

MAGNETITE IN SOKLI CARBONATITE MASSIF AND IN TULPPIO OLIVINITE

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Occurrence, ilmenite exsolutions and composition of magnetite in the carbonatite massif of Sokli and in the olivinite of Tulppio have been studied. In the carbonatite massif, magnetite of magmatic carbonatites is hypidio-idiomorphic, contains only very fine-grained ilmenite exsolutions (ulvöspinel), and the minor components TiO_2 , MgO, MnO and Al_2O_3 of magnetite show a decreasing tendency in the successive I → II → IV magmatic stages. Magnetite of metacarbonatite is xenomorphic, containing a great number of ilmenite exsolutions indicating a complicated thermal history of these rocks. The magnetite of the magmatic carbonatites has lower TiO_2 and higher MnO, Al_2O_3 , MgO and ZnO contents than that of the metacarbonatites, on the average. Magnetite of the Tulppio olivinite is fine-grained, and the minor element contents, excepting Cr and Si, are lower than those in the carbonatite massif.

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Introduction

This paper briefly describes the occurrence of magnetite in the Sokli carbonatite massif and in the Tulppio olivinite, and presents some microprobe analyses of it. The purpose of the study was to find out the differences, if any, between magnetites representing different rock groups. Samples of the carbonatite complex have been collected from drill holes all over the complex, and a sample of Tulppio olivinite has been taken from a pit about four kilometers southwest from the carbonatite exocontact (Vartiainen, 1980). A detailed geology of the carbonatite massif has been given earlier (Vartiainen, 1980).

K. Heinänen has analyzed magnetite and examined ilmenite exsolutions. H. Vartiainen is responsible for other subjects of this paper.

Occurrence

Magnetite is a common rock-forming or accessory mineral in almost all rock varieties of the carbonatite massif. It appears as an accessory mineral in the Tulppio olivinite too. The average amounts, grain size, and forms has been summarized in Table 1.

Magnetite of the Tulppio olivinite differs from that of the rocks of the carbonatite com-

Table 1. Amount, grain size, and form of magnetite in the rocks of carbonatite massif and in the olivinite of Tulppio.

| | Amount, average volume-% | Grain size, mm | Grain form |
|------------------------------|-----------------------------|----------------|------------------|
| <i>Pre-carbonatite rocks</i> | | | |
| Olivinite of Tulppio | 1—2 | 0 — 1 | idiom.-hypidiom. |
| Magnetite-olivinite | 20—40 | 10 —50 | xenomorphic |
| Pyroxenite | 0—10 | 1 — 5 | » |
| <i>Magmatic carbonatites</i> | | | |
| Stage I, phoscorite | 25—35 | 5 —10 | idiom.-hypidiom. |
| » II, sövite | 3—6 | 1 — 5 | » |
| » III, phoscorite | 15—25 | 5 —10 | hypidiom.-xenom. |
| » IV, sövite | 2—5 | 1 — 5 | idiom.-hypidiom. |
| <i>Metacarbonatites</i> | | | |
| Metaphoscorite | 15—25 | 5 —20 | xenomorphic |
| Metasilicosövite | 3—6 | 0.5—5 | » |
| <i>Metasomatites</i> | | | |
| Amphibole rock | 0—5 | 0.5—3 | xenomorphic |
| Mica-amphibole rock | 0—10 | 1 —10 | » |
| Mica rock | 0—20 | 1 —10 | » |

plex in smaller grain size and lower amount. The largest magnetite grains occur in the magnetite-olivinites of the carbonatite massif where the grain size may rise over 10 cm (Fig. 1). In general, magnetite of magnetite-olivinite, pyroxenite, metacarbonatites, and metasomatites is granulated, resorbed and veined by carbonates. Replacement by carbonates may be so intense that only the ilmenite lamellae preserved indicate the contours of original magnetite grains (Fig. 2). These characteristics are lacking in the mag-

netite of magmatic carbonatites, where magnetite usually is fresh and typified by idiomorphic and hypidiomorphic grain forms. These magnetites may also have been corroded by carbonates but to a much smaller extent than those in the former rocks.

Ilmenite exsolutions

Titaniferous magnetite commonly contains ilmenite formed by exsolution through the



Fig. 1. Moderately phlogopitized magnetite (black) in pegmatoidal magnetite olivinite. Veinlets of carbonate and carbonatite cut the magnetite. Drill hole 436 at 24.0 metres. Scale bar, 1.0 cm.

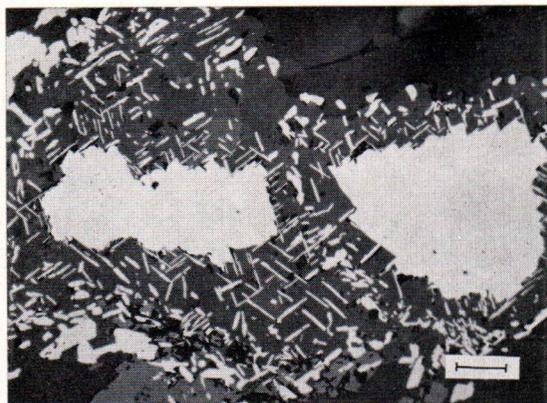


Fig. 2. Partly altered magnetite (light gray) in metaphoscorite derived from pyroxenite. The area of ilmenite lamellae indicate the original contours of magnetite. Drill hole 358 at 219.7 metres. Scale bar, 0.5 mm.

oxidation of an ulvite component of the originally homogeneous single-phase magnetite (Buddington and Lindsley, 1964). There are several generations of ilmenite exsolutions in the magnetite of metaphoscorites of the Sokli massif which can be described as follows:

- coarse granular-like ilmenite, which occurs between magnetite grains and in cracks of magnetite (Fig. 3 A)
- coarse granular ilmenite in magnetite (0.01–0.1 mm, Fig. 3 B)
- regular coarse exsolution lamellae (about 0.5 mm long and about 5 μm wide, Fig. 3 B)
- regular small exsolution lamellae (about 10 μm long, less than 0.5 μm wide).

These different types of ilmenite exsolutions occur irregularly in magnetite grains of metaphoscorites, even so that two or three different exsolution types may exist in one and the same grain (Fig. 3 B). The great number of exsolutions indicates that a great part of titanium may have exsolved as ilmenite from magnetite. This is supported by the spot analyses of clean places next to ilmenite exsolutions. According to the analyses the average TiO_2 content in the clean places of magnetite ranges between 0.4 and 2.0 %.

Lacking of ilmenite exsolutions (Fig. 4 A) makes the magnetite of magmatic carbonatites different from that of the metacarbonatites. A great magnification, however, reveals that this magnetite is unhomogeneous (Fig. 4 B), resembling the ulvöspinel described by Ramdohr (1969, p. 904).

Composition

Whole magnetite grains were analysed by an electron microprobe analyzer so that a square-shaped scanning area covered as big

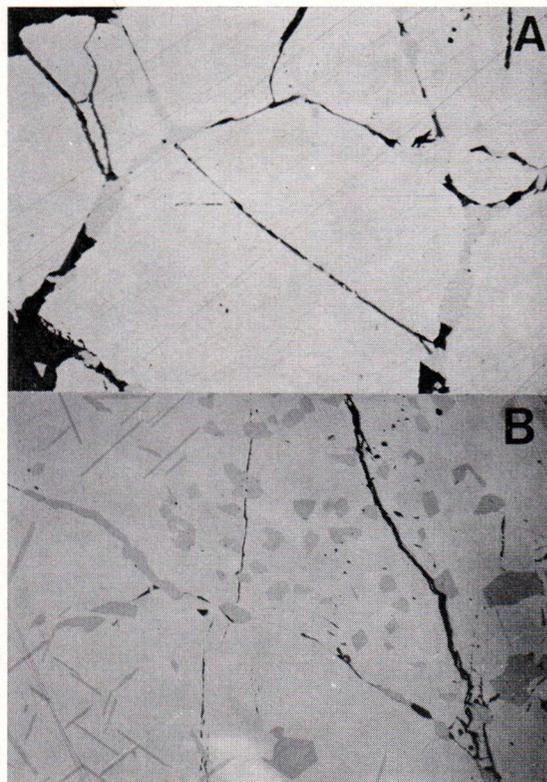


Fig. 3. Ilmenite exsolutions in the magnetite of metaphoscorites. A. Ilmenite exsolutions (medium gray) between magnetite grains (light gray) and in cracks of magnetite. Drill hole 4 at 105.7 metres. Magnification, $\times 200$. B. Coarse, granular ilmenite exsolutions (dark gray on the right) and coarse ilmenite lamellae (left) in one and the same magnetite grain (light gray). Drill hole 358 at 118.5 metres. Magnification, $\times 200$.

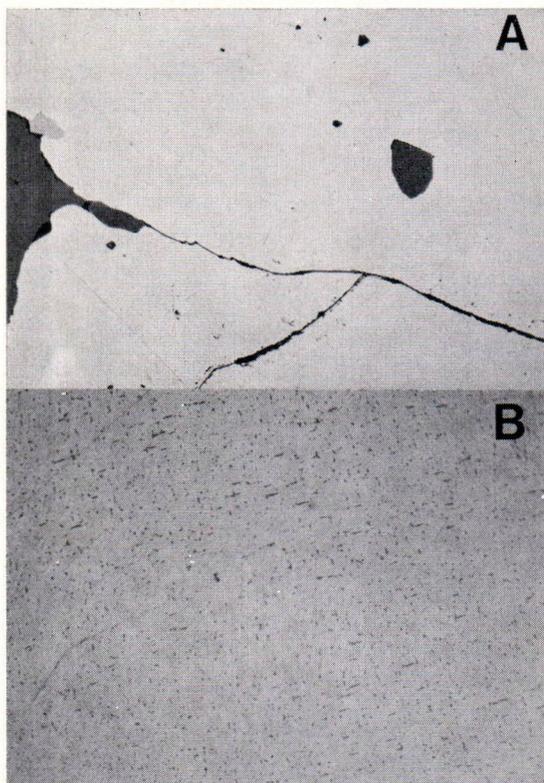


Fig. 4. Magnetite in magmatic phoscorite. Drill hole 250 at 59.7 metres. A. Homogeneous-looking magnetite (light gray). Magnification, $\times 200$. B. A greater magnification of the same grain shows unhomogeneity similar to ulvöspinel. Magnification, $\times 1000$.

an area of the grain under study as possible. The standard samples were scanned similarly. This method, unlike spot analyses, gives the original composition of magnetite before the exsolution of ilmenite, eliminating the effects of possible compositional zoning in grains. The values given in Table 2 are averages of three grain analyses per sample. There are only slight relative variations between grain analyses in a sample, e.g. the variation of iron is about one per cent and that of TiO_2 from 10 to 20 per cent.

The results of the analyses have been arranged according to host rocks in Table 2. The magnetite of magmatic carbonatites represents rocks from four stages. Because of

metasomatic alteration it has been difficult to group metacarbonatitic host rocks. The sample 946-0069 of metaphoscorite of an unidentified origin represents an amphibole-rich variant, the sample 946-0072 a mica-rich variant, and the last two strongly altered, heterogeneous rocks. Both metasilicosövitites are tetraferriphlogopite-richterite-bearing types.

The averages of minor components TiO_2 , MgO , MnO , and Al_2O_3 given in Table 2 have been plotted in Fig. 5. The magnetite of magmatic carbonatites has crystallized in successive generations as follows:

Stage I \rightarrow Stage II \rightarrow Stage IV.

The magnetite of Stage I is mainly preserved in the Stage III, and therefore the corresponding values are presented separately in Fig. 5. The results indicate that the minor components (TiO_2 , MgO , MnO , Al_2O_3) show a tendency to decrease during the crystallization of the magnetite of magmatic carbonatites whereas iron shows a contrary trend. Observations of Table 2 and Fig. 5:

TiO₂: The magnetite of phoscorites (Stage I and III) has a higher TiO_2 content (2.4—5.7 %) than that of sövitites and silicosövitites (1.2—2.1 %). The higher TiO_2 content of the Stage III compared to Stage I in Fig. 5 does not necessarily mean an increased TiO_2 content, but is more likely due to too few analyses, since high TiO_2 values (5 % TiO_2) occur also in Stage I (Table 2). Actually, during hydrothermal stage (Stage III), minor components in magnetite lattice have strongly decreased, which is verified by spot microprobe analyses. Two magnetite grains, with magnetite of Stage I enclosed by an altered or recrystallized magnetite phase of Stage III have been analyzed (Fig. 6). The results have been plotted in Fig. 7. TiO_2 as well as other minor components (MgO , MnO , Al_2O_3) have clearly decreased.

Table 2. Whole grain electron microprobe analyses of Sokli magnetites.

| Sample | DH no | Depth m | Stage | Rock | Fe % | TiO ₂ % | MnO % | V ₂ O ₃ % | Cr ₂ O ₃ % | SiO ₂ % | Al ₂ O ₃ % | MgO % | ZnO % |
|------------------------------|--------------|---------|-------|---------------------------------------------------|------|--------------------|-------|---------------------------------|----------------------------------|--------------------|----------------------------------|-------|-------|
| <i>Magmatic carbonatites</i> | | | | | | | | | | | | | |
| 946—0017 | 250 | 59.7 | I | Phoscorites | 67.7 | 3.15 | .95 | .19 | .01 | .13 | .48 | 3.11 | |
| 946—0018 | 289 | 112.1 | I | | 63.9 | 3.30 | .90 | .28 | .01 | .01 | .20 | 2.67 | |
| 946—0019 | 281 | 58.0 | I | | 65.1 | 5.01 | .84 | .12 | .01 | .44 | .84 | 3.20 | .11 |
| 946—0020 | 260 | 77.0 | I | | 67.1 | 2.43 | .74 | .21 | .01 | .02 | .25 | 2.85 | .10 |
| 946—0027 | 250 | 128.8 | II | Sövites and silicosövites | 66.6 | 1.21 | .77 | .14 | .01 | .05 | .85 | 3.61 | .10 |
| 948—1039 | 374 | 230.5 | II | | 67.8 | 1.99 | .84 | .13 | .01 | .01 | .51 | 2.83 | .08 |
| 948—0128 | 433 | 166.4 | II | | 69.4 | 1.68 | .48 | .14 | .01 | .01 | .41 | 1.10 | .08 |
| 946—0031 | 261 | 44.0 | II | | 69.1 | 1.50 | .45 | .16 | .01 | .01 | .53 | 1.41 | .09 |
| 946—0032 | 358 | 200.1 | II | | 70.3 | 1.55 | .37 | .14 | .01 | .02 | .43 | 1.41 | .08 |
| 946—0035 | 329 | 183.0 | III | Phoscorites | 67.1 | 5.75 | .57 | .22 | .01 | .02 | .13 | .86 | .12 |
| 946—0036 | 331 | 37.2 | III | | 67.8 | 5.40 | .53 | .22 | .02 | .07 | .13 | 1.10 | .12 |
| 946—0038 | 332 | 84.2 | III | | 68.9 | 3.41 | .56 | .17 | .01 | .01 | .13 | 1.20 | .11 |
| 946—0039 | 340 | 135.5 | III | | 68.4 | 3.01 | .49 | .34 | .01 | .02 | .10 | .98 | .11 |
| 946—0042 | 340 | 131.9 | IV | Sövites and silicosövites | 69.8 | 1.46 | .16 | .31 | .01 | .02 | .23 | .44 | .03 |
| 946—0043 | 342 | 110.2 | IV | | 68.8 | 2.15 | .57 | .20 | .01 | .02 | .17 | 1.59 | .10 |
| 946—0044 | 359 | 232.2 | IV | | 69.6 | 1.44 | .26 | .25 | .01 | .01 | .10 | 1.10 | .09 |
| <i>Metacarbonatites</i> | | | | | | | | | | | | | |
| 946—0063 | 4 | 153.5 | | Metaphoscorites altered from magnetite-olivinites | 67.9 | 4.16 | .45 | .15 | .01 | .05 | .19 | 1.64 | .09 |
| 946—0065 | 358 | 118.5 | | | 66.4 | 6.0 | .42 | .19 | .02 | .09 | .24 | 1.84 | .05 |
| 948—0126 | 433 | 91.2 | | | 68.0 | 2.28 | .67 | .34 | .01 | .03 | .16 | 1.44 | .08 |
| 948—0127 | 433 | 138.2 | | | 66.6 | 3.13 | .82 | .55 | .02 | .00 | .22 | 2.26 | .11 |
| 948—0129 | 433 | 172.1 | | | 67.5 | 2.41 | .66 | .15 | .01 | .00 | .69 | 1.78 | .10 |
| 948—0016 | 331 | 169.0 | | 65.6 | 3.40 | .47 | .16 | .01 | .00 | .88 | 1.72 | .10 | |
| 946—0066 | 193 | 122.0 | | Metaphoscorites altered from pyroxenites | 67.8 | 3.82 | .16 | .19 | .01 | .02 | .21 | .22 | .03 |
| 946—0067 | 343 | 137.0 | | | 68.9 | 2.57 | .38 | .30 | .01 | .01 | .24 | .44 | .08 |
| 946—0068 | 262 | 142.3 | | | 67.4 | 5.00 | .10 | .33 | .01 | .01 | .12 | .20 | .03 |
| 947—0196 | 358 | 371.3 | | | 68.1 | 3.32 | .14 | .16 | .01 | .02 | .08 | .23 | .04 |
| 946—0069 | 358 | 270.2 | | Metaphoscorites of unidentified origin | 67.2 | 6.44 | .35 | .21 | .01 | .03 | .14 | .31 | .03 |
| 946—0072 | 195 | 135.5 | | | 69.2 | 2.54 | .28 | .10 | .01 | .07 | .27 | .58 | .07 |
| 946—0074 | 345 | 164.5 | | | 62.2 | 2.50 | .40 | .27 | .01 | .10 | .10 | 1.38 | .09 |
| 947—0203 | 371 | 85.4 | | | 69.5 | 2.30 | .28 | .13 | .01 | .01 | .14 | .45 | .05 |
| 947—0200 | 370 | 109.5 | | Metasilicosövites | 69.9 | 2.04 | .18 | .17 | .05 | .01 | .09 | .25 | .11 |
| 947—0201 | 370 | 123.3 | | | 70.3 | 1.87 | .22 | .15 | .02 | .00 | .06 | .43 | .06 |
| <i>Tulppio olivinite</i> | | | | | | | | | | | | | |
| 948—1040 | Pit 26/MH/67 | | | Olivinite | 71.5 | .08 | .02 | .04 | .04 | .07 | .08 | .40 | .04 |

All metaphoscorites are characterized by high TiO₂ contents (2.3—6.4 %). The highest TiO₂ (6.4 %) contents in the Sokli magnetite derives from the metaphoscorite (sample 946-0069, Table 2). The magnetite of metasilicosövites has a lower TiO₂ content (about 2.0 %) than that of the metaphoscorites.

MgO, MnO, and Al₂O₃: The MgO and MnO contents in the magnetite of the magmatic carbonatites distinctly decrease towards younger generations excepting Al₂O₃ which

deviates from this trend in Stage II. The Al₂O₃ values in Table 2 suggest that Al₂O₃ contents are at the same level in Stage I and II but lower in Stage III and IV.

In metacarbonatites, the magnetite of metaphoscorite originating from the magnetite-olivinite differs from the other metaphoscorites with regard to higher MgO, MnO, and Al₂O₃ contents. The magnetite of metasilicosövites is more decreased in these components than in the metaphoscorites. Be it no-

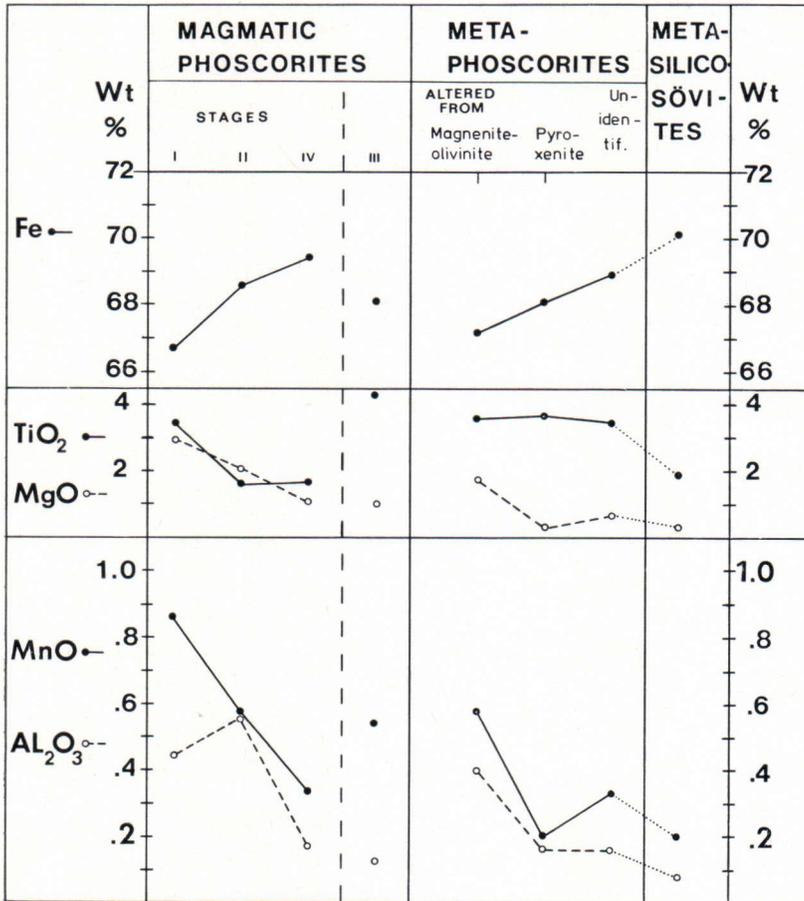


Fig. 5. Variation in minor elements of the magnetites of magmatic carbonatites and metasilicosövites.

ticed that the magnetite of metasilicosövites contains more TiO₂ and less MgO, MnO, and Al₂O₃ than the magnetite of magmatic sövites and silicosövites.

V₂O₃: The average contents of V₂O₃ in magnetite of different rock groups range from 0.14 to 0.25 % and in separate analyses from 0.13 to 0.33 %. The exceptionally high value of 0.55 % comes from metaphoscorite originating from magnetite-olivinite (sample 948-0127 / DH 433 / 138.2). Two other magnetites representing the same drill hole give normal values.

Cr₂O₃: Cr₂O₃ stays stable in all magnetites i.e. between 0.01 and 0.02 % excepting in metasilicosövite, where it rises up to 0.05 %.

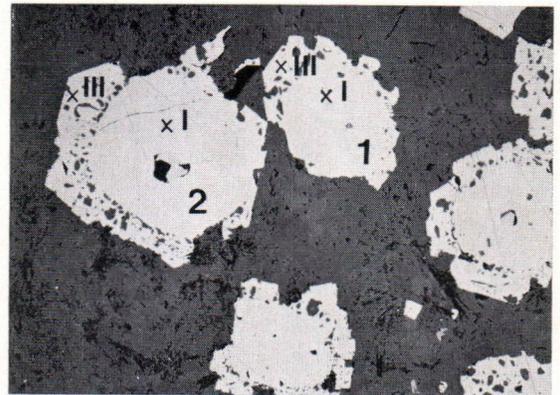


Fig. 6. Altered or recrystallized magnetite of Stage III enclosing the primary magnetite of Stage I. Symbols: x I = Analysed point of Stage I magnetite; x III = Analysed point of Stage III magnetite. Drill hole 331 at 37.2 metres. Magnification, x 100.

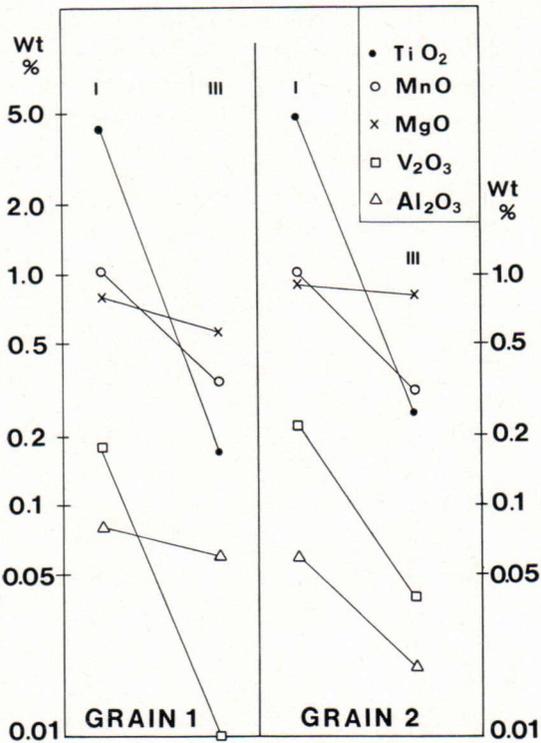


Fig. 7. Variation in the minor elements of magnetite grains in Stage III phoscorite. I = Stage I magnetite; III = Stage III magnetite. Analysed points are seen in Fig. 6.

SiO₂: The values below 0.13 % may represent the real SiO₂ contents in a magnetite lattice. The high value of 0.44 % for the sample 946-0019 may be due to a silicate inclusion, to which refers also the high Al₂O₃ content (0.84 %) as compared with the average (0.44 %) of Stage I phoscorites (Table 2).

ZnO: Magnetites of magmatic carbonatites have higher ZnO contents, i.e. 0.07 to 0.12 % than those of the metacarbonatites, i.e. 0.05 to 0.09 %, on the average.

Discussion

The magnetite of magmatic carbonatites is characterized by an idiomorphic-hypidiomorphic habit and a grain size of 1 to 10 mm. The magnetite of metacarbonatites, deriving from pre-carbonatitic rocks, shows granulation of originally big crystals (diameter up to 10 cm), the grains are veined and replaced by carbonates and micas. Besides, the chemistry of these magnetites shows some differences. The magnetite of the magmatic carbonatites has lower TiO₂ and higher MnO, Al₂O₃, MgO and ZnO contents than that of the metacarbonatites on the average. The contents of all minor elements, excepting Cr and Si, in the magnetite of Tulppio olivinite are lower than those in the former rocks (Table 3).

A great number of ilmenite exsolutions in the magnetite of metacarbonatites refers to a complicated thermal history of these rocks. The ilmenite exsolutions in the magnetite derived from the pre-carbonatitic magnetite olivinite and pyroxenite may be partly original, partly produced during thermomorphism caused by carbonatite intrusion.

Table 3. Average composition of magnetite in magmatic carbonatites, metacarbonatites, and Tulppio olivinite.

| | Fe % | TiO ₂ % | MnO % | V ₂ O ₃ % | Cr ₂ O ₃ % | SiO ₂ % | Al ₂ O ₃ % | MgO % | ZnO % |
|-----------------------|---------|-----------------------|----------|------------------------------------|-------------------------------------|-----------------------|-------------------------------------|----------|----------|
| Magmatic carbonatites | 68.2 | 2.78 | .58 | .21 | .01 | .06 | .32 | 1.78 | .10 |
| Meta-carbonatites | 68.6 | 3.16 | .33 | .21 | .02 | .03 | .20 | .77 | .07 |
| Tulppio olivinite | 71.5 | .08 | .02 | .04 | .04 | .07 | .08 | .40 | .04 |

The magnetite of magmatic carbonatites contains plenty of ulvite but only little ilmenite. This magnetite probably is in its original state, indicating that no stronger metamorphism has taken place after the intrusion of carbonatite.

The variation in the occurrence, composition and exsolution of magnetite of separate rock groups refers to differences in the crystallization environment and the geological history of the host rocks of magnetite.

Composition of the magnetite of carbonatites has been studied by Prins (1972). He concludes that the magnetite of carbonatites contains less trace elements (MnO, MgO, Al_2O_3 , V_2O_3 and CaO, whose total average is 2.3 wt-%) than the magnetite of salic rocks (4 wt-%). The averages (MnO, MgO, Al_2O_3 , V_2O_3 , Cr_2O_3 and ZnO) of the magnetite of Sokli magmatic carbonatites and metacarbonatites (Table 3) are 3.00 wt-% and 1.6 wt-%, respectively. According to Prins (1972) homogeneous magnetite of carbonatite contains 1 wt-% TiO_2 on the average, and magnetite carrying exsolved ilmenite not more than 6 wt-%. With regard to composition (average TiO_2 from 2.78 to 3.6 wt-%) the magnetite of Sokli carbonatite complex can be regarded as a typical magnetite of carbonatite. Deans and Seager (1978) have presented analyses of magnetite of volcanic carbonatites. They show above the average V_2O_3 content

(0.33 wt-%) and below the average MgO (0.26 wt-%) and Al_2O_3 (0.11 wt-%) contents as compared to the Sokli averages, which are: 0.21, 1.28, and 0.26 wt-%, respectively.

Using electron microprobe spot analyses Prins (1972) has shown that carbonatite magnetite is strongly zoned which results from decreasing of Ti, Mn and Mg from the middle towards the edges of magnetite grains, but V and Al do not show any clear trends. Even in the composition of crystallizing carbonatite magma the decreasing of Ti, Mn and Mg seems to be a general trend. The results of the Sokli whole grain magnetite analyses (Fig. 5) support these observations. During crystallization of Sokli magmatic carbonatites, V, Cr and Zn have not changed, but thereafter Zn was enriched in late carbonatite veins of Stage V forming an independent mineral (sphalerite).

Dissanayaka and Vincent (1972) have found out that zinc is enriched in the ultimate residual magmatic fractions of basic igneous complex of Skaergaard but this has been a continuous process.

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