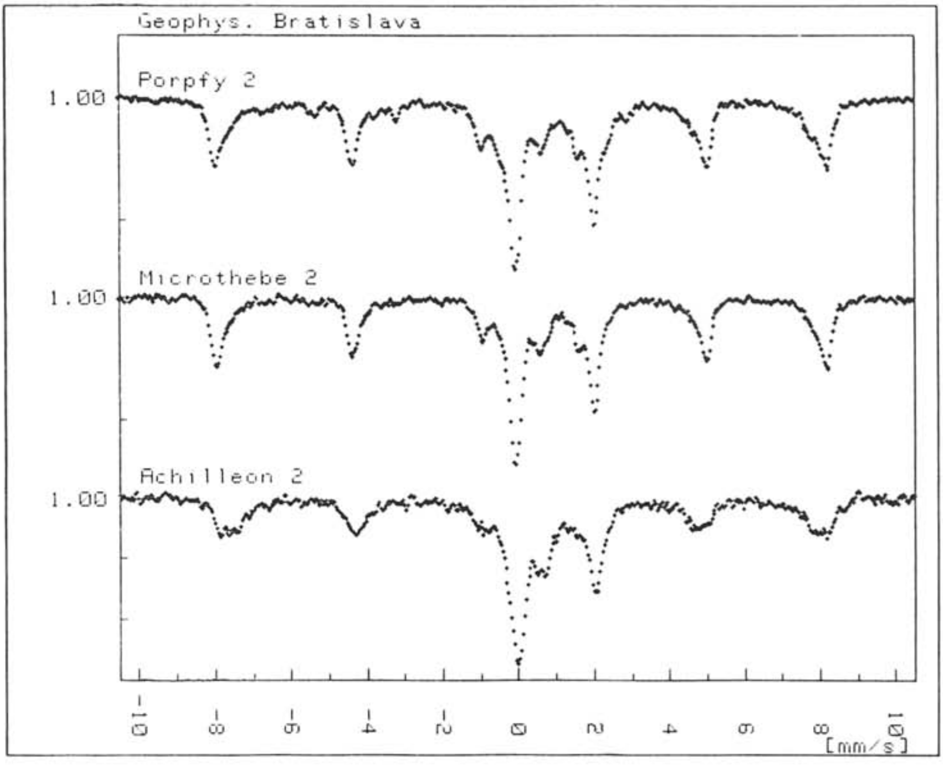


Fig. 8. Mössbauer spectra of magnetic fraction from olivine basanites of the localities Porphyrion, Microthebe and Achilleion.

blende-pyroxene andesite of the loc. 2. Titanomagnetites with a higher content of Fe_2TiO_4 have been confirmed in some samples (KM-4c, KM-5c/1) on the basis of T_c measurements and Mössbauer spectroscopy results. Ilmenite lamellae have been detected in the sample K-10/4 by microprobe analysis.

Identified titanomagnetites are supposed to be of a primary origin. They are mostly in the single domain state with the uniaxial anisotropy, considering the shape of the $\varkappa$-t curves on the Figs. 9 and 10 (according to Radhakrishnamurty et al., 1982).

— An explanation concerning the carriers of magnetism in olivine basanites of the localities Achilleion, Microthebe and Porphyrion is more complicated. The results of T_c measurements have shown the presence of haematite — mainly in the multidomain state (Fig. 10, samples Ach. 2/3, Microthebe 2, Porphyrion 2). Haematite has been confirmed also by means of optical, X-ray, and Mössbauer spectroscopy analyses, besides magnetite (or maghemite) in olivine basanites. Haematites are tiny and dispersed. Both ilmenite and brookite have been detected by X-ray spectroscopy, and other Ti-oxides by means of microprobe analyses. The presence of ilmenite was detected by Orlický (1986) on the basis of conspicuous increase of magmatic susceptibility ($\varkappa$) with increasing

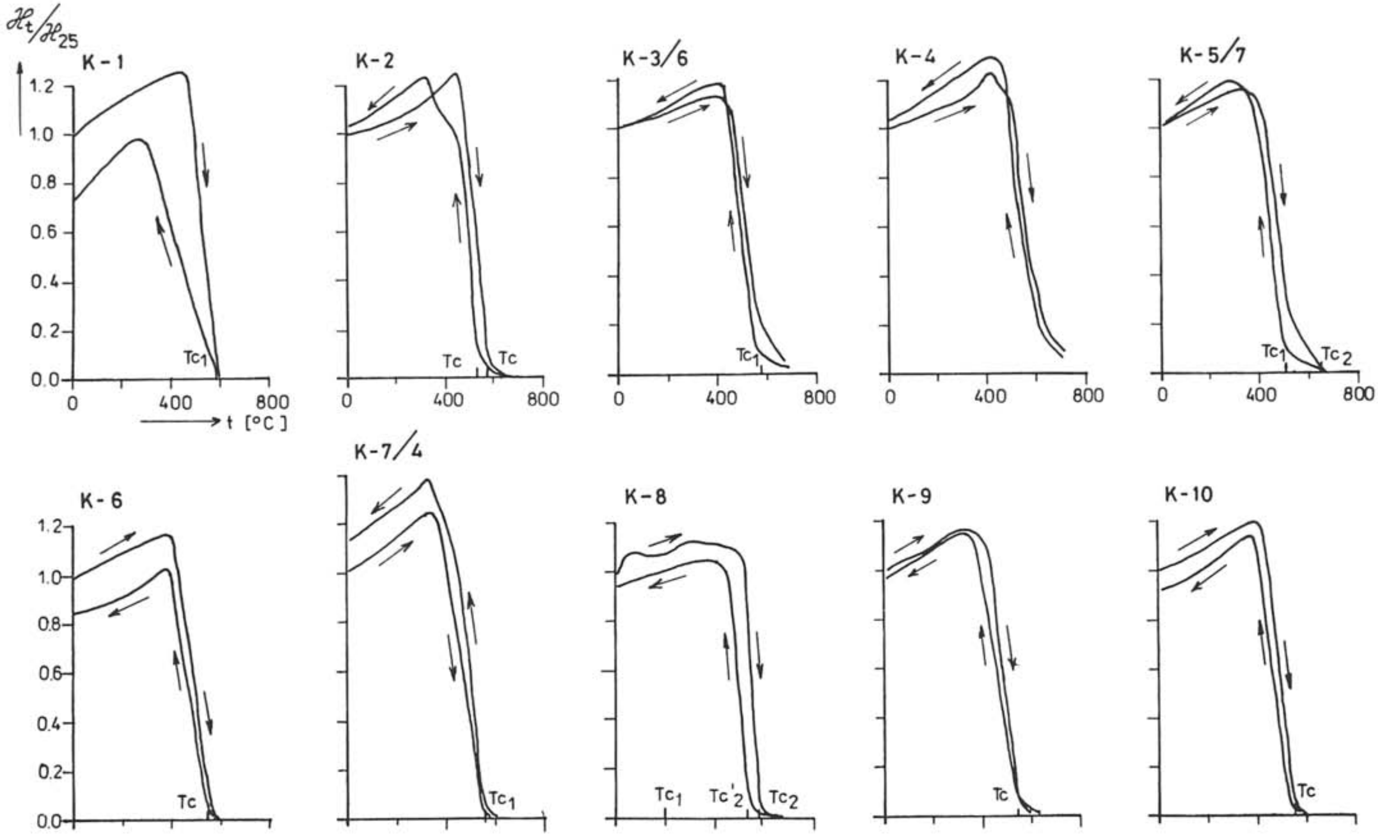


Fig. 9. Magnetic susceptibility versus temperature curves.

Explanatory notes: $\varkappa$ — magnetic susceptibility of powdered sample of rock at the temperature t ($\varkappa_t$) and at the room temperature ($\varkappa_{26}$); T_C — Curie temperature of magnetic mineral (T_{C1}, T_{C2} — Curie temperature of different mineral); T'_c — Curie temperature of powdered rock after heating to 750 °C and cooling to the room temperature; K-1-K-10 — samples from extrusive domatic doby near by the Kammeno-Chorio village.

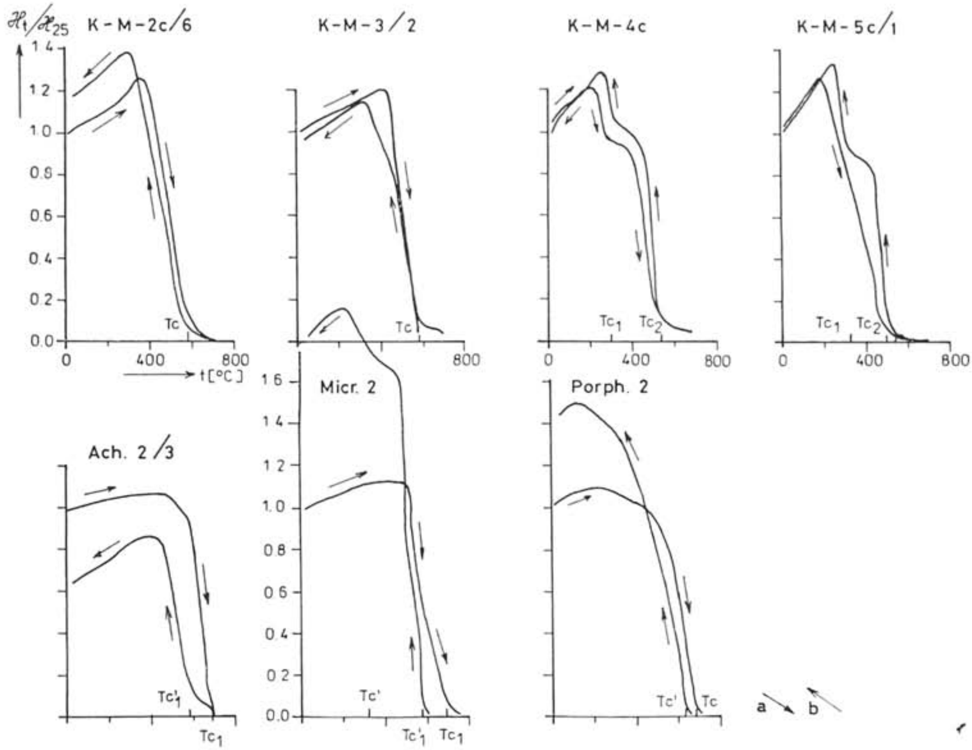


Fig. 10. Magnetic susceptibility versus temperatuse curves.
Explanatory notes: K-M-2c 6 — K-M-5c 1 — powdered samples from the loc. 2 (along the road from Kammeno-Chorio to Methana); Ach. 2/3, Micr. 2, Porph. 2 — samples of olivine basanites from the localities Achilleion, Microthebe and Porphyrion; a — curve of $\varkappa_t/\varkappa_{25} \rightarrow f(t)$ during heating, b — during the cooling from 750 °C — to room temperature. Other symbols see the Fig. 9.

temperature of the olivine basanite a comparison of $\varkappa$ before and after heating to over 750 °C and cooling to the laboratory temperature. A conspicuous increase of $\varkappa$ of powdered olivine basanites from the Microthebe and Porphyrion localities follows from the results of T_c measurements (see Fig. 10, the curve of cooling of the sample). The lower Curie temperature following the temperature treatment of the sample is related to this process too (see Fig. 10, Microthebe 2, Porphyrion 2).

All presented results have shown that the carriers of RMP in olivine basanites were titanomagnetites in the original state of the rocks. But they have been altered since their origin. While a wide range of mineralogical changes is produced by alteration processess, our concern is only with the changes affecting the original magnetic phase, titanomagnetite, and other minerals whose altered products are likely to be ferrimagnetic.

In basic igneous rocks magnetic particles usually have an average composition between ulvospinel (Fe_2TiO_4) and true magnetite (Fe_3O_4). Both these minerals

Table 2

Microprobe analyses of Fe-Ti oxides

Designation of the sample	Number of analysed positions	FeO (%) (average)	FeO min.	FeO max.	TiO_2 (%) (average)	TiO_2 min.	TiO_2 max.
K-5/8	4	88.51	86.54	90.63	5.74	4.51	8.21
K-10/4	5	85.39	82.89	87.84	4.96	3.99	6.63
	2	54.03	53.92	54.23	40.18	40.03	40.33
K-M-3c/4	6	81.73	74.39	88.59	6.37	0.91	16.69
K-M-5c/2	6	85.25	82.47	87.72	9.35	4.87	11.54
Achilleion 4/3	1	73.33			14.22		
	1	45.62			41.92		
Microthebe 2/2	3	73.81	59.2	89.66	12.0	0.0	26.15
	4	43.44	41.83	47.96	45.26	43.43	46.24
Microthebe 4/1	3	90.44	89.46	90.91	0.05	0.01	0.09
	4	46.86	43.22	48.99	42.72	40.15	45.84

Besides the results mentioned above, microprobe analyses of Fe-Ti oxides in selected samples of rocks have been carried out — results are given in the Tab. 2.

have a cubic crystal structure which allows for a complete solid solution of end members the titanomagnetite series. The change in composition from magnetite towards ulvospinel is marked by an increase in size and distortion of the cell, also by a change of magnetic characteristics. The Curie temperature (T_c) of the Fe_2TiO_4 is cca - 200 °C, of Fe_3O_4 is 585 °C. T_c gradually increases from − 200 °C to 585 °C with decrease of Fe_2TiO_4 within the solid solution of titanomagnetite. Titanomagnetite particles are often preserved in basic rocks if they cooled rapidly and their composition is close to either Fe_3O_4 or Fe_2TiO_4 (Tarling, 1974). In more slowly cooled rocks, however, an exsolution takes place resulting in intergrown crystals of magnetite and ulvospinel. Petrological studies of these intergrowths suggest that the majority of this exsolution takes place while the rock is still cooling, but exsolution can also take place very gradually at normal temperature. Timing of this exsolution is of fundamental importance to palaeomagnetic studies since it results in the acquisition of chemical remanent magnetic polarization (CRMP).

Final products of the alteration of original titanomagnetites in investigated olivine basanites are mostly haematites and ilmenites, in addition to small amount of magnetite and maghemite. Ilmenite is not stable under natural conditions. It is usually oxidised and hydrated : hydrated ilmenite → arizonite ($Fe_2 . 3TiO_2$) → leucoxen → rutile (anatas or brookite). This is the reason why also Ti-oxides have been identified as products of alteration processes in question.

An influence of secondary alterations of basaltic rocks on titanomagnetite properties is evident. It means that the magnetic minerals are of secondary origin and remanent magnetic polarization is also the secondary one of chemical origin (CRMP).

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