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by Atso Vorma

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# ALKALI FELDSPARS OF THE WIBORG RAPAKIVI MASSIF IN SOUTHEASTERN FINLAND

BY

ATSO VORMA

WITH 24 FIGURES AND 5 TABLES IN TEXT

GEOLOGINEN TUTKIMUSLAITOS
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Three, possibly four granitic intrusive phases characterize the Wiborg rapakivi massif. The rocks of the first phase crystallized rapidly from a dry magma at a comparatively high temperature. The second phase crystallized at a lower temperature, in a broad temperature range, from a magma richer in volatiles. Sudden changes in the volatile pressure during the crystallization of the magma characterize the third and fourth phases.

The catalyzing action of the volatiles is believed to be the main reason of the Al/Si ordering and the exsolution grade in alkali feldspars. Orthoclase crypto- or microperthite characterizes the more basic members of each intrusive phase. The amount and grade of perthitic albite increase and its thermal state decreases as the differentiation products become more siliceous. At the same time, the potassic phase gradually sinks to a lower thermal state while the volatile and silica contents increase and the calcium content decreases in the rock. The alkali feldspar of the more basic varieties is richer in potassium than that of the more siliceous varieties.

The conclusions are based on X-ray powder and single crystal data, on microscopical study, and on wet chemical analyses of rapakivi alkali feldspars.

Comparison of the chemical analyses of different rapakivi varieties with latest experimental studies on the granite system by other researchers shows that in the typical rapakivi plagioclase started to crystallize before the alkali feldspar.

Helsinki 1971. Valtion painatuskeskus

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## INTRODUCTION

In the course of the geological remapping of the Wiborg rapakivi massif in southeastern Finland, the author, who under Professor Ahti Simonen took part in this project for many years, became interested in the rapakivi granite alkali feldspars and their significance in the rapakivi problem. Upon Professor Simonen's prompting, the author undertook the study of these feldspars. The project was carried out during a period of many years in addition to other investigations. Now that the remapping of the rapakivi massif is almost at an end, it is deemed appropriate to release this study.

In the present study, it is considered important to correlate the samples firmly to the field and also to use samples regarding which other detailed data are obtainable. The study is based on more than 200 specimens from different rapakivi varieties. More than 200 alkali feldspar samples were separated from more than 110 specimens for X-ray powder work. About 180 thin sections were studied and 37 single crystal X-ray determinations done. Besides the X-ray determinations on the composition of alkali feldspars, ten wet chemical analyses were perfomed.

In ascertaining the positive correlation between the phenomena studied, the petrographic description must unfortunately appear in the heavy form it has taken. The paper places special emphasis on the correlation of the perthite texture, twinning and thermal state to the influence of the catalyzing action of the vapour phase in different rapakivi granite varieties.

## DESCRIPTION OF THE ROCK SAMPLES

The different rapakivi granite varieties from the Wiborg (Viipuri) rapakivi granite massif have been petrographically described by various authors. Reference is here made only to the works of Sederholm (1923), Wahl (1925, 1938), Popoff (1928), Hackman (1934), Velikoslavinskiy (1953), Savolahti (1956), Simonen (in Laitakari and Simonen, 1963) and Simonen and Vorma (1969). The two last-mentioned papers briefly define the names of the rapakivi varieties in current use among Finnish petrologists. This terminology is exclusively used in the present paper. For the purpose of this work, it is necessary to give a more detailed description of the different rapakivi varieties than is given in the works of Simonen, and Simonen and Vorma cited, and also to correlate the synonyms used in the literature. In addition, the following description tells how the different varieties are thought to be genetically related. At this point, it should be remarked that the Wiborg rapakivi association also includes rock types not investigated during the present study. These are the more basic differentiation products (labradorites, norites, gabbros and labrador porphyrites) as well as the effusive rocks comagmatic with rapakivi granite (those in the islands of Someri (Sommarö) and Suursaari (Hogland) in the Gulf of Finland, at the southern border of the Wiborg rapakivi granite area). No pegmatites are included in the present study.

The samples studied by X-ray powder method (112), from which more than 200 potash feldspar fractions were separated, are distributed among the following petrographic rapakivi types (see Table 2).

### *Dark and darkish, even-grained granites; group I*

Dark and darkish, even-grained rapakivi granites (almost black, dark green, dark grey, etc.) are mainly rocks of medium or coarse grain size. The rock contains abundant quartz, plagioclase and potash feldspar in variable proportions; and hornblende, biotite, fayalite and, exceptionally, pyroxene are the mafic silicates. Iddingsite, grunerite and chlorite occur as alteration products. Characteristic of the dark and darkish varieties is the common occurrence in them of xenoliths of different rock types. In the present paper, the dark and darkish, even-grained rapakivi granites have been divided into three groups. The granites of the first subgroup (Ia) occur in the surroundings of the town of Lappeenranta, near the NE border of the Wiborg rapakivi massif. The rock is called tirilite (Wahl 1925, pp. 69—71 and Hackman 1934, pp. 27—32). For chemical analyses see Table 1, anal. No. 1 and Hackman's paper, p. 79, anal. 12. The small dark and darkish rapakivi masses met with south of Lappeenranta, near the border against the USSR, are also included in the same group with tirilites. In the Lappeenranta area, the tirilites change gradually to a brownish-red hornblende granite, which is the so-called Lappee syenite (Wahl 1925), also referred to as Lappee granite (Hackman 1934) (see the hornblende granites in group II), and which in turn grades over into a porphyritic variety, known as Sinkko granite (Hackman 1934). In the present treatment this is classifield under Vb. Against non-rapakivitic country rock, the tirilite often exhibits a small-grained contact variety, which is granite-porphyritic in appearance. According to the present author's investigations (1965) and those of Velikoslavinskiy (1953), the Lappee granite, with its more basic tirilitic varieties, represents an older intrusion phase than the typical rapakivi granite, wiborgite.

The tirilites are characterized by the presence of a large amount of plagioclase, often seen to occur as large idiomorphic phenocrysts; occasionally also rounded aggregates of plagioclase (synneusis) are met with, as are sparsely scattered potash feldspar ovoids, which are either mantled by plagioclase or unmantled.

The dark and darkish, even-grained rapakivi granites in the coastal islands of the Gulf of Finland form the second subgroup, Ib. This group of rocks forms a narrow zone trending east-west through the Haapasaari group of islands (Simonen, personal communication; Wahl 1925, pp. 25—26, and 1938, pp. 88—90). The rock resembles the foregoing tirilite, though it contains as phenocrysts more dark idiomorphic basic plagioclase and sparsely scattered potash feldspar ovoids. The common occurrence of grunerite as a deuteric alteration product (Simonen and Vorma 1969) is another feature which distinguishes this dark rapakivi from the tirilites of the Lappeenranta area. In micrographic texture there is also a clear difference between these granites (see p. 28). The age relation of the Ib-type dark and darkish granites to wiborgite is uncertain. Simonen (personal communication) reports that a wiborgite xenolith has been found in this rock. For chemical analyses of this variety the reader is referred to the paper of Wahl (1938, p. 92, Table 1, Nos. 1 and 2).

All the other even-grained, dark-coloured rapakivi granite specimens investigated are included in the third subgroup, Ic. Genetically this group is heterogeneous. Specimen No. 320/ML/53 represents a marginal variety of the brownish-red hornblende rapakivi of Suomenniemi (a satellite rapakivi massif just to the north of the Wiborg rapakivi massif; see the sketch map in Fig. 1). No. 759/ML/54 is from the dark green granite-porphyritic marginal variety (fayalite-bearing) of the hornblende rapakivi dike at Jaala—Iitti, on the northwest border of the Wiborg rapakivi massif, described by Lehijärvi and Lonka (1964). According to their results, the dike is younger than wiborgite, being petrographically a granite porphyry, over 20 km in length and from a few hundred meters to three kilometers in breadth. A chemical analysis of this »tirilite» is given in Table 1, No. 2.

### *Even-grained hornblende granites; group II*

Even-grained hornblende rapakivi granite forms petrographical group II. In it are included: the granite of Lappee (see under Ia; for chemical analyses see Hackman 1934, p. 78, anal. 5—7) and the granite of the Suomenniemi massif (see under Ic; chemical analysis of a representative sample is given in Table 1, No. 11). Also its granite porphyritic contact varieties against the non-rapakivitic country rocks are included in this group, even though these are petrographically mostly biotite granites. Third, the hornblende granite sample No. 751/ML/54 of Jaala—Iitti dike (see under Ic) is grouped here. A chemical analysis is given in Table 1, No. 10.

Group II is petrologically inhomogeneous. The Lappee granite is older than the wiborgite, and the age relation of the Suomenniemi granite massif to the main rapa-

TABLE 1.

Chemical composition, weight norms and mineralogical composition of representative rapakivi granites from the Wiborg rapakivi massif, SE Finland.

| | Tirilite | | Wiborgite | | | | Pyterlite | | Porphyritic rapakivi | Even-grained | | | | Porphyry aplite | Quartz porphyry |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Dark and darkish | | | Red | | | | Hbl-rapakivi | | Biotite rapakivi | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| $SiO_2$ | 63.72 | 67.96 | 64.70 | 66.08 | 69.44 | 68.88 | 75.36 | 76.69 | 76.20 | 68.05 | 74.40 | 74.87 | 73.80 | 74.38 | 70.88 |
| $TiO_2$ | .96 | .67 | 1.12 | 1.00 | .33 | .49 | .21 | .25 | .15 | .68 | .23 | .23 | .31 | .27 | .35 |
| $Al_2O_3$ | 14.29 | 12.96 | 13.45 | 14.28 | 14.01 | 13.74 | 11.57 | 10.68 | 11.90 | 12.77 | 11.91 | 12.39 | 12.06 | 12.10 | 11.87 |
| $Fe_2O_3$ | 1.92 | 1.92 | 2.24 | 2.17 | .80 | 1.02 | .95 | .96 | .27 | 1.75 | 1.13 | .25 | 1.08 | .75 | 3.73 |
| FeO | 5.74 | 4.20 | 4.99 | 2.96 | 3.39 | 3.62 | 1.50 | 1.93 | 1.54 | 4.36 | 1.60 | 1.89 | 1.92 | 1.89 | 1.28 |
| MnO | .13 | .09 | .10 | .04 | .11 | .06 | .02 | .03 | .02 | .10 | .02 | .02 | .03 | .03 | .04 |
| MgO | .69 | .54 | .94 | 1.27 | .26 | .47 | .16 | .17 | .02 | .58 | .23 | .24 | .24 | .31 | .64 |
| CaO | 3.28 | 2.49 | 3.06 | 1.69 | 2.04 | 1.92 | .83 | 1.01 | 1.16 | 2.05 | 1.17 | .82 | .90 | .78 | .90 |
| $Na_2O$ | 2.68 | 3.04 | 2.59 | 1.76 | 2.69 | 2.94 | 2.37 | 2.27 | 2.54 | 2.91 | 2.49 | 2.42 | 2.30 | 2.53 | 1.78 |
| $K_2O$ | 4.73 | 4.92 | 5.09 | 6.60 | 6.36 | 5.79 | 5.89 | 5.15 | 5.20 | 5.12 | 5.58 | 5.79 | 6.21 | 5.76 | 6.27 |
| $P_2O_5$ | .38 | .28 | .48 | .48 | .19 | .14 | .04 | .04 | .02 | .29 | .04 | .03 | .06 | .04 | .07 |
| $H_2O+$ | .64 | .56 | 1.04 | 1.68 | .44 | .75 | .69 | .47 | .41 | .92 | .69 | .47 | .59 | .56 | 1.46 |
| $H_2O-$ | .14 | .07 | .16 | .30 | .20 | .20 | .14 | .08 | .09 | .14 | .15 | .08 | .17 | .13 | .26 |
| F | — | — | .12 | — | .05 | .21 | .28 | .40 | .33 | — | — | .42 | .29 | .33 | — |
| $Li_2O$ | — | — | .02 | — | — | .06 | .04 | .02 | .04 | — | — | .05 | .01 | .03 | — |
| $Rb_2O$ | — | — | .04 | — | — | .04 | .05 | .05 | .13 | — | — | .06 | .06 | .06 | — |
| $Cs_2O$ | — | — | — | — | — | — | — | .00 | — | — | — | .00 | — | — | — |
| $CO_2$ | .44 | — | — | .11 | — | — | — | — | — | — | .07 | — | — | — | .18 |
| | 99.74 | 99.70 | 100.14 | 100.42 | 100.31 | 100.33 | 100.08 | 100.20 | 100.02 | 99.72 | 99.71 | 100.03 | 100.03 | 99.95 | 99.71 |
| $-O = F_2$ | — | — | .05 | — | .02 | .09 | .12 | .17 | .14 | — | — | .18 | .12 | .14 | — |
| | 99.74 | 99.70 | 100.09 | 100.42 | 100.29 | 100.24 | 99.96 | 100.03 | 99.88 | 99.72 | 99.71 | 99.85 | 99.91 | 99.81 | 99.71 |
| $Rb_2O$ | — | — | .017 | — | — | .024 | .045 | — | — | — | — | .045 | .045 | .045 | — |
| SrO | — | — | .021 | — | — | .015 | .003 | — | — | — | — | .005 | .003 | .004 | — |
| $ZrO_2$ | — | — | .049 | — | — | .054 | .042 | — | — | — | — | .045 | .050 | .051 | — |
| BaO | — | — | .12 | — | — | .13 | .06 | — | — | — | — | .05 | .04 | .05 | — |

Weight norms

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| q | 19.76 | 24.48 | 21.41 | 25.47 | 23.16 | 23.27 | 36.45 | 40.60 | 37.97 | 24.84 | 35.19 | 35.28 | 33.55 | 34.51 | 33.85 |
| or | 27.95 | 29.06 | 30.06 | 39.02 | 37.58 | 34.24 | 34.79 | 30.45 | 30.73 | 30.28 | 32.96 | 34.27 | 36.69 | 34.01 | 37.08 |
| ab | 22.66 | 25.70 | 21.92 | 14.90 | 22.76 | 24.70 | 20.04 | 19.20 | 21.50 | 24.65 | 21.08 | 20.45 | 19.46 | 21.40 | 15.05 |
| an | 13.02 | 7.21 | 10.04 | 5.23 | 7.37 | 7.29 | 3.56 | 3.73 | 5.62 | 6.62 | 4.95 | 3.87 | 4.09 | 3.59 | 3.98 |
| c | — | — | — | 2.32 | — | — | — | — | .03 | — | — | .72 | .10 | .40 | .69 |
| wo | .31 | 1.37 | .84 | — | .65 | .55 | .12 | .42 | — | .71 | .24 | — | — | — | — |
| en | 1.72 | 1.35 | 2.34 | 3.16 | .64 | 1.17 | .40 | .42 | .05 | 1.45 | .57 | .60 | .60 | .77 | 1.60 |
| fs | 7.61 | 5.20 | 5.66 | 2.07 | 5.24 | 5.11 | 1.68 | 2.40 | 2.39 | 5.62 | 1.66 | 2.92 | 2.16 | 2.45 | — |
| ap | .89 | .66 | 1.12 | 1.12 | .43 | .33 | .10 | .10 | .05 | .66 | .10 | .07 | .13 | .10 | .16 |
| il | 1.82 | 1.27 | 2.12 | 1.90 | .62 | .93 | .39 | .47 | .29 | 1.29 | .44 | .44 | .59 | .52 | .67 |
| mt | 2.78 | 2.78 | 3.24 | 3.15 | 1.16 | 1.48 | 1.37 | 1.39 | .39 | 2.55 | 1.64 | .37 | 1.57 | 1.09 | 3.24 |
| hm | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 1.50 |
| | 98.52 | 99.08 | 98.75 | 98.34 | 99.61 | 99.07 | 98.90 | 99.18 | 99.02 | 98.67 | 98.83 | 98.99 | 98.94 | 98.84 | 97.82 |

Modal composition (even-grained rapakivi)

x = present, (x) = occasionally present, — = not detected; only the most important accessories given

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Quartz | 20.4 | × | × | × | × | × | × | × | × | 26.8 | 28.6 | 33.2 | 44.3 | × | × |
| Plagioclase | 23.7 | × | × | × | × | × | × | × | × | 24.2 | 20.1 | 5.8 | 2.3 | × | × |
| Potash fp. | 44.1 | × | × | × | × | × | × | × | × | 39.0 | 38.9 | 56.8 | 46.9 | × | × |
| Olivine | 1.0 | × | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Hornblende | 9.0 | × | × | × | × | × | — | — | — | 3.0 | 6.0 | — | — | × | — |
| Biotite | .5 | × | × | × | × | × | × | × | × | 6.4 | 4.4 | 4.1 | 5.3 | × | × |
| Chlorite } | .3 | — | × | × | × | × | × | × | × | — | — | × | — | × | × |
| Iddingsite } | | × | × | × | × | — | — | — | — | — | × | — | — | — | — |
| Ore | .6 | × | × | × | × | × | × | × | × | × | × | × | × | × | — |
| Zircon | × | × | × | × | × | × | × | × | × | × | × | × | × | × | × |
| Apatite | .2 | × | × | × | × | × | — | — | — | × }.6 | × }1.8 | — }.1 | — }.8 | × | — |
| Fluorite | — | — | (×) | — | (×) | × | × | × | × | × | × | × | × | × | × |
| Calcite | .2 | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Grunerite | — | × | × | — | × | — | — | — | — | — | — | — | — | — | — |
| Sericite | × | × | × | × | × | × | × | × | × | × | × | × | × | × | — |

1. Dark-coloured, even-grained rapakivi granite (tirilite). Tullisenlampi, Lemi. No. 35b/AS/54. Anal. P. Ojanperä (Simonen and Vorma 1969). Modal composition by Simonen (1961). — 2. Tirilite. Kokkolanmäki, Jaala. No. 759/ML/54. Anal. P. Ojanperä (Lehijärvi and Lonka 1964). — 3. Dark-coloured wiborgite. Northwest of Lake Pyhäjärvi, Artjärvi. No. A1. Anal. P. Ojanperä, F determined by A. Heikkinen (Laitakari and Simonen 1963). — 4. Dark-coloured wiborgite. Orrengrund, Pernaja. No. 102/54/MLa. Anal. P. Ojanperä. — 5. Green rapakivi (wiborgite). Kaitjärvi, Luumäki. (Sample No. 3/AV/69 from the same locality). Anal. N. Sahlbom (Hackman 1934). — 6. Wiborgite. Road cut, Lapinjärvi. No. A2. Anal. P. Ojanperä, F determined by A. Heikkinen (Laitakari and Simonen 1963). — 7. Pyterlite. Road cut, Liljendahl. No. A3. Anal. P. Ojanperä, F determined by A. Heikkinen (Laitakari and Simonen 1963). — 8. Pyterlite. Sutela, Kotka. (Sample No. 284/ALo/56 from the same locality). Anal. P. Ojanperä, F determined by A Heikkinen (Simonen and Vorma 1969). — 9. Porphyritic rapakivi. Verla, Iitti. No. 714/ML/54. Anal. P. Ojanperä, F determined by A. Heikkinen (Simonen and Vorma 1969). — 10. Hornblende rapakivi. Sahaniemi, Iitti. No. 751/ML/54. Anal. P. Ojanperä (Lehijärvi and Lonka 1964). — 11. Hornblende rapakivi. Vanonen, Mäntyharju. From the Suomenniemi rapakivi massif. No. 28/AS/53. Anal. P. Ojanperä. — 12. Even-grained rapakivi granite. W of Lake Kirkkojärvi, Myrskylä. No. A4, Anal. P. Ojanperä, F determined by A. Heikkinen, modal composition by Simonen (in Laitakari and Simonen 1963). — 13. Even-grained rapakivi granite. Road cut, Lapinjärvi. No. A5. Anal. P. Ojanperä, F determined by A. Heikkinen, modal composition by Simonen (in Laitakari and Simonen 1963). — 14. Porphyry aplite. Porlammi, Lapinjärvi. No. A6. Anal. P. Ojanperä, F determined by A. Heikkinen (Laitakari and Simonen 1963). — 15. Quartz porphyry. Hamina. No. 18/AS/56. Anal. P. Ojanperä. — Note: Rb, Sr, Zr and Ba determinations below the wet chemical analyses were determined by V. Hoffrén by X-ray fluorescence method.

kivi intrusion phase (wiborgite) is unknown. The granites in question are coarse-grained biotite-hornblende granites with sparsely scattered, bigger potash feldspar phenocrysts, many of which are ovoidal in shape. The granite of the Jaala—Iitti dike is granite-porphyritic in appearance and younger than the intrusion phase of wiborgite (IIIb) and porphyritic rapakivi (Va) (Lehijärvi and Lonka 1964, p. 135).

### *Wiborgites; group III*

Dark and darkish wiborgites are grouped under IIIa. This group thus also contains wiborgites which are, so far as colour is concerned, intermediate between the dark and normal wiborgites. The rocks grouped here mostly have a sparse content of potash feldspar ovoids. In addition, they contain dark-coloured, zoned plagioclase as porphyritic grains or in synneusis. The main minerals are the same as in normal wiborgite (to be discussed next under IIIb), in addition to which fayalite, iddingsite and grunerite are usually present. Furthermore, the plagioclase and hornblende contents are higher than those in normal wiborgite. Most of the dark wiborgites lie quite close to the contact zone against the country rock of the massif. For representative chemical analyses, see Table 1, Nos. 3—5.

The normal wiborgite, i.e., the classical rapakivi granite variety showing the typical rapakivi texture, is under IIIb in this paper. It is a coarse-grained porphyritic granite with potash feldspar ovoids, measuring from 3 to 4 cm in diameter; and most of the ovoids are surrounded by plagioclase mantles, from 1 to 3 mm in thickness. The ovoids are densely distributed. The main minerals are potash feldspar, plagioclase and quartz, which all occur in at least two generations. Ferrohastingsitic hornblende and lepidomelanitic biotite are the typical mafic silicates (Simonen and Vorma 1969), while iddingsite and chlorite are found as alteration products. The intrusion of wiborgite represents the major intrusion stage of the Wiborg rapakivi granite. Chemically and texturally, it is a quite homogeneous rock, which covers 76 per cent of the area of the Finnish part of the massif (Simonen and Vorma 1969). Even though the rock is homogeneous over wide areas, it has not gained mineral equilibrium. This is reflected by the two mineral generations present, and by the mineral intergrowths to be discussed later. Representative chemical analyses are to be found in Table 1, No. 6; as well as in Hackman 1934, p. 78, anal. 1; and Wahl 1925, p. 77, Table 1, anal. 4—6.

### *Pyterlites; group IV*

Pyterlite is texturally related to wiborgite. However, in this rapakivi variety most of the ovoids are devoid of plagioclase mantles (Wahl 1925; Simonen and Vorma 1969). Chemical differences in comparison with wiborgite are reflected by its lower plagioclase and higher potash feldspar content. Biotite is the predominant Fe-Mg silicate, while hornblende is mostly lacking. Chemical compositions of representative pyterlites are listed in Table 1, Nos. 7 and 8 and in Wahl 1925, p. 77, Table 1, anal. 1—3.

Mostly, there is a gradual transition between wiborgite and pyterlite (Wahl 1925, p. 26; Simonen and Vorma 1969, p. 7). In the Soviet part of the Wiborg rapakivi massif, Velikoslavinskiy (1953) described a porphyritic rapakivi with a coarse-grained groundmass. This granite also undergoes a gradual transition to wiborgite. The description corresponds with the characteristics of pyterlite described by Wahl. It is possible that all pyterlites are not necessarily related to wiborgites by gradual transition. Sviridenko (1968) in his thorough study on the Salmi rapakivi massif, NE of Lake Ladoga, stated that the second phase, following the first intrusive phase of wiborgite, was characterized by an even-grained rapakivi granite. This phase was then emplaced before the third intrusive phase arrived represented by pyterlite.

### *Porphyritic granites; group V*

Porphyritic rapakivi granite, here grouped under Va, is characterized by an abundance of angular potash feldspar phenocrysts (from 0.5—3 cm in diameter) without mantles of plagioclase. The groundmass is medium- to coarse-grained. In many instances, there is a gradual transition in grain size between the groundmass potash feldspar and the phenocryst potash feldspar. The mineralogical and chemical composition of this variety is quite similar to that of pyterlite. The only difference between these varieties is a texturel one, the phenocrysts occurring in the porphyritic variety tend to be more automorphic than those in the pyterlite, where there is a marked tendency to ovoidal shapes. Evidently, the intrusion is simultaneous with that of pyterlite and wiborgite. The chemical composition of a representative sample is shown in Table 1, No. 9.

In addition to these coarse-porphyritic granites, a few specimens are grouped under Vb. This subgroup is quite inhomogeneous and hence not included among the $2V\alpha$ and reflection type histograms (p. 44). In addition to the remarks in Table 2, the specimens listed under Vb require the following characterization. Specimens S and 1/AV/68 are from the Sinkko granite of Hackman (1934, pp. 24—25), i.e., from a light gray porphyritic granite with densely distributed, angular, white potash feldspar phenocrysts between 0.5 and 1.5 cm in diameter in a medium-grained groundmass. Only very seldom are potash feldspar ovoids, ranging from 2 cm to 6 cm in diameter, to be found. The gradual transition between the granites of Lappee and Sinkko was discussed under granite type II. For a more detailed petrographic description and chemical analyses, see Hackman 1934 (pp. 24—25 and p. 78, anal. 4). The intrusion phase of tirilite—Lappee granite—Sinkko granite precedes, in the present author's opinion that of wiborgite.

The two specimens 16a/AS/54 and 19/AS/54 evidently are genetically related to the afore-mentioned coarse-porphyritic granite (Va), and thus also their intrusion phase is contemporaneous with that of wiborgite. The two specimens 137/AV/59 and 185/AV/59 are from a granite porphyry apophyse or dike 6 km long and from 200 to 600 m broad. This rock was mentioned by Wahl in 1925 (p. 25) and by Hackman in 1934 (pp. 12—13; chemical analysis on p. 78, anal. 2) and described by Vorma in 1965 (pp. 42—43). This granite porphyry, which in places is quite coarse-grained, often grading over to porphyritic granite, has in other places a 50—100 m broad, fine-grained, non-porphyritic, marginal modification, which is banded near the contact against the granodioritic country rock; during emplacement the country rock here had been quite cool and the granite porphyry underwent rapid crystallization (Vorma, *op.cit.*, pp. 52—53). The same rock has similar banded contacts, in this case forming a zone some meters broad, against its porphyritic rapakivi granite country rock. In the author's view the granite porphyry in question might be related in age to the Jaala—Iitti hornblende granite dike (see Ic and II). From the Soviet part of the Wiborg rapakivi massif, Velikoslavinskiy described (1953, pp. 20—24) a porphyritic granite with a fine-grained groundmass. This rock, in the light of the description given, is of the sampe type as the foregoing granite porphyry and younger than wiborgite.

### *Even-grained biotite granites; group VI*

The even-grained biotite granites, listed in Table 2 under VI, form a quite inhomogeneous group. These rocks are usually red or reddish, with a grayish tint sometimes prevailing. Among these granites, the medium-grained variety prevails over the coarse-grained. The major minerals are postash feldspar, quartz, and plagioclase. Biotite is the main Fe-Mg silicate. Occasionally, scattered ovoids of potash feldspar are to be found. Most of the rocks investigated evidently are either contemporaneous or younger than wiborgite. It will be shown that, in spite of the inhomogeneous petrological character of this group, the potash feldspars in all these granites resemble each other. For representative chemical analyses of the even-grained biotite rapakivi granites, see Table 1, Nos. 12 and 13.

Of the granites (VI) investigated, notice should be given to a gray medium-grained, topaz-bearing variety; the magma from which it was produced evidently was rich in volatiles, especially fluorine. Another variety worth mentioning is a fine-grained granite represented by specimens 204a and 204c/AV/59 and described by Vorma (1965, p. 47). Especially at the locality where sample 204c was collected, a conspicuously marked trachytic fabric appears. Narrow laths of potash feldspar (about 1 mm thick and 5 mm to 8 mm long) occur in a roughly parallel arrangement. In addition, the rock contains sparsely scattered, large potash feldspar ovoids. The age relation of this variety to other rapakivi varieties is not clear. From the Soviet part of the Wiborg rapakivi massif, Velikoslavinskiy (1953, pp. 24—28) described a trachytoid rapakivi that completely corresponds to sample 204c/AV/59. In his view, this phase represents a still younger intrusion phase than that of the granite porphyries (in the original paper porphyritic granite with a fine-grained groundmass).

### *Porphyry aplites; group VII*

The porphyry aplite is a rapakivi granite that contains sparsely distributed, mantled or unmantled ovoids of potash feldspar in a fine-grained aplite-granitic matrix (Simonen and Vorma 1969, p. 7). The mineral and chemical composition of the porphyry aplite is similar to that of the pyterlite and even-grained rapakivi granite. In the present study, those porphyry aplites occurring massif-like and often grading over to biotite granite have been grouped under VII. In the histograms (p. 44) some massive granite porphyries are included in this group. A chemical analysis of a representative porphyry aplite is given in Table 1, No. 14.

### *Dike rocks; group VIII*

The dike rocks investigated during the present study, excluding those described under Ic and II, have been grouped under VIII in Table 2. The dike rocks — granite porphyry, porphyry aplite, aplite and quartz porphyry — are mineralogically related to the biotite rapakivi described previously and cut both the principal rapakivi granites and the country rocks of the rapakivi.

Among the dike rocks, the quartz porphyry is of main interest for the present study. The phenocrysts are idiomorphic potash feldspar, plagioclase and quartz. In many instances, a marked alignement of potash feldspar phenocrysts parallel to the contacts of the dikes is to be observed. The marginal parts of the dikes against their country rocks are devoid of phenocrysts, the groundmass being aphanitic. In the central part of the dikes, the groundmass is somewhat more coarse-grained than at the contacts but still microcrystalline. A spherulitic structure, occasionally even a perlitic structure (Simonen, personal communication), is sometimes observed. A chemical analysis of specimen No. 18/AS/56 is given in Table 1, No. 15.

The foregoing description should suffice to give both the petrographical and the geological background for the study of the alkali feldspar from different rapakivi granite varieties. Figure 1 gives on a simplified map the localities of the specimens studied and listed in Table 2. Table 1 gives the petrochemical background for the specimens investigated. It contains data concerning those chemically analysed rapakivi granites from which pieces were obtained for this study. In two exceptions (Nos. 5 and 8), pieces of the original samples were not available. In these cases, however, since the locality of the samples analysed is known, it was possible to procure cor-

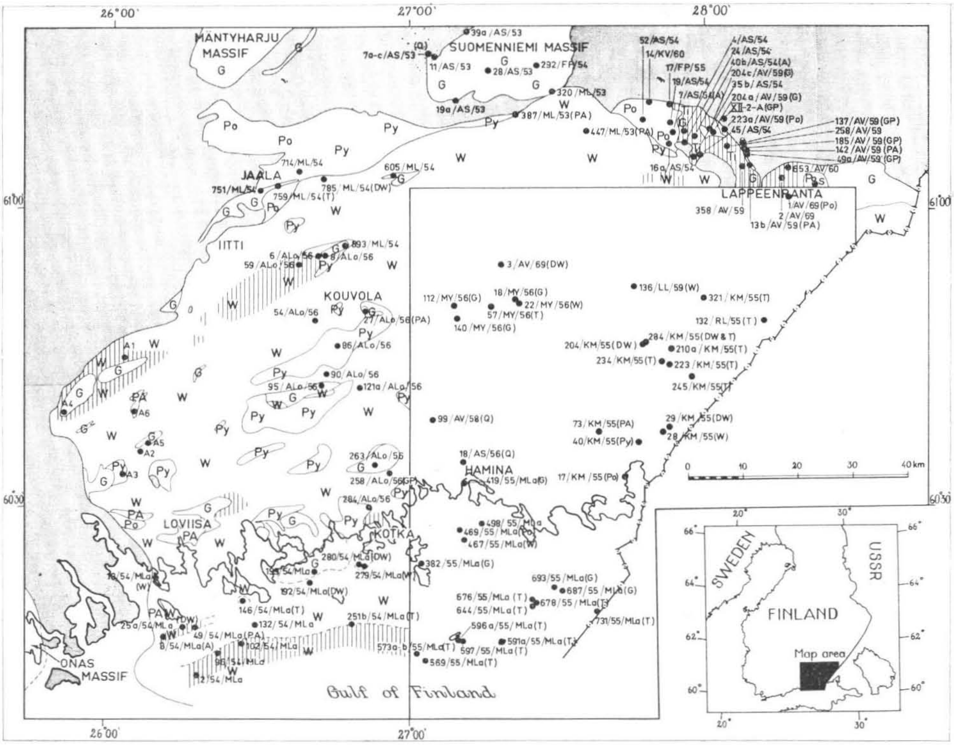

FIG. 1. Generalized geologic map of the Finnish part of the Wiborg rapakivi granite massif simplified from geological map quadrangles, scale 1 : 100 000, hitherto published. Rock type symbols: W, wiborgite; DW, dark and darkish wiborgites; Py, pyterlite; Po, porphyritic rapakivi granite; G, even-grained rapakivi; T, dark and darkish even-grained rapakivi granites, often with scattered phenocrysts; PA, porphyry aplite; GP, granite porphyry; A, aplite; Q, quartz porphyry; vertical striation, dark rapakivi granites (dark wiborgites and tirilites). The grey area is the country rock of rapakivi. Sample localities for potash feldspar studied by the X-ray methods marked by dots. Rock type symbol is given in parantheses after the specimen number when the rock type is different from that shown by the geological map and in those cases where geological maps are not available (SE-part of the figure). The sketch is simplified from the maps by Laitakari and Simonen (1962), Simonen and Lehijärvi (1963), Laitala (1964, 1965), Lehijärvi (1964, 1969), Vorma (1964), Simonen (1965), Simonen and Tyrväinen (1965), Meriläinen (1966) and Simonen and Laitala (1970).

responding new material. Most of the analyses in Table 1 have been published earlier. Nos. 4, 11 and 15 are new. Prof. Ahti Simonen placed at the author's disposal both analyses and the corresponding specimens. In the norm calculations, F, Li, Rb and $CO_2$ were omitted, as they have been determined only from a few specimens.

Table 1 also gives the modal composition by point count analyses for the even-grained varieties. Only the more common accessory minerals are included. At a later stage, a separate study on the accessory minerals will be published. From one of the analysed granites (No. 1, Table 1), fayalite (Simonen 1961) and ferrohastingsite (Simonen and Vorma 1969) have been previously studied.

## MINERALOGY OF THE RAPAKIVI GRANITE ALKALI FELDSPAR

### Abundance

The estimations of the alkali feldspar contents in the coarse-grained rapakivi granite varieties, wiborgite—pyterlite—porphyritic rapakivi, are approximate because of the difficulty in performing measurements. In the even-grained varieties the determinations give more reliable results.

Dark and darkish, even-grained varieties (group I): Table 1 in Simonen's paper (1961, p. 372) gives modal compositions for eight granites of this group. The average figure for alkali feldspar is 44 percent by volume. Savolahti (1962, p. 42) gives ca. 47 % for the green marginal variety of hornblende rapakivi of the Ahvenisto massif, Vorma (1965, p. 48) 46 % for a tirilite near Lappeenranta. Hackman's figures (1934, p. 29) of 27 % to 38 % for potash feldspar in this group of granites, in some papers referred to as modal compositions, are modes calculated from chemical analyses. When the measured modes mentioned, recalculated as percentages by weight, are compared with those of Hackman's, the difference points to an approximate chemical bulk composition of the alkali feldspars in question, ca., 30 % Ab in solid solution.

Among the even-grained biotite granites (group VI), the figure for alkali feldspar is slightly higher than the foregoing. The point count analyses give an approximate figure of 50 percent by volume. In the Salmi rapakivi massif, the measured alkali feldspar content in the even-grained granites varies from 47.9 % to 57.1 % (Sviridenko 1968, p. 23).

In the wiborgite of the Wiborg massif (group III), no exact measurements are available of the alkali feldspar contents other than both modal and normative compositions calculated from the chemical analyses. Hackman (1934, p. 8) gives a figure of 32.5 % for potash feldspar. If the bulk chemical composition of alkali feldspar in wiborgite is assumed to be $Or_{70}Ab_{30}$, the alkali feldspar content in wiborgite amounts to 45—50 %. This figure is somewhat lower than Sviridenko's, which ranges from 52.9 % to 67.3 % for the wiborgites in the Salmi rapakivi massif. According to Velikoslavinskiy's estimate (1953, p. 51), the ovoids constitute about 50 % and the groundmass 50 % by volume of the wiborgite rapakivi in the Wiborg massif. The few point-count analyses available to the present author on the groundmass of wiborgite give alkali feldspar contents from about 40 to 60 percent by volume.

Direct measurements of the alkali feldspar contents of either pyterlite or porphyritic rapakivi are not available from the Wiborg rapakivi massif. According to the chemical analyses, the alkali feldspar contents should be over 50 %, possibly close to 55 %. From the Salmi rapakivi granite massif, Sviridenko (1968, p. 32) reports alkali feldspar contents in pyterlites from 47 to 63.5 percent by volume.

Estimations of the alkali feldspar contents in porphyry aplite and granite porphyry (groups VII and VIII) are also scarce. For the porphyry aplites from the Ahvenisto massif Savolahti (1956, p. 50) reports alkali feldspar contents of 42 % to 50 % in

TABLE 2.

Rapakivi granite specimens from the Wiborg rapakivi massif investigated by the X-ray powder method. Bulk chemical composition of alkali feldspar and of the potassic phase, both for the groundmass and phenocryst feldspars. Structural type for each feldspar as well as optical axial angle given if measured.

| Specimen number | X-ray determination | | | | | | | | | 2Vα | | | Fe-Mg silicate paragenesis | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Groundmass | | | | Phenocrysts | | | | | | | | | |
| | % by wt. Or | | | | % by wt. Or | | | | | | | | | |
| | Bulk composition | Composition of the potassic phase | Structural type | Obliquity (in structural types *IV*, *III*/*V* and *V*) | Bulk composition | Composition of the potassic phase | Structural type | Obliquity (in structural types *IV*, *III*/*V* and *V*) | Type of phenocryst | Range in the groundmass | Phenocrysts | Type of phenocryst | | |
| | Ia. *Dark and darkish-coloured, even-grained rapakivis (incl. tirilites).* | | | | | | | | | | | | | |
| 258/AV/59 ..... | 72.5 | 89.7 | *I* | | | | | | | 60—62 | | | Fa | |
| 358/AV/59 ..... | 73.7 | 93.5 | *I* | | | | | | | | | | Fa | |
| 2/AV/69 ....... | 75.2 | 89.6 | *I* | | 70.8 | 90.4 | *I* | | P | | | | Fa | |
| 24/AS/54 ....... | 77.1 | 91.9 | *II*/*III* | | | | | | | 71—72 | | | Fa | Contact variety |
| 35b/AS/54 ...... | 76.3 | 89.5 | *I* | | 73.7 | 89.0 | *I* | | P | 54—63 | 57 | P | Fa | |
| 45/AS/54 ....... | — | 92.7 | *III*/*V* | 0.80 | 84.4 | 93.8 | *V* | 0.82 | A | 76—90 | 88 | A | Bi | Contact variety |
| 132/RL/55 ...... | 76.5 | 87.8 | *I* | | | | | | | 48 | | | Cp | |
| 210a/KM/55 .... | 69.9 | 89.6 | *II* | | 69.4 | 89.8 | *II*/*III* | | A | 68—76 | | | Hbl | |
| 223/KM/55 ..... | 78.4 | 89.3 | *I* | | | | | | | 62—66 | | | Fa+Cp | |
| 234/KM/55 ..... | 74.6 | 89.2 | *I* | | | | | | | 61—65 | | | Hbl | |
| 245/KM/55 ..... | 76.0 | 88.4 | *I* | | | | | | | 60—61 | | | Fa | |
| 284a/KM/55 .... | — | — | *III* | | — | 90.6 | *II*/*III* | | W | 81—83 | | | Bi | A granite-porphyritic variety |
| » ..... | | | | | — | — | *III* | | P | | | | | |
| 321/KM/55 ..... | 72.4 | 89.4 | *I* | | | | | | | 56—64 | | | Fa+Cp | |
| | Ib. *Dark and darkish-coloured, even-grained rapakivis.* | | | | | | | | | | | | | |
| 146/54/MLa .... | 83.7 | — | *III*/*V* | 0.76 | 70.8 | 93.7 | *II* | | A | 70 | | | Fa | Coarse-grained |
| 251b/54/MLa ... | — | — | *III* | | | | | | | 68—72 | | | Fa | |
| 569/55/MLa .... | 79.1 | 91.4 | *II*/*III* | | | | | | | 74—78 | | | Hbl | |
| 573a/55/MLa ... | 78.9 | 89.9 | *II*/*III*, *IV* | 0&0.63 | — | 93.5 | *I*/*II* | | P | 62 | | | Fa | |
| 573b/55/MLa ... | 84.0 | 95.9 | *V* | 0.76 | 82.5 | — | *II*/*III* | | P | | | | Fa | |
| 591a/55/MLa ... | — | — | *III* | | | | | | | 85 | 78—88 | | Fa | |
| 596a/55/MLa ... | 77.1<br>(60.2) | 90.5 | *I*/*II* | | 77.6 | 92.5 | *I* | | A | 53—73 | | | Fa | |
| 597/55/MLa .... | 80.9 | 88.3 | *II* | | 77.0 | 90.6 | *I*/*II* | | A | 66—68(—78) | | | Fa | |
| 644/55/MLa .... | 79.7 | 89.9 | *II* | | 77.3 | 90.8 | *I* | | P | 64—76 | | | Fa | |
| 676/55/MLa .... | 78.0 | 91.2 | *II*/*III* | | | | | | | 62—70 | | | Hbl | |
| 678/55/MLa .... | 76.9 | 91.4 | *I* | | | | | | | 60—68 | | | Fa | |
| 731/55/MLa .... | 78.8 | 90.2 | *I* | | | | | | | 67—70(—88) | | | Fa | |

Ic. *Dark and darkish-coloured, even-grained rapakivis*

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 57/MY/56 | 69.3 | 90.2 | *I/II* | | 70.4 | 91.0 | *II/III* | | W | 76—78 | | | Fa | |
| 759/ML/54 | 71.4 | — | *I** | | | | | | | | | | Fa | Granite-porphyritic variety (Jaala—Iitti dike) |
| 320/ML/53 | 76.5 | 90.5 | *I/II* | | | | | | | 56—57 | | | Fa | Contact variety of Suomenniemi granite (Hbl-granite) |

II *Hornblende rapakivis (even-grained) and their contact varieties*

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 653/AV/60 | 82.0 | 88.0 | *I/II* | | 77.1 | 87.8 | *II* | | A | 60—64 | | | Fa | Lappee granite |
| 4a/AS/54 | — | — | *III* | | | | | | | 65—78 | | | Hbl | » » |
| 292/FP/54 | 76.8 | 93.9 | *V* | 0.90 | | | | | | 70—82 | | | Fa | Suomenniemi granite |
| 11a/AS/53 | — | 93.8 | *V* | 0.90 | — | 95.6 | *III/V* | 0.80 | A | 82—83 | 90 | A | Bi | Granite-porphyritic contact variety of Suomenniemi gr. |
| 19a/AS/53 | — | 96.2 | *III/V* | 0.75 | | | | | | 58—68 | | | Bi | » |
| 39a/AS/53 | 78.3 | 95.0 | *V* | 0.90 | 73.4 | 94.5 | *V* | 0.86 | A | 80—90 | 84 | A | Fa | » |
| 28/AS/53 | 77.9 | — | *V* | 0.84 | — | — | *III* | | P | 78—86 | | | Fa | Suomenniemi granite |
| 751/ML/54 | — | — | *IV* | 0&0.72 | 79.5 | 88.6 | *II* | | A | 73—76 | | | Hbl | From the granite-porphyritic Jaala—Iitti dike |

IIIa. *Dark and darkish wiborgites*

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3/AV/69 | — | — | *III* | | — | — | *IV* | | P | 73 | 74 | P | Fa | |
| A1 | — | — | *IV* | 0&0.80 | 73.8 | 89.3 | *II* | | P | 65—68 | 66 | W | Fa | |
| 785/54/ML | 71.8 | 89.7 | *I/II* | | — | — | *I* | | W | | | | Fa | |
| 59/ALo/56 | 77.5 | 90.1 | *II* | | 76.9 | 90.2 | *I/II* | | P | 60—67 | | | Fa | |
| 29/KM/55 | 84.8 | 89.5 | *II/III* | | — | — | *III* | | P | | | | Hbl | |
| » | | | | | 83.9 | 88.6 | *II* | | W | | | | | |
| 204/KM/55 | 78.4 | — | *II* | | 78.3 | 93.1 | *I/II* | | P | 64 | | | Fa | |
| » | | | | | 76.6 | 88.6 | *I* | | W | | | | | |
| 284b/KM/55 | 73.4 | 89.1 | *I* | | 70.3 | — | *I* | | P | | | | Fa | |
| 2/54/MLa | 75.9 | 89.3 | *II* | | 77.5 | 89.7 | *I/II* | | P | 68 | 68 | P | Fa | |
| » | | | | | 78.8 | 91.1 | *I* | | W | | | | | |
| 25a/54/MLa | — | — | *III* | | 73.7 | 92.5 | *I* | | P | | | | Fa | |
| » | | | | | 75.0 | 92.1 | *I* | | W | | | | | |
| 96/54/MLa | 77.9 | 92.8 | *I/II* | | 73.4 | 89.9 | *I* | | P | 69 | | | Hbl | |
| » | | | | | 74.7 | 89.3 | *I/II* | | W | | | | | |
| 102/54/MLa | 81.1 | 91.8 | *I* | | | | | | | 45—47 | | | Fa | |
| 192/54/MLa | 74.6 | 93.2 | *II/III* | | 72.8 | 94.1 | *I* | | P | 68—72 | 68 | P | Hbl | |
| » | | | | | 76.4 | 91.1 | *I/II* | | W | | 63 | W | | |
| 280/54/MLa | 72.1 | 90.3 | *I* | | 72.0 | 89.5 | *I* | | P | 72—75 | 69 | W | Hbl | |
| » | | | | | 74.8 | 86.2 | *I* | | W | | | | | |

*Table 2, (cont.)*

| Specimen number | X-ray determination | | | | | | | | | 2Vα | | | Fe-Mg silicate paragenesis | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Groundmass | | | | Phenocrysts | | | | | | | | | |
| | % by wt. Or | | | | % by wt. Or | | | | | | | | | |
| | Bulk composition | Composition of the potassic phase | Structural type | Obliquity (in structural types *IV*, *III*/*V* and *V*) | Bulk composition | Composition of the potassic phase | Structural type | Obliquity (in structural types *IV*, *III*/*V* and *V*) | Type of phenocryst | Range in the groundmass | Phenocrysts | Type of phenocryst | | |
| IIIb. *Normal wiborgites* | | | | | | | | | | | | | | |
| A2 | — | — | *IV* | 0 & 0.60 | 71.0 | 91.1 | *I*/*II* | | P | 66—68 | 64 | P | Hbl | |
| » | | | | | 72.7 | 92.3 | *I* | | W | | 80 | W | | |
| » | | | | | | | | | | | 66 | A | | |
| 22/MY/56 | 80.4 | — | *II*/*III*, *IV* | 0 & 0.85 | 77.8 | 89.9 | *I*/*II* | | P | 67 | 63 | P | Hbl | |
| » | | | | | 76.0 | 91.1 | *I* | | W | | | | | |
| 54/ALo/56 | 80.4 | 94.8 | *V* | 0.73 | — | — | *III* | | P | 64—75 | | | Bi | |
| » | | | | | — | 89.4 | *III* | | W | | | | | |
| 90/ALo/56 | — | — | *IV* | 0 & 0.68 | 68.9 | 91.4 | *II* | | P | 70—75 | 57 | W | Hbl | |
| » | | | | | 70.2 | 92.2 | *II* | | W | | | | | |
| 121a/ALo/56 | — | — | *IV* | 0 & 0.82 | — | 98.7 | *III*/*V* | 0.86 | P | 62 | 64 | W | Hbl | |
| » | | | | | 72.4 | 92.3 | *I*/*II* | | W | | | | | |
| 28/KM/55 | 77.4 | 91.4 | *II*/*III* | | 77.6 | — | *III* | | P | 68—83 | 84, 86 | P | Hbl | |
| » | | | | | 85.3 | 91.7 | *I*/*II* | | W | | 74—81 | W | | |
| 18/54/MLa | — | 90.4 | *II* | | 71.2 | 90.3 | *II* | | P | | 78, 80 | W | Hbl | |
| » | | | | | 73.7 | 91.0 | *II* | | W | | | | | |
| 279a/54/MLa | — | — | *III* | | 73.3 | 91.4 | *II*/*III* | | P | 68—76 | 70 | P | Hbl | |
| » | | | | | 74.3 | 90.6 | *II* | | W | | 56, 62, 69 | W | | |
| 467/55/MLa | — | — | *IV* | 0 & 0.68 | 72.9 | 90.6 | *II* | | P | | | | Fa | |
| » | | | | | 73.9 | 89.9 | *II*/*III* | | W | | | | | |
| 132/54/MLa | — | — | *IV* | 0 & 0.80 | — | — | *IV* | 0 & 0.85 | A | 64—70 | | | Bi | Coarse-grained alteration product of wiborgite |
| IV. *Pyterlites* | | | | | | | | | | | | | | |
| 6/ALo/56 | 78.6 | — | *II*/*III*, *III* | | 76.7 | 91.3 | *II*/*III* | | P | 58—75 | | | Bi | |
| 86/ALo/56 | — | — | *III* | | 74.5 | 90.3 | *II*/*III* | | P | 67—70 | ~60 | P | Bi | |
| 284/ALo/56 | 80.3 | 96.9 | *V* | 0.80 | — | — | *III* | | P | | 70 | P | Bi | |
| 40/KM/55 | 77.6 | 90.5 | *II*/*III* | | 72.9 | 89.9 | *II*/*III* | | P | 61—76 | | | Hbl | |
| A3 | 80.0 | 96.7 | *V* | 0.80 | — | — | *IV* | 0 & 0.70 | P | | 74 | P | Bi | |
| » | | | | | | | | | | | 54 | A | | |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Va. *Porphyritic rapakivis; red; coarse-grained* | | | | | | | | | | | | | | | |
| 714/ML/54 | | | | | — | — | *III* | | A | ∼78 | 76, 70—84 | A | Bi | | |
| 17/KM/55 | — | — | *III, III/V* | 0.63 | — | — | *III* | | A | ∼78 | 78 | A | Bi | | |
| 17b/FP/55 | — | — | *IV* | 0 & 0.74 | — | — | *III* | | A | | | | Bi | | |
| 223/A/AV/59 | 88.3 | 94.7 | *V* | 0.88 | — | — | *IV* | 0 & 0.69 | A | 84 | 88, 89 | A | Bi | A ca. 100 m broad seam between tirilite and granodiorite | |
| 14/KV/St/60 | | | | | 84.8 | 93.3 | *V* | 0.62 | A | | | | Bi | | |
| 469/55/MLa | | | | | 78.2 | 96.8 | *V* | 0.87 | A | ∼80 | 90 | A | Bi | | |
| 52/AS/54 | 81.7 | 90.2 | *II/III* | | 78.3 | 89.2 | *II/III, II* | | A | 59—66 | 74—81,80—84 | A | Bi | Grey | |
| Vb. *Porphyritic rapakivis; other types* | | | | | | | | | | | | | | | |
| S | 82.2 | 89.5 | *II/III* | | 79.7 | 88.2 | *II/III* | | A | | | | Bi | Sinkko granite | |
| 1/AV/69 | 78.6 | 90.2 | *II* | | 82.5 | 87.2 | *I/II* | | A | | | | Bi | » » | |
| » | | | | | 82.8 | 89.2 | *II* | | P | | | | | P = large pyterlitic ovoid | |
| 16a/AS/54 | 78.2 | 87.6 | *I* | | 74.6 | 89.4 | *I* | | A | | 69—70 | A | Fa | Porphyritic, fine-grained alteration product of Va-group granite. | |
| 19/AS/54 | — | — | *IV* | 0 & 0.72 | — | — | *IV* | 0 & 0.50 | A | | 68 | A | Bi | Granite-porphyritic | |
| 137/AV/59 | — | — | *III* | | 80.2 | 89.6 | *II/III* | | A | 58—80 | 79 | A | Bi | Granite-porphyritic, coarse; near Va-group | |
| 185/AV/59 | 80.2 | 90.2 | *II* | | 78.9 | 86.9 | *II* | | A | 68—78 | 62—66 | A | Bi | » | |
| VI. *Biotite rapakivis; even-grained; mostly red or reddish* | | | | | | | | | | | | | | | |
| 199a/54/MLa | — | — | *III* | | — | — | *IV* | 0 & 0.72 | A | 63—65 | 67—77 | P | Bi | Grey | Coarse-grained |
| 382/55/MLa | 87.3 | 95.9 | *V* | 0.78 | | | | | | 74—80 | | | Bi | | |
| 419/55/MLa | — | — | *V* | 0.75 | | | | | | 72—88 | | | Bi | | |
| 687/55/MLa | — | 96.5 | *V* | 0.75 | — | — | *III* | | P | (58—) 75—83 | | | Bi | | |
| 893/55/ML | 86.6 | — | *V* | 0.83 | | | | | | | | | Bi | | |
| A4 | — | 97.4 | *III/V* | 0.80 | | | | | | 72—78 | | | Bi | | Medium-grained |
| A5 | — | — | *III* | | | | | | | 70—72 | | | Bi | | |
| 8/ALo/56 | 88.4 | 96.2 | *V* | 0.85 | | | | | | 66 | | | Bi | | |
| 95/ALo/56 | 77.5 | 96.2 | *III/V* | 0.57 | | | | | | 73 | | | Bi | | |
| 263/ALo/56 | 94.6 | 97.1 | *III/V* | 0.80 | | | | | | 82—68 | | | Bi | Grey | |
| 605/54/ML | — | — | *IV* | 0 & 0.78 | | | | | | | | | Bi | | |
| 112/MY/56 | — | 94.3 | *III/V* | 0.76 | | | | | | 71—77 | | | Bi | | |
| 140/MY/56 | 79.6 | 93.8 | *V* | 0.80 | | | | | | 72—82 | | | Bi | | |
| 18/MY/56 | — | — | *IV* | 0 & 0.70 | — | — | *III* | | P | 68—70 | | | Bi | Grey | Fine-grained |
| 693/55/MLa | 88.7 | 95.4 | *V* | 0.80 | | | | | | 72—80 | | | Bi | | |
| 204a/AV/59 | 84.3 | 89.1 | *II/III* | | | | | | | | | | Bi | Grey | |
| 204c/AV/59 | 85.9 | 89.9 | *II/III* | | | | | | | 66—90 | | | Bi | Grey | |

*Table 2, (cont.)*

| Specimen number | X-ray determination | | | | | | | | | 2Vα | | | Fe-Mg silicate paragenesis | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Groundmass | | | | Phenocrysts | | | | | | | | | |
| | % by wt. Or | | | | % by wt. Or | | | | | | | | | |
| | Bulk composition | Composition of the potassic phase | Structural type | Obliquity (in structural types *IV*, *III*/*V* and *V*) | Bulk composition | Composition of the potassic phase | Structural type | Obliquity (in structural types *IV*, *III*/*V* and *V*) | Type of phenocryst | Range in the groundmass | Phenocrysts | Type of phenocryst | | |
| VII. *Porphyry aplites* | | | | | | | | | | | | | | |
| A6 | — | — | *IV* | 0 & 0.77 | 69.9 | 91.3 | *I*/*II* | | P | 66—80 | 70 | W | Hbl | |
| » | | | | | 66.5 | 92.1 | *I*/*II* | | | | | | | |
| 73/KM/55 | 91.0 | 95.8 | *V* | 0.75 | — | — | *IV* | 0 & 0.67 | P | 78—90 | 74 | A | Hbl | |
| » | | | | | 83.2 | 96.5 | *V* | 0.63 | A | | | | | |
| 447/53/ML | — | — | *III* | | 63.8 | 91.8 | *II* | | P | 69—75 | | | Bi | |
| 27/ALo/56 | 82.3 | 95.9 | *V* | 0.85 | 74.8 | — | *II*/*III*, *IV* | 0 & 0.74 | A | 63—81 | 71—76 | A | Hbl | |
| 49a/54/MLa | 74.6 | 97.4 | *III*/*V* | 0.69 | 84.7 | 95.0 | *V* | 0.74 | P | 55—74 | | | Bi | |
| VIIIa. *Dike rocks; granite porphyries* | | | | | | | | | | | | | | |
| 49/A/AV/59 | — | — | *III* | | — | — | *III* | | P | 73—82 | 82 | A | Bi | 25 m broad dike cutting granodiorite |
| XII—2—A | 90.9 | 93.8 | *V* | 0.94 | 86.8 | 92.0 | *V* | 0.94 | A | 80—83 | 80, 83 | A | Bi | Over 10 m broad dike cutting granodiorite |
| 258/ALo/56 | — | 96.2 | *V* | 0.85 | — | 96.0 | *V* | 0.87 | A | | | | Bi | Relation to the wiborgitic country rock unknown |
| VIIIb. *Dike rocks: porphyry aplites* | | | | | | | | | | | | | | |
| 387/53/ML | 82.5 | 87.5 | *II* | | — | 87.8 | *II*/*III* | | P | 66—80 | | | Bi | Dike nature uncertain; sharp contact to the pyterlitic country rock |
| 13b/AV/59 | — | — | *IV* | 0 & 0.67 | — | — | *III* | | A | 60—85 | | | Bi | Less than 1 m broad dike cutting the coarse granite porphyry grouped under Vb |
| 142/AV/59 | 89.3 | 95.0 | *V* | 0.82 | | | | | | 72—86 | | | Bi | Grey, less than 2 m broad dike cutting granodiorite |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| VIIIc. *Dike rocks: aplites* | | | | | | | | | | | | | | |
| 40b/AS/54 ...... | 81.5 | 95.4 | *III/V* | 0.76 | | | | | | 66—70 | | | Bi | Cutting the Ia-group dark granite |
| 7/AS/54 ........ | 89.1 | — | *III/V* | 0.67 | | | | | | 64—75 | | | Bi | Cutting the Va-group porphyritic granite |
| 8/54/MLa ...... | 84.5 | 97.2 | *III/V* | 0.74 | 80.6 | 97.4 | *V* | 0.68 | A | 72—82 | | | Bi | Cutting the IIIa-group wiborgite |
| VIIId. *Dike rocks: quartz porphyries* | | | | | | | | | | | | | | |
| 99/AV/58 ...... | 70.2 | — | *II/III* | | 97.1 | 97.9 | *V* | 0.79 | A | | | | Bi | 2—3 m broad dike cutting wiborgite |
| 18/AS/56 ....... | — | — | *III* | | 88.1 | — | *V* | 0.75 | A | | | | Bi | 2—3 m broad dike cutting coarse rapakivi |
| 7b/AS/53 ....... | 89.0 | 96.4 | *V* | 0.83 | 80.8 | 94.8 | *V* | 0.93 | A | | 69—80 | A | Bi | From the centre of a 20 m broad dike cutting the country rock of rapakivi |
| 7c/AS/53 ....... | 90.1 | 97.0 | *V* | 0.86 | — | 95.8 | *V* | 0.83 | A | | | | Bi | Contact variety of the foregoing dike |

Notes: Columns »Structural type»: if the same for heated and unheated sample, only one figure is given; if different structural type, both are given — first for the heated sample.

Columns »Obliquity»: when $\Delta = 0$ and $\Delta = \Delta_1$ at the same time present, as in structural type *IV*, the $\Delta$-value corresponding to the stronger X-ray peak (or peaks) underlined.

Columns »Type of phenocryst»: W = wiborgitic ovoid; P = pyterlitic ovoid; A = angular phenocryst.

Column »Fe-Mg silicate paragenesis»:

| | | | |
|---|---|---|---|
| Fa | coexisting | with | fayalite and/or iddingsite (+hornblende + biotite + grunerite) |
| Cp | » | » | clinopyroxene (+hornblende + biotite) |
| Hbl | » | » | hornblende (+biotite) |
| Bi | » | » | only biotite |

The optical 2V$\alpha$ determination for phenocrysts mostly is from a different phenocryst from the one used for X-ray study.

Specimen No. 596a/55/MLa (under Ib) shows in heated sample two $\bar{2}01$ maxima; the composition corresponding to the weaker one is in parantheses.

* The whole rock

the groundmass. The figure for the rock as a whole is slightly higher. The coarse-ovoidal rapakivi with a fine-grained groundmass (evidently corresponding to the granite porphyry of the present paper) from the Salmi rapakivi massif contains between 50.7 % and 57.3 % alkali feldspar (Sviridenko 1968, p. 24).

The foregoing figures suffice to show that alkali feldspar is by far the most important rock-forming mineral in rapakivi granites. Its amount varies but little from variety to variety. Mostly, the alkali feldspars constitute slightly more than 50 percent by volume of the rapakivi granites. The dark and darkish, even-grained varieties are exceptions, which contain about 45 % of alkali feldspar.

## Mode of occurrence

The mode of occurrence, intergrowths and inclusions of rapakivi granite alkali feldspar in the Wiborg massif have thoroughly been described by Wahl (1925) and Popoff (1928). In the following, only the most essential features are discussed.

In the typical rapakivi, wiborgite, alkali feldspar occurs in two generations: as phenocrysts and in the groudmass. The phenocrysts are ovoidal in shape (Fig. 2), mostly from 3 cm to 4 cm, in exceptional cases up to 27 cm, in diameter (Wahl 1925, p. 47). The phenocryst alkali feldspar occurs either as a single crystal, a Carlsbad twin, or, presumably in most of the cases encountered, composed of more than two grains sectorally grown, but not related by any twinning operator (synneusis?). The ovoidal alkali feldspar in wiborgite (wiborgitic ovoids) is surrounded by an oligoclase

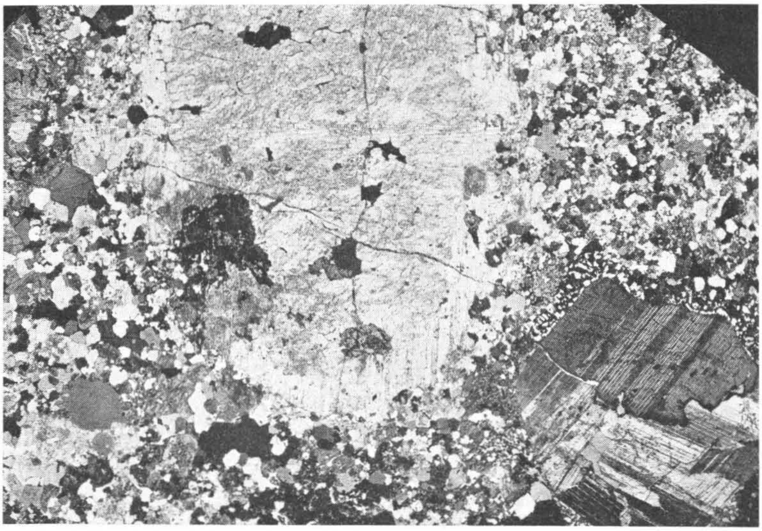

FIG. 2. A wiborgitic ovoid in the middle of the photograph. Lower right corner occupied by synneusis group of plagioclase. Wiborgite, No. 90/ALo/56. Crossed nicols, 6x. Photo: Erkki Halme.

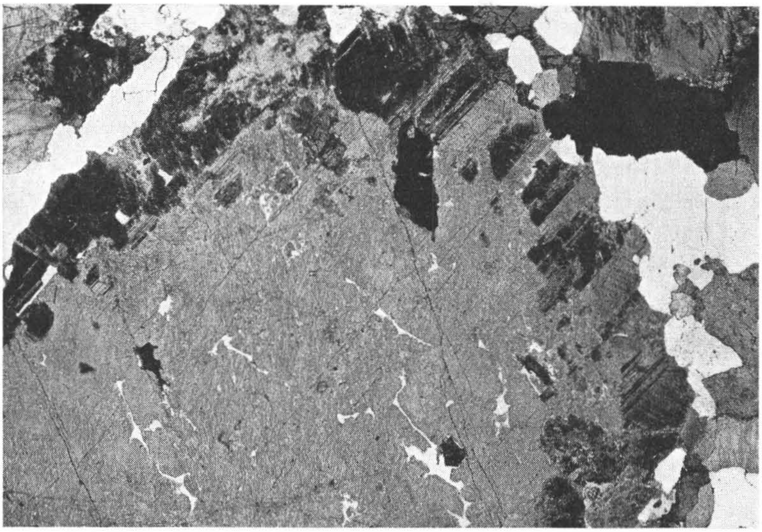

FIG. 3. Wiborgitic ovoid with concave quartz and plagioclase inclusions in the core alkali feldspar. The mantle consisting of one polysynthetically twinned plagioclase individual shows rugged boundary against the groundmass. Wiborgite, No. 192/54/MLa. Crossed nicols, 12x. Photo: Erkki Halme.

mantle, measuring from 1 mm to 3 mm in thickness. In places, the mantle is apt to be discontinuous; often the continuation of the plagioclase mantle is represented by a zone of drop quartz inclusions in alkali feldspar. Some of the ovoids are unmantled (pyterlitic ovoids). Regarding the distribution of mantled and unmantled ovoids in wiborgite and pyterlite, see the paper of Simonen and Vorma (1969, p. 8). In places, the large ovoids, and in other places, the small ones are those mantled by plagioclase. The crystallographic orientation of the plagioclase forming such a mantle with respect to the ovoid alkali feldspar has been thoroughly discussed by Popoff (1928). The boundary surface between the mantle of plagioclase and the groundmass is often rugged (Fig. 3), but in many cases also ovoids are met with (Fig. 4) with a smooth mantle surface (resorption?) The twinning of the mantle plagioclase has been investigated by Popoff, who states (*op.cit.*, pp. 13—14): »Ich erhielt nämlich den Eindruck, dass Albit- und Periklinzwillinge auf der Ovoidoberfläche nicht regellos verteilt, sondern einer bestimmten Regel unterworfen sind, die sich darin äussert, dass jede von diesen Zwillingsarten besonders gerne an den Stellen der Ovoidoberfläche auftritt, wo letztere zur Verwachsungsebene der Zwillinge mehr oder weniger senkrecht steht, das heisst, dass die Albitzwillinge vorzugsweise auf den annähernd (001), die Periklinzwillinge dagegen am besten auf den (010) entsprechenden Teilen der Ovoidoberfläche zur Ausbildung gelangen, während die (100) entsprechenden Teile der Oberfläche, sowie die Zwischengebiete beide Zwillingssysteme in etwa gleicher Entwickelung zeigen.» As inclusions, the mantle plagioclase

FIG. 4. Wiborgitic ovoid with inclusions of plagioclase and quartz. Upper part of figure represents the groundmass against which the mantling plagioclase shows a smooth surface with coves indicating resorption. Wiborgite, No. 54/ALo/56. Crossed nicols, 12x. Photo: Erkki Halme.

contains almost idiomorphic drop quartz, magnetite, hornblende aggregates, biotite, xenomorphic quartz, and alkali feldspar. On the border against the alkali feldspar of the ovoid there occur drop quartz, allotriomorphic quartz and untwinned albite, forming a seam.

Also the alkali feldspar of the ovoids is usually rich in inclusions. The reddish colour of the feldspar is due to the staining by iron oxide. According to Wahl (1925, p. 48), alkali feldspar was originally rich in ferriorthoclase. The ovoid feldspar is either orthoclase or microcline, or both. In addition to the iron oxide (hematite) pigment, plagioclase, hornblende, biotite, quartz, fluorite and zircon occur as inclusions. According to Wahl, the hornblende, biotite and zircon are older than the potash feldspar. The biotite and zircon are idiomorphic. The hornblende is in many cases corroded, especially in the centre, and partly replaced by quartz and fluorite. Among the inclusions of special interest is plagioclase. Part of this plagioclase occurs in perthitic intergrowth with potash feldspar, partly as inclusions in the form of almost idiomorphic crystals. The following observations by Popoff (1928, pp. 11—12) on the occurrence of these plagioclase inclusions and their relation to the mantle plagioclase are worth quoting: »An mehreren Stellen der Plagioklasumrahmung bemerkt man einen allmählichen Übergang von den Plagioklaseinschlüssen, die stets im Kalifeldspatkern enthalten sind, zu den Körnern der Umrahmung. Da diese Plagioklaseinschlüsse einen automorphen Charakter besitzen und oft von Kristallflächen begrenzt sind, machen die durch Weiterwachsen derselben entstandenen Plagioklaskörner der Umrahmung einen, dem Kalifeldspat des Kernes gegenüber, automorphen Eindruck. Besonders drastisch ist die Erscheinung, wenn die Plagioklaseinschlüsse, was sehr oft vorkommt, eine von dem Kalifeldspatkern ganz unabhängige Lage einnehmen. — — — Immer war die Oberfläche des Ovoidkernes entweder ziemlich eben oder kavernös angefressen und die Plagioklassubstanz schmiegte sich an diese Oberfläche an, drang auch in die Vertiefungen ein. Es scheint mir nicht unwahrscheinlich, dass auch die Unregelmässigkeiten in der Anordnung des Hüllenplagioklases, auf die ich bei der Beschreibung der Ovoidpräparate hingewiesen habe, gerade auf das Vorhandensein zufällig gelagerter Plagioklaseinschlüsse zurückzuführen sind, die stellenweise an der Oberfläche der Kalifeldspatkerne zum Vorschein kamen und, als die Kristallisation des Plagioklases einsetzte, als impfende Zentren wirkten und lokale Störungen in der regelmässigen Ausbildung der Plagioklasrinden hervorriefen. Eine Stütze für diese Annahme finde ich in der Beobachtung, dass die Plagioklasrinden, in der Regel, umso vollkommener orientiert sind, je weniger Plagioklaseinschlüsse der betreffende Kalifeldspatkern beherbergt. Ziemlich frei von Plagioklaseinschlüssen waren mehrere plagioklasumrandete Ovoide aus dem Gestein der Steinbrüche von Pyterlahti, und in der Umrahmung dieser Ovoide konnte ich nicht eine einzige Unregelmässigkeit feststellen. Dagegen fehlten Störungen nie, wenn der Ovoidkern von Plagioklaseinschlüssen stark verunreinigt war. Das Gesagte bezieht sich auf das gesamte Material, welches mir augenblicklich zur Verfügung steht.»

Another mineral of importance as inclusions in ovoid alkali feldspar is quartz. The occurrence of quartz at least in two generations has been regarded as characteristic of rapakivi granites (Wahl 1925). Popoff (1928, pp. 19—28) distinguished four generations of quartz in wiborgite: 1, the automorphic groundmass quartz (2—5 mm in diameter, originally high quartz); 2, xenomorphic groundmass quartz; 3, the drop quartz occurring as inclusions in ovoids; and, 4, the so-called concave quartz present as inclusions in ovoids. The drop quartz (3) occurs as roundish grains in the ovoid alkali feldspar, in places also in the mantle plagioclase. This quartz occasionally occurs as irregularly distributed inclusions in the ovoids, although occasionally, the third generation quartz takes part in the building of the concentric rings of inclusions in ovoids. The concave quartz (4) is always xenomorphic against the alkali feldspar and forms aggregates that extinguish optically as a whole. This quartz occurs in rapakivi only as inclusions in ovoid alkali feldspar and on the border surface between ovoid alkali feldspar and the plagioclase mantle. The concave quartz has a marked tendency to envelop other inclusions present in the ovoid alkali feldspar (plagioclase, mica and hornblende). The crystallographic orientation of these quartz inclusions in relation to the host alkali feldspar is regular, according to Popoff (1928, pp. 29—40), and follows Fersman's trapetzohedral law for graphic granite. Popoff's (*op.cit.*, p. 39) measurements of the quartz-alkali feldspar ratios in these intergrowths gave ca. 90 % by weight of alkali feldspar and 10 % by weight of quartz, i.e., the intergrowths contain much less quartz than does a typical graphic feldspar. Savolahti (1962, p. 56)

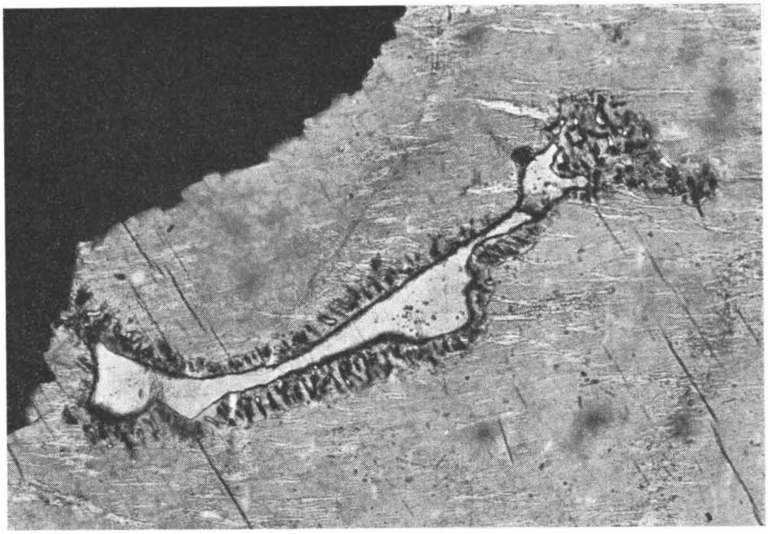

FIG. 5. A concave quartz inclusion in the alkali feldspar of a pyterlitic ovoid. The quartz is rimmed by an albite-quartz myrmekite. Wiborgite, No. 192/54/ MLa. Crossed nicols, 116 x. Photo: Erkki Halme.

calls attention to the resemblance of the form of concave quartz to the form of magma inclusions in alkali feldspar. Also a metasomatic origin for this kind of quartz has been proposed (Erdmannsdörffer 1949). To supplement the petrographic description of the concave quartz, a small detail should be mentioned: In some cases the concave quartz is surrounded by an albite-quartz myrmekite rim (Fig. 5).

In places, the amount of inclusions in the ovoids increases to the extent that the centre forms a granitic aggregate. In rare cases, the whole ovoid inside the mantle consists of a granitic aggregate, in some cases only the very centre consists of granitic material, while the peripheral parts are of alkali feldspar surrounded by a plagioclase rim. Wahl (1925, pp. 54—60) described ovoids with uncommon features, such as a single plagioclase mantle enveloping two orthoclase ovoids, one orthoclase ovoid engulfing another, balls with more than one concentric plagioclase mantle (up to 5 shells), and large granite balls, up to 20 cm or even 50 cm in diameter, surrounded by plagioclase mantles. The present author has also run across granite balls surrounded by a potash feldspar mantle (see also Velikoslavinskiy 1953, p. 15, Figs. 7 and 8, and p. 55, Fig. 33). A granite ball containing three pyterlitic potash feldspar ovoids, the granite ball of which was surrounded by a plagioclase mantle, was also mentioned by Wahl. This diversity among the ovoids must be taken into account when any hypothesis is given to explain the process producing the rapakivi texture.

The groundmass alkali feldspar is always xenomorphic. The groundmass of dark-coloured wiborgite is invariably characterized by a micrographic texture (Fig. 6). In the normal wiborgite, this texture was recorded in about 50 % of the thin sections

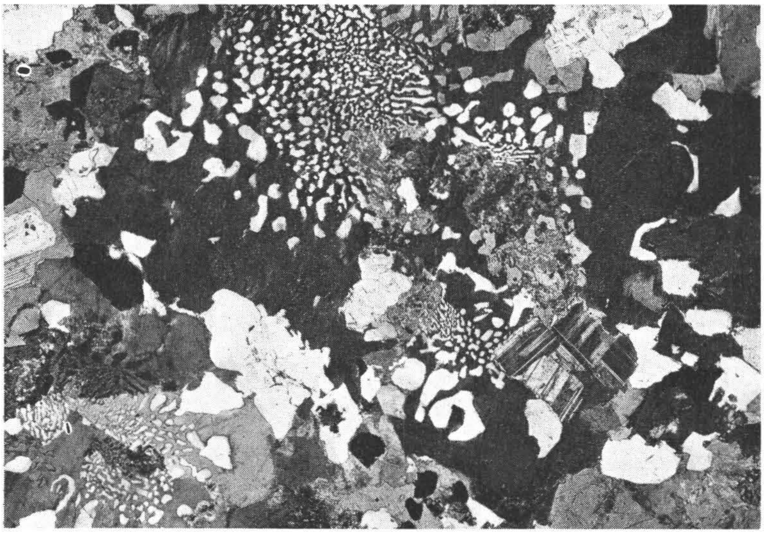

FIG. 6. Micrographic texture in the groundmass of dark wiborgite. No. 59/ALo/56. Crossed nicols, 16 x. Photo: Erkki Halme.

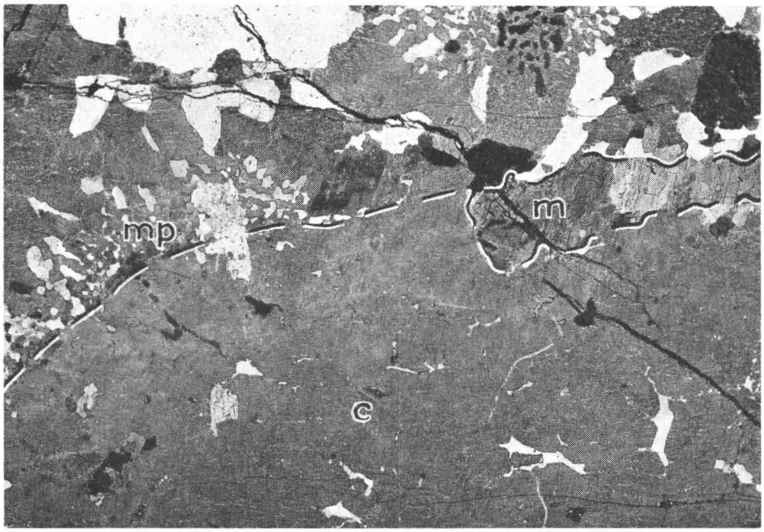

FIG. 7. Wiborgitic ovoid with a break in the plagioclase mantle. Induction of micropegmatitic groundmass alkali feldspar on the surface of core alkali feldspar, i.e., on the continuation of outer surface of plagioclase mantle. m, mantling plagioclase; c, core alkali feldspar; mp, micropegmatite on the break in the mantle. Dark wiborgite, No. 280/54/MLa. Crossed nicols, 12 x. Photo: Erkki Halme.

studied. When the graphic texture characterizes the groundmass alkali feldspar, the marginal parts of the pyterlitic ovoids likewise exhibit this texture. Also when the plagioclase mantle of wiborgitic ovoid is discontinuous, and the ovoid alkali feldspar has grown xenomorphically against the groundmass, the marginal parts of this feldspar are micrographically intergrown with quartz (Fig. 7). This quartz often extinguishes simultaneously with the adjacent concave quartz in ovoids.

In the pyterlitic rapakivi granite, the mode of occurrence of alkali feldspar is similar to that in wiborgite. Only the plagioclase shell is missing. The pyterlitic ovoids have the same minerals as inclusions as the wiborgitic ones in wiborgite (the concave quartz and drop quartz included). The large ovoidic alkali feldspar crystals are here surrounded in many instances by a ring of idiomorphic quartz crystals, 2—5 mm in diameter, to form a so-called »margination texture». In only one thin section has the present author observed a micrographic texture in pyterlite. Here, too, as in wiborgite, when the groundmass is characterized by a graphic texture, the marginal parts of the ovoids also exhibit the same texture. In some of the specimens, no distinction in the grain size can be made between the groundmass and the phenocryst alkali feldspar.

The alkali feldspar in the porphyritic rapakivi (group Va in Table 2) is similar to that in the pyterlite. A microscopically observable difference is that the phenocrysts in the porphyritic rapakivi variety tend to be more idiomorphic than in the pyterlite. Another difference is the rarity of concave quartz inclusions in the phenocrysts of this group, drop quartz being the predominant inclusion in the alkali feldspar. No graphic texture was found in a single thin section among the granites of this group.

The porphyritic granites grouped under Vb contain alkali feldspar whose manner of occurrence is identical with that already described in the foregoing paragraph. The fine-grained iddingsite- and hornblende-bearing variety, 16a/AS/54, is an exception in that it is characterized by a groundmass with a micrographic texture.

In the dark and darkish-coloured, even-grained granites (group I, Fig. 8) the plagioclase ($An_{25-35}$; often zoned) and quartz are idiomorphic against the alkali feldspar. The petrographic nature of the alkali feldspar in the sparsely scattered ovoids is identical with that of wiborgite. A graphic texture is met with only exceptionally in the dark-coloured, even-grained granites (tirilites) in the surroundings of Lappeenranta (group Ia), while among the granites of the coastal islands (group Ib) the graphic texture is nearly an invariable feature. A graphic texture has also developed in the tirilitic portion of the Jaala—Iitti granite porphyry dike (Ic). Drop quartz commonly occurs as inclusions in the alkali feldspar of the dark-coloured, even-grained granite.

In the hornblende rapakivi (II), the alkali feldspar is petrographically similar to that of the dark-coloured, even-grained rapakivi. In the granite porphyritic contact varieties, the micrographic texture is often observed.

In the even-grained biotite rapakivi granite, the prevailing alkali feldspar is microcline perthite with very few inclusion. In many places, inclusions are totally

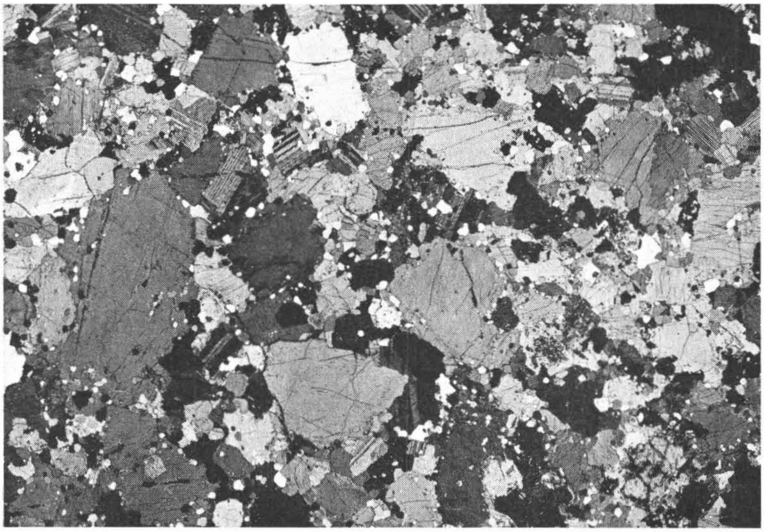

FIG. 8. Occurrence of cryptoperthitic alkali feldspar in tirilite (large untwinned grains). No. 258/AV/59. Crossed nicols, 8 x. Photo: Erkki Halme.

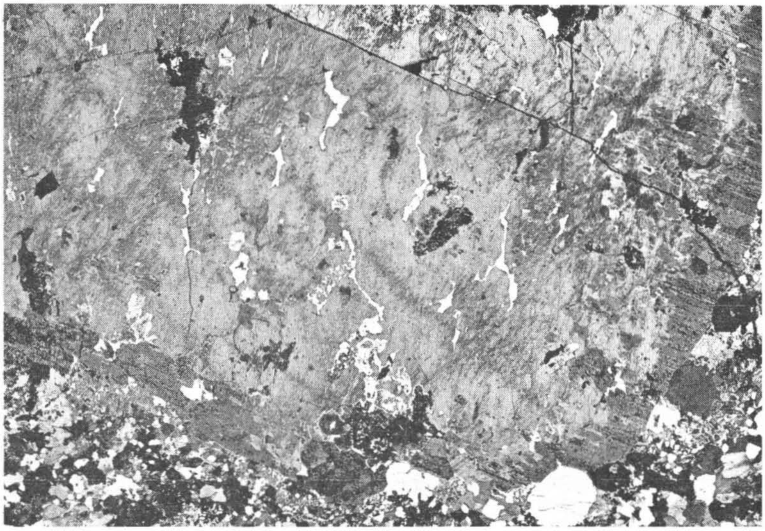

FIG. 9. Wiborgitic ovoid in porphyry aplite. The concave quartz inclusions, in the middle of photograph, have tendency towards micrographic texture. No. A6. Crossed nicols, 8 x. Photo: Erkki Halme.

lacking. The mineral is allotriomorphic against quartz and plagioclase. A micrographic texture is present only exceptionally. In the fine-grained varieties, this texture is probably more common. The small number of thin sections made from these fine-grained granites, however, precludes any further conclusions. The groundmass alkali feldspar present in the porphyry aplites (group VII) is microcline perthite, as in the foregoing. The graphic texture was observed in two of the nine thin sections investigated. The character of the alkali feldspar in the ovoids embedded in the porphyry aplite is similar to those in the wiborgite (Fig. 9). Concave quartz and drop quartz occur as inclusions, and the marginal parts of the pyterlitic ovoids are graphically intergrown with quartz when the graphic texture characterizes the groundmass. When no graphic texture appears in the groundmass, the drop quartz inclusions predominate over the concave quartz in the ovoids.

The specimens from the aplite dikes investigated contain allotriomorphic microcline. No micropegmatitic texture was observed in the thin sections studied. Wahl (1925, pp. 28 and 66) claims, however, that the aplite dikes or fine-grained granite dikes are characterized by a graphic texture.

The few specimens from the quartz porphyry dikes studied are interesting because in two of them the thermal state of the idiomorphic phenocryst potash feldspar differs from that of the spherulitic, in places micropegmatitic groundmass potash feldspar (see pp. 47—48 and 66—67). In the other samples, the groundmass potash feldspar occurs as small allotriomorphic grains.

## Twinning and perthite texture

### *Dark and darkish, even-grained granites; group I*

Dark and darkish, even-grained rapakivi granites are characterized by a non-cross-hatched alkali feldspar, occasionally marked by an undulating extinction. Cross-hatched grains or patches of cross-hatching in alkali feldspar occur only exceptionally. Most of the grains are microscopically non-perthitic, and only minute portions of the grains are characterized by a perthite texture. Film perthite with exsolved plagioclase lamellae of 1—2 $\mu$ ¹) thickness is the prevailing perthite type. It occasionally grades over to string perthite. A small number of the grains, especially those with an undulating extinction or cross-hatching, are characterized by a poorly developed vein perthite texture (5—20 $\mu$). Only exceptionally, in an alkali feldspar with a very marked undulating extinction or cross-hatching, is the vein perthite texture well developed; exsolution lamellae with a thickness up to 50 $\mu$ are to be found. All the afore-mentioned perthite types can at the same time characterize a single specimen, even one single crystal.

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¹) In the following, the figures in parentheses as, e.g., (10—30 $\mu$) indicate the thickness of the lamellae of the sodium phase in the perthite.

The sparse phenocrysts in the granites of group I are characterized by the same kind of alkali feldspar as in the foregoing.

Comparisons between the thin sections from the coastal islands (group Ib) and from the surroundings of Lappeenranta and the area south of Lappeenranta (Ia) yield the impression that there is a small difference between the perthite textures in these rocks. In the dark-coloured, even-grained rapakivi granites from the islands the perthite texture is slightly further developed than in the tirilites of group Ia.

### *Even-grained hornblende granites; group II*

The hornblende rapakivi (group II) is characterized by microperthite with drop quartz, in places idiomorphic quartz, as inclusions. One of the specimens of Lappee granite shows untwinned potash feldspar with a well-developed vein perthite texture (5—30 $\mu$) and in places an undulatory extinction. In same places film perthite and in other places even patch perthite prevails. The other specimen contains cross-hatched microcline with a weak, irregular vein perthite texture (20 $\mu$). The two specimens from the Suomenniemi massif (Table 2) have cross-hatched microcline as the prevailing alkali feldspar. Mostly, the vein perthite texture is well developed; in certain cases, there occur grains largely lacking in perthitic intergrowth. In the granite porphyritic contact varieties, the fine-grained groundmass alkali feldspar is mostly cross-hatched, and the perthite texture is rather weak. It is represented by an irregular vein perthite texture (10—40 $\mu$). Evidently, what has taken place here is a discontinuous precipitation of albite during the exsolution stage. The larger alkali feldspar crystals mostly have a well-developed vein perthite texture (in places 10—20 $\mu$, in places up to 100 $\mu$). This grades over in many cases to patch perthite texture. At the same time, part of the crystal may be represented by a film perthite texture. The hornblende rapakivi from the Jaala—Iitti dike contains a quite homogeneous alkali feldspar. Cross-hatching is encountered only exceptionally. To a great extent the grains lack the perthite texture, and in some cases it appears in a weak irregular form.

### *Wiborgites; group III*

Cross-hatching in the groundmass alkali feldpar of dark-coloured wiborgite is quite inhomogeneous. Unhatched alkali feldspar predominates over the cross-hatched variety. The mineral is mainly characterized by a faint vein perthite texture (5—20 $\mu$, occasionally up to 40 $\mu$). Only exceptionally is the vein perthite texture very well developed. In most of the specimens, there are alkali feldspar grains or patches in the grains in which either no perthite texture can be detected at all or which are

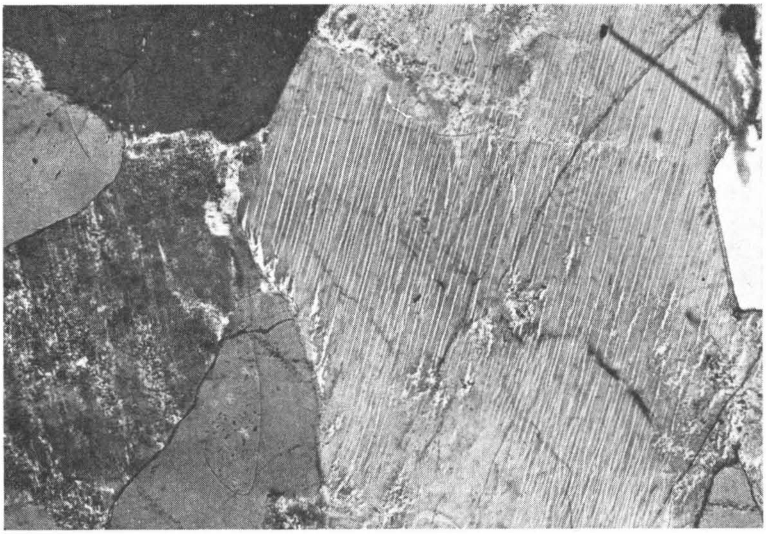

FIG. 10. Exceptionally well-developed film perthite texture in the groundmass alkali feldspar of dark wiborgite. No. 59/ALo/56. Crossed nicols, 72 x. Photo: Erkki Halme.

characterized by a film perthite texture (3—5 μ, Fig. 10). Occasionally, the film perthite grades over into string perthite. Also, in some instances, the vein perthite grades over into patch perthite, occasionally also even to a chess board albite. In the dark-coloured wiborgite, the microperthite textures are better developed than in the dark-coloured, even-grained rapakivi granites and more poorly developed than in the red and reddish-coloured wiborgite.

Both the wiborgitic and pyterlitic ovoids of the dark wiborgite are characterized by the same kind of perthite as the groundmass alkali feldspar. The amount and grade of perthitic exsolution show the same type of variation as the groundmass. Also the ratio of cross-hatched alkali feldspar to the feldspar without cross-hatching or only with an undulatory extinction is the same as in the groundmass.

In the normal wiborgite (group IIIb), the groundmass alkali feldspar is mostly unhatched but, more often than in the foregoing cases, cross-hatched grains and patches with cross-hatching in the grains are encountered. This feldspar is a microperthite with quite a well-developed vein perthite texture (10—30 μ, occasionally in cross-hatched areas reaching up to 100 μ). The film perthite texture (2—5 μ) is often seen in the untwinned parts of the alkali feldspar. The same is also true of the string perthite texture, which, however, is not as common as the film perthite. Quite often, the vein perthite grades over into patch perthite.

Both the wiborgitic and pyterlitic ovoids are characterized by the same kind of microperthite as the groundmass (Fig. 11) just referred to. Patch perthite is often encountered in wiborgitic ovoids quite near the plagioclase mantles. Cross-hatching

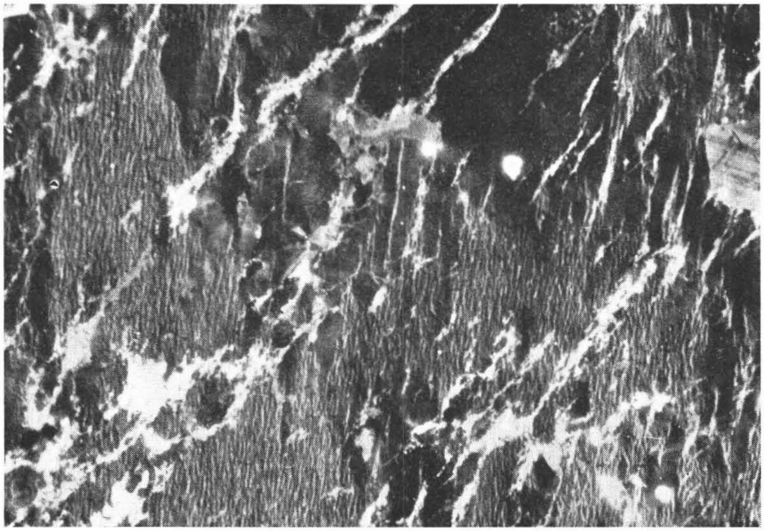

FIG. 11. Alkali feldspar of a pyterlitic ovoid in wiborgite. Well-developed film perthite texture with sodic phase lamellae 2 $\mu$ thick. Vein perthite texture also well-developed and characterized by albite lamellae 10—20 $\mu$ thick. Potash feldspar gray or black — where both film and vein perthite occur, orthoclase is present; when film perthite is missing, microcline is present (upper part of the figure). No. 43/AS/54. Crossed nicols, 98 x. Photo: Erkki Halme.

is slightly more often present in the pyterlitic than in the wiborgitic ovoids. In most specimens, however, the untwinned patches predominate over the cross-twinned patches and patches with an undulatory extinction.

### *Pyterlites; group IV*

In the pyterlite, the groundmass alkali feldspar is characterized in places by a marked undulatory extinction and in places by marked cross-hatching. The vein perthite texture is very well developed, with densely occurring plagioclase veins of 10—30 $\mu$ in width. Often the vein perthite grades over into patch perthite.

The twinning and the perthite texture possessed by the alkali feldspar in the ovoids of pyterlite are identical with the corresponding features in the groundmass feldspar. In some of the specimens, no distinction in grain size between the potash feldspars of the groundmass and the ovoids can be made.

### *Porphyritic granites; group V*

In porphyritic rapakivi granites (subgroup Va) the groundmass alkali feldspar is universally characterized by cross-hatched microcline. In some of the specimens, microcline coexists with non-cross-hatched alkali feldspar which usually has an undulating extinction. Orthoclase is met with as a rarity. A well-developed vein perthite texture (10—50 $\mu$, in some cases up to 200 $\mu$) characterizes the alkali feldspar. In many instances, the vein perthite grades over into patch-perthite; in very few cases, the groundmass alkali feldspar is practically devoid of plagioclase exsolutions; and in some spots between the vein perthitic plagioclase lamellae, film perthite (2—5 $\mu$) has been encountered.

The phenocryst alkali feldspar always exhibits a marked vein perthite texture (10—30 $\mu$ and up to 100 $\mu$), also when the perthite exsolutions are almost lacking in the groundmass alkali feldspar. In addition, film and patch perthite textures are occasionally found in the phenocryst alkali feldspar. The phenocryst alkali feldspar is mostly cross-hatched, although sometimes there are patches of untwinned feldspar in the microcline. These patches always have a wavy extinction, indicating initial microclinization.

Porphyritic granites forming subgroup Vb are petrologically inhomogeneous. Also the alkali feldspar in this group is rather inhomogeneous. Both the groundmass and the phenocryst alkali feldspars of the granite of Sinkko are in some places featured by cross-twinning, in other places are homogeneous or show only an undulatory extinction. The groundmass alkali feldspar is characterized in some areas by cross-hatching together with a comparatively well-developed vein perthite texture (10—50 $\mu$), while the untwinned areas often show a string perthite texture. The alkali feldspar in the phenocrysts exhibits similar perthite textures (10—100 $\mu$). The granite porphyry samples (see Table 2) reveal the presence of phenocryst alkali feldspar with highly developed cross-hatching and containing drop quartz and concave quartz in addition to plagioclase as inclusions. Here and there the margins are micrographically intergrown with quartz. The perthite texture is similar to that in group Va. The groundmass alkali feldspar is ubiquitously cross-hatched microcline. The perthite texture is very weakly developed (discontinuous precipitation of perthite) or totally lacking. Albite rims between the groundmass potash feldspar grains and against the plagioclase are often encountered. Sample 19/AS/54, a local granite-porphyritic variety of the Va-type porphytic granite, exhibits in the cross-hatched phenocrysts a strong vein perthite texture (20—100 $\mu$) grading over into patch perthite, in places also into film perthite. Here again, the fine-grained groundmass alkali feldspar is almost lacking in the perthite texture.

## *Even-grained biotite granites; group VI*

The coarse and the medium even-grained biotite rapakivi granites are characterized mostly by cross-hatched microcline. In only three thin sections of the 21 investigated is there no cross-hatched potash feldspar present and two of these

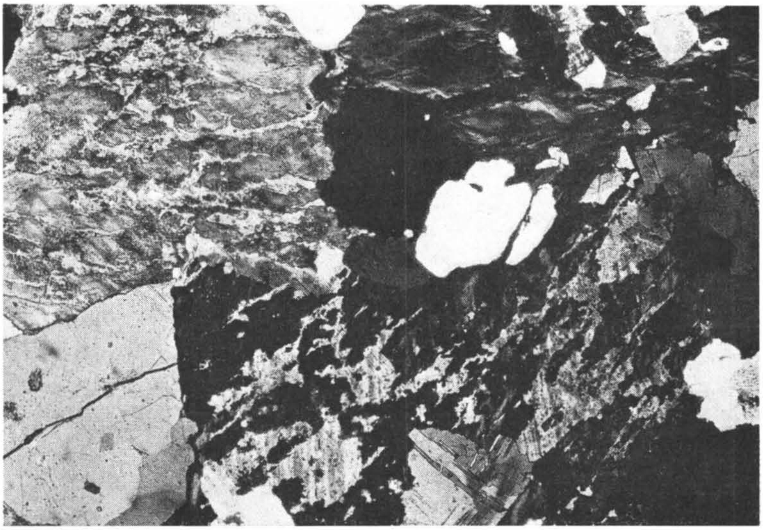

FIG. 12. Highly developed vein perthite texture grading over to patch perthite texture. Even-grained biotite granite, No. 893/54/ML. Crossed nicols, 24 x. Photo: Erkki Halme.

contain potash feldspar with a strong undulatory extinction. The cross-hatched microcline is often accompanied by potash feldspar without cross-hatching but with a marked undulatory extinction. Exceptionally, also grains of orthoclase are met with.

The alkali feldspar contained in the even-grained granite is characterized by a well-developed, strong vein perthite texture (10—50 $\mu$, exceptionally up to 200 $\mu$). Often this grades over to a patch perthite texture (Fig. 12) and, furthermore, occasionally to a chess-board albite. The grains with an undulatory or a homogeneous extinction in places are characterized by a film perthite texture.

The topaz-bearing biotite rapakivi specimen 263/ALo/56 is of some interest because during the crystallization the magma presumably was rich in volatiles, especially fluorine. The alkali feldspar is a cross-hatched microcline with a weak vein perthite texture (see the figures for the composition of the potash phase and the bulk composition, in Table 2). Occasionally, this grades over to patch perthite. Evidently owing to the presence of volatiles, exsolution occurred by discontinuous precipitation. The same process evidently also took place in the fine-grained even-grained biotite granites. Here the alkali feldspar is a microcline that is either cross-hatched or has an undulatory extinction and that exhibits a very irregular, weak vein perthite texture or contains grains lacking in perthitic intergrowth. Some grains, however, possess a well-developed vein perthite texture (10—20 $\mu$), and other ones even a patch perthite texture.

### *Porphyry aplites; group VII*

The porphyry aplites of group VII contain, in their fine-grained groundmass, allotriomorphic cross-hatched microcline or potash feldspar with an undulatory extinction. The perthite texture is weakly and irregularly developed. Discontinuous precipitation of albite evidently also here was the mechanism by which exsolution of the albite took place. Some of the grains are lacking in albite exsolutions, some have a film perthite texture, and some contain irregular vein perthite (10—20 $\mu$), some even patch perthite. When the grain size of the groundmass is coarser, the vein perthite texture also becomes more regular, the veins ranging up to 60 $\mu$ in thickness. The phenocrysts (including ovoids) consist of either cross-hatched or unhatched alkali feldspar, which in places reveals an undulatory extinction. The perthite texture ranges from a weakly developed irregular vein perthite to a well-developed, dense vein perthite texture (10—30 $\mu$, exceptionally up to 100 $\mu$). Film and string perthites have occasionally been met with in the unhatched areas.

### *Dike rocks; group VIII*

Only three thin sections of aplite were studied. In them, a cross-hatched microcline always prevails. Seldom are grains without cross-hatching encountered. Mostly the perthite texture is poorly developed; it is a vein perthite texture with scattered plagioclase exsolution lamellae (10—20 $\mu$). In one of the three sepcimens, some of the grains show a well-developed vein perthite texture (20—40 $\mu$), some a film perthite texture, and some of the grains lack exsolution lamellae.

In the quartz porphyries, the phenocryst alkali feldspar either lacks a perthite texture or in some cases shows a faint vein perthite texture (30 $\mu$) or even a patch perthite texture. In most instances, the phenocrysts do not show any cross-hatching, but occasionally cross-hatching with very thin lamellae can be seen. The groundmass alkali feldspar is so fine that usually no microscopically detectable perthite texture can be seen. If exsolution did take place, it presumably was by discontinuous precipitation of albite. In some of the specimens the groundmass alkali feldspar has a spherulitic (in places even perlitic) structure (Fig. 13).

### *Summary*

The observations given in the foregoing are based on 1, measurements by a micrometer ocular of the thickness of the albite lamellae in perthite, 2, the interdependence of the perthite type and the nature of the potassic phase (twinned, or untwinned, or with an undulatory extinction, indicating initial cross-hatching), and 3, the frequency of occurrence of these potash feldspar types in different rapa-

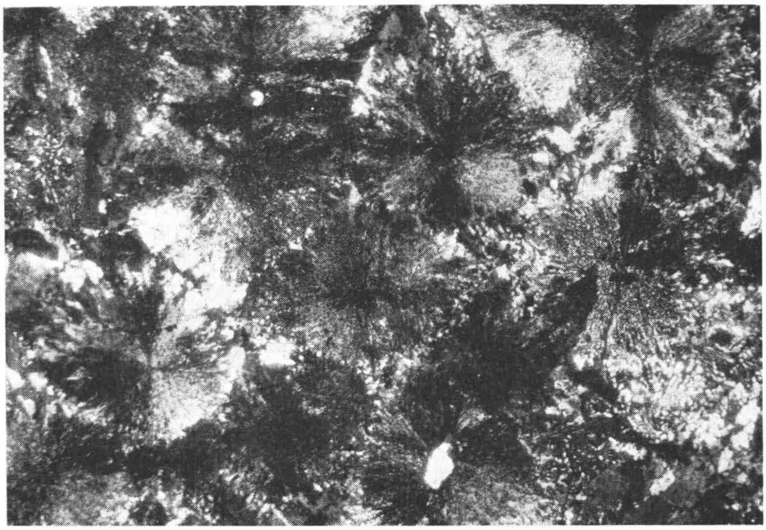

FIG. 13. Spherulitic structure in the groundmass of quartz porphyry. No. 18/AS/56. Crossed nicols, 37 x. Photo: Erkki Halme.

kivi granite varieties. The data given prove that cross-twinning and perthite development go hand in hand in the tirilite—dark wiborgite—normal wiborgite—pyterlite/porphyritic rapakivi—even-grained biotite rapakivi series. Non-cross-hatched potash feldspar is mostly characterized by film, string and vein perthite textures with quite narrow veins. Simultaneously with the increase of patches with cross hatching, also the vein perthite texture grows coarser and coarser. At the same time, the film perthite and string perthite textures are replaced by a vein perthite texture (actually the films and strings coalesce to form veins). This scheme predominates when the alkali feldspar is coarse- or medium-grained. In fine-grained groundmass alkali feldspar, the precipitation of perthite evidently took place over the grain boundaries ¹) i.e. discontinuous precipitation of perthite.²)

### *Examples of the crystallization history*

This descriptive chapter should be supplemented by a couple of examples that might shed some light upon the crystallization history of feldspars in the rapakivi

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¹) This causes a difficult problem when the bulk chemical composition of alkali feldspar in fine-grained granites is discussed.

²) Kornfält (1969, p. 14) recently published a study on the alkali feldspars from the Ragunda rapakivi massif, Sweden. It is noteworthy that he did not find any correlation between the triclinicity and perthite type.

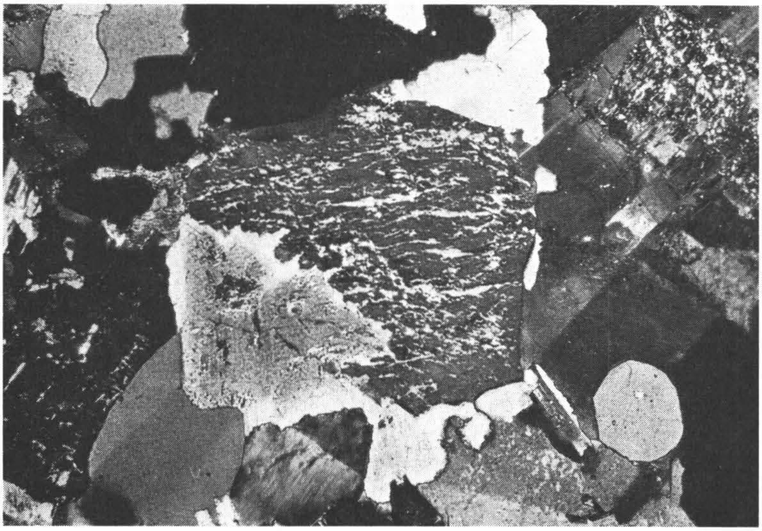

FIG. 14. Idiomorphic plagioclase crystal, partly replaced by alkali feldspar. The perthite texture is possibly a replacement perthite. Even-grained biotite granite, No. 247/MT/56. Crossed nicols, 72 x. Photo: Erkki Halme.

granites. The first example is given in Fig. 14 (247/MT/56). The rock is an even-grained rapakivi. The centre of the photograph shows an automorphic feldspar crystal. Its lower left corner consists of oligoclase. The bulk of the crystal is microperthite, the albitic veins in the perthite having the same optical orientation as the albite rim around the oligoclase portion of the crystal. Evidently, a replacement phenomenon is involved (autometasomatosis, K-feldspar replacing oligoclase). If the K-metasomatosis took place at temperatures below the solvus temperature in the join $KAlSi_3O_8$-$NaAlSi_3O_8$, as it is here presumed, then the perthite texture cannot, as a whole, be a result of exsolution but at least part of it must be a replacement perthite. Another question then is how complete the reorganization of the plagioclase component in the perthite was during the formation of perthite. Was it merely an exchange between K and Na ions, or was also the silicate framework rebuilt during the formation of replacement perthite. The next example sheds more light upon this question.

Fig. 15 is a microphotograph of an even-grained biotite rapakivi of medium coarseness (312/MT/56) with sparsely scattered potash feldspar ovoids. The potash feldspar often shows a micropegmatitic texture. In a plagioclase grain ($An_8$), clouded by sericite, the (001)-cleavage and polysynthetic acline A twinning are visible. Owing to the sericite inclusions in the plagioclase, the twinning is poorly visible in the photograph. Part of the plagioclase is replaced by potash feldspar ($2V\alpha = 78°$). Here,

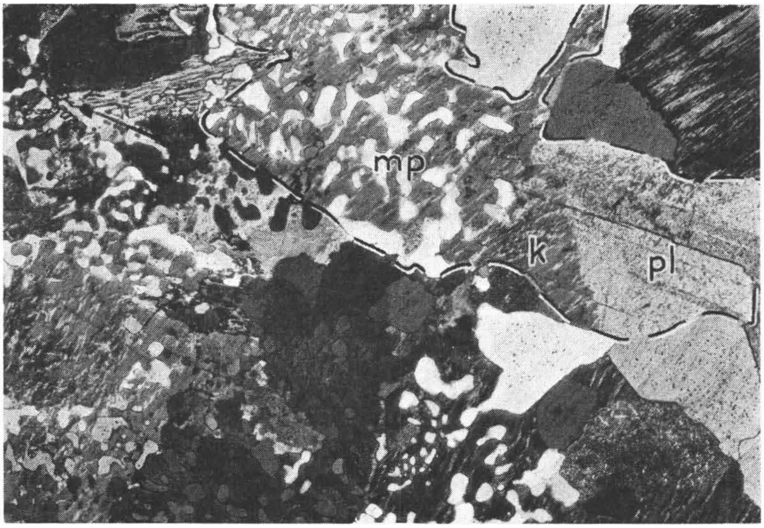

FIG. 15. Plagioclase (pl), $An_8$, twinned according to the Aclin A law and partly replaced by alkali feldspar (k). The micropegmatitic part (mp) almost devoid of perthitic intergrowth. For more details, see the text. Even-grained biotite granite, No. 312/MT/56. Crossed nicols, 42 x. Photo: Erkki Halme.

as previously noted, too, in combination with potash feldspar the albite remnants form a microperthite texture. It is noteworthy that the (001)-cleavages in the plagioclase also continue into the microperthite and that the acline A lamellae of the plagioclase also continue into the albite phase of the microperthitic part of the grain. Together this plagioclase and microperthite form a single hypidiomorphic grain. Evidently, during the replacement, the Na-phase of the microperthite was left as a plagioclase relict where practically no reorganization of the material has taken place. After its partial replacement of the plagioclase, the potash feldspar continued to grow xenomorphically. At this stage, it also underwent micrographic intergrowth with quartz. Here the thermal state of the potassic phase is slightly lower ($2V\alpha = 84°$) than in the replacement »zone». The perthite texture is very weakly developed and the potash feldspar itself has a strong undulatory extinction.

Fig. 16 shows another photograph of sample 312/MT/56. It displays a potash feldspar grain consisting of an idiomorphic core with drop quartz inclusions and a xenomorphic margin, the inner part of it micrographically intergrown with quartz. It is quite possible that the idiomorphic inner part is a pseudomorph after plagioclase (see the foregoing case of the acline A-twinned plagioclase crystal).

These examples suffice to show that potassium metasomatic processes (autometasomatic, in the present author's opinion) took place during the crystallization of the rapakivi granites.

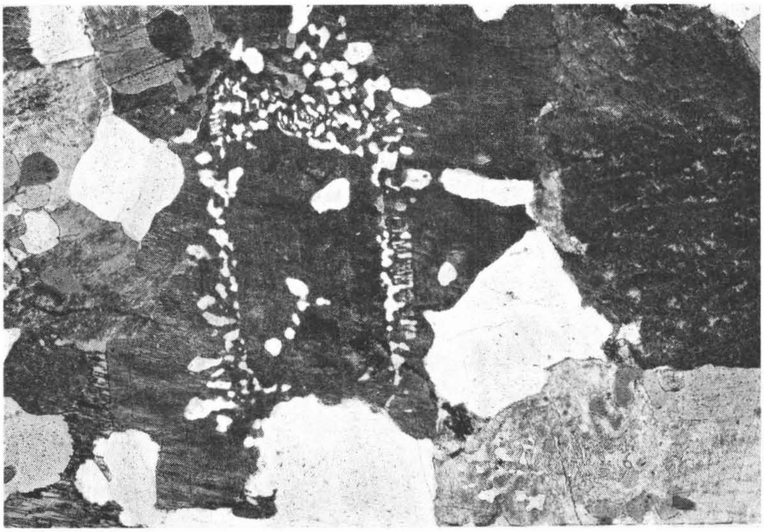

Fig. 16. Idiomorphic alkali feldspar core surrounded by graphic feldspar sphere. For more details, see the text. Same thin section as in Fig. 15. Crossed nicols, 24 x. Photo: Erkki Halme.

## OPTIC AXIAL ANGLE

Most of the specimens studied by X-ray powder or single crystal methods were subjected also to optical 2V determinations. Usually from 3 to 8 groundmass potash feldspar grains were measured. The results appear in Table 2, in which the measured ranges of $2V\alpha$ for each specimen are given. The value given for the phenocryst potash feldspar is mostly based on a single determination. Optic axial angles were also measured on the potash feldspar in certain specimens, that were not studied by X-ray methods and not listed in Table 2. All the 2V measurements are summarized on the left side in the histograms of Fig. 19.

The histograms show that there are small, yet systematic differences in the optical 2V of potash feldspar between the different rapakivi granite varieties. It should be emphasized that the 2V in each rapakivi variety covers a broad range in the histogram. The variation from grain to grain in a single hand specimen is quite small as far as the rock types shown at the top of Fig. 19 are concerned. Farther down in Fig. 19, among the more acid rock types, crystallized from a magma richer than the more basic varieties in volatiles, the variation of the 2V in a single hand specimen increases. The 2V measurements are somewhat more subjective than the triclinicity determination on the right side of the figure. While the triclinicity data are based on a large number of groundmass potash feldspar grains separated by heavy liquids, the optical determinations are based on a limited number of grains, the selection of

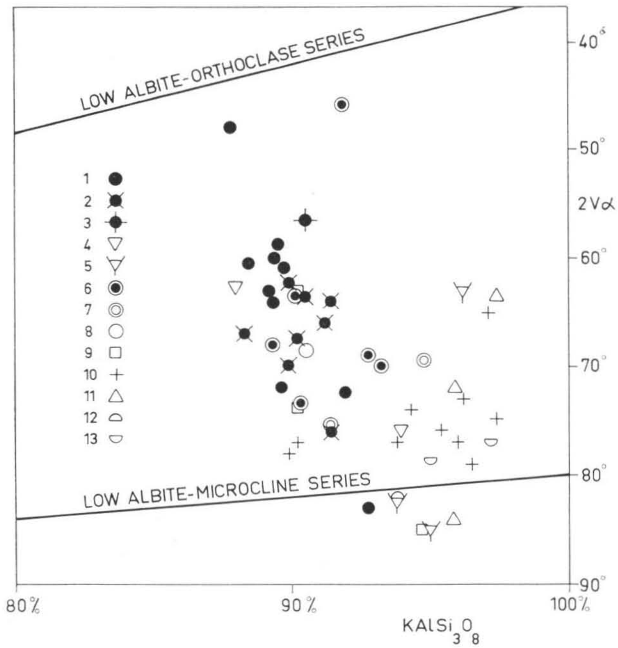

FIG. 17. The optical axial angle 2V$\alpha$ of rapakivi granite alkali feldspar plotted against the composition of the potassic phase. 1, Tirilite (Ia); 2, tirilite (Ib); 3, tirilite (Ic); 4, hornblende rapakivi (II); 5, contact varieties of hornblende rapakivi (II); 6, dark wiborgite (IIIa); 7, normal wiborgite (IIIb); 8, pyterlite (IV); 9, porphyritic granite (V); 10, even-grained biotite rapakivi (VI); 11, porphyry aplite (VII); 12, granite porphyry (VIIIa); 13, porphyry aplite (VIIIb) and aplite (VIIIc).

grains to be measured being more or less subjective — it is much easier to measure a homogeneous grain than a grain with thin cross-hatching. That evidently is one reason why the 2V-frequency histogram does not show the variation from rock type to rock type as well as does the reflection type histogram, to be discussed on p. 45.

The 2V data on phenocryst potash feldspar are too scanty to allow any judgment on the difference between the thermal states of potash feldspar in groundmass and in phenocrysts.

In Fig. 17 the 2V$\alpha$ of the alkali feldspar is plotted against the composition of the potassic phase of perthite. Of the porphyritic rapakivi granite varieties, only the groundmass potash feldspar is included in the figure, since there are but a few such phenocrysts or ovoids from which both the composition and the optical axial angle were determined. Fig. 17 shows more clearly than the histograms (Fig. 19) the variation in the structural state of the potash feldspar in different rapakivi granite varieties. The grouping of the even-grained biotite rapakivi in the lower right corner is evident, as is also the grouping of the tirilite at the upper left. Most of the potash feldspars from porphyritic or ovoidal rapakivi granite fall in an intermediate position between these two varieties.

Figure 17 shows, using the nomenclature of Tuttle, that the rapakivi granite alkali feldspars range from the orthoclase—low albite series (orthoclase cryptoperthites and orthoclase microperthites) to the microcline—low albite series (microcline microperthite). Most are intermediate between these series.

## X-RAY DIFFRACTION STUDIES

### Thermal state of the potassic phase of perthite

The thermal state of rapakivi granite alkali feldspar was determined by the method of Goldsmith and Laves (1954a and b) by measuring the separation $d_{131}$-$d_{1\bar{3}1}$ in the X-ray powder pattern (triclinicity $\triangle = 12.5(d_{131}-d_{1\bar{3}1})$. Smear mounts were made of each of the potash feldspars separated by heavy liquids and X-ray diffractometer patterns were run, using filtered copper radiation.

Tentatively, the 131 and $1\bar{3}1$ reflections of the 200 samples show the following structural types (i.e., reflection types) in the potassic phase (Fig. 18):

| | |
|---|---|
| *I* | Orthoclase only |
| *I/II* | Orthoclase with subordinate high microcline |
| *II* | Orthoclase with high microcline or only high microcline |
| *II/III* | Orthoclase with subordinate intermediate microcline |
| *III* | Orthoclase with intermediate microcline (single broad peak; unresolved) |
| *IV* | Orthoclase with intermediate microcline (three peaks) |
| *III/V* | Nearly maximum microcline or intermediate microcline with subordinate orthoclase or high microcline |
| *V* | Intermediate microcline or maximum microcline only. |

The results are summarized in Table 2 and Fig. 19. Table 2 also gives the obliquity, when ever possible to measure it, i.e., of the structural types *IV*, *III/V* and *V*.

The right hand column of Fig. 19 gives the distribution of the structural types for both the groundmass potash feldspar and the phenocrysts among the different rapakivi granite varieties.

The following regularities are found in the distribution of the structural types between the different rapakivi varieties as well as within a single variety:

— The more basic varieties of each assumed intrusion phase are characterized by an alkali feldspar with a quite high thermal state, which gradually becomes lower and lower in the less basic varieties generally richer in both $SiO_2$ and volatiles

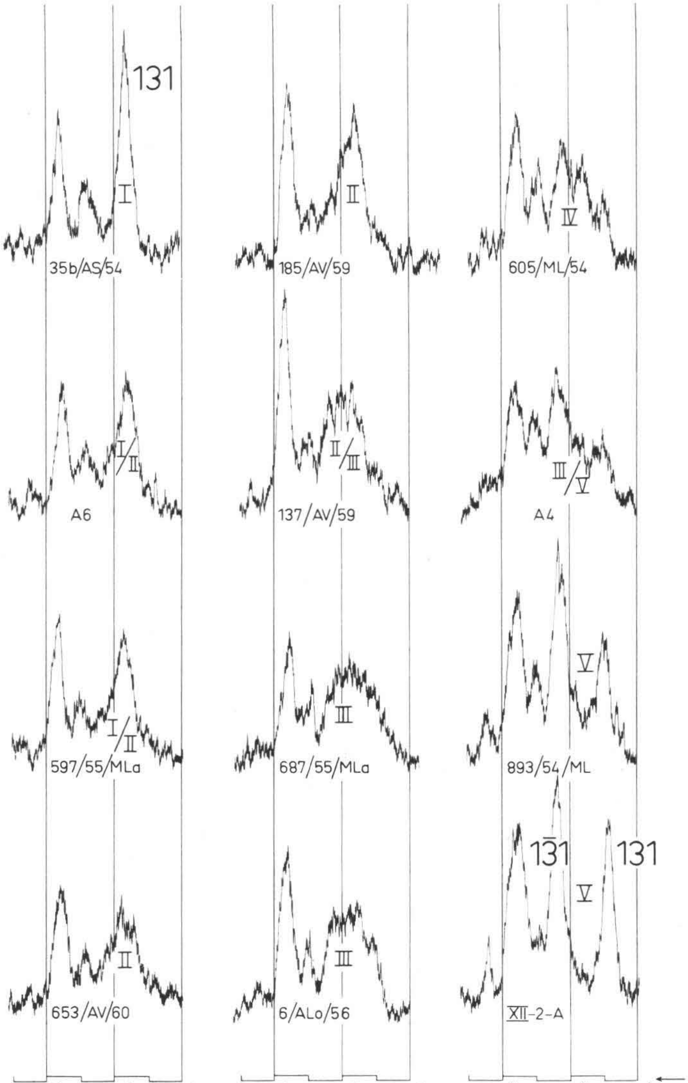

FIG. 18. Examples of the reflection types on which the tentative structural types *I—V* are based. See the text.

(compare Dietrich 1962, p. 409). The lowest thermal states are met with in the dike rocks genetically related to rapakivi and, strangely enough, in the granite porphyritic contact varieties.

- The phenocrysts (ovoids) statistically have a slightly higher thermal state than the groundmass alkali feldspar.

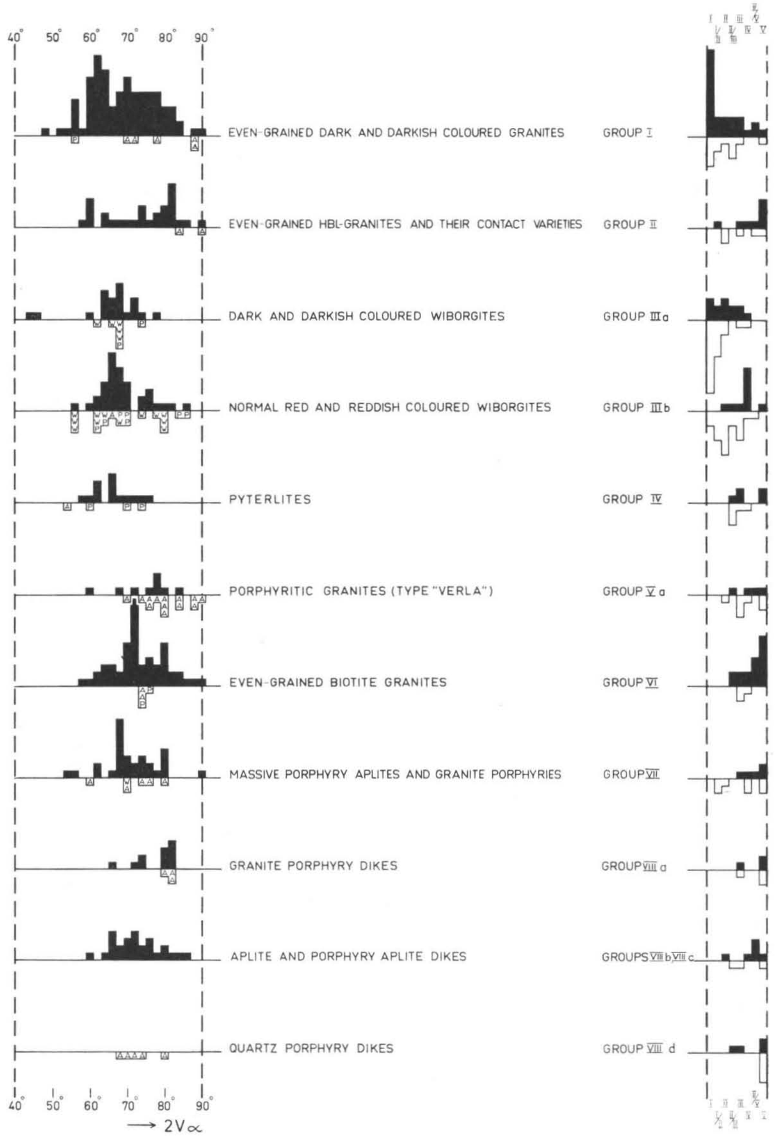

FIG. 19. Histograms illustrating the distribution of 2Vα and structural types in alkali feldspar of different rapakivi granite varieties in the Wiborg massif. Black, groundmass alkali feldspar; unshaded, phenocrysts; A, angular phenocryst; P, pyterlitic ovoid; W, wiborgitic ovoid.

— Among structural types *IV*, *III*/*V* and *V*, a systematic change in obliquity.
— The interdependence between the obliquity and composition in the alkali feldspars with structural types *III*/*V* and *V*.

Fig. 19 shows how the character of alkali feldspar gradually changes from orthoclase to almost maximum microcline in the rapakivi series: dark and darkish, even-grained granite—dark and darkish wiborgite—normal wiborgite—pyterlite/coarse porphyritic rapakivi—biotite granite/porphyry aplite—dike rocks. The change partly takes place with increasing $SiO_2$, with increasing pressure of water vapour and other volatile constituents, especially fluorine, and with decreasing CaO.[1]

Even the limited data in Table 1 give hints that the F content in dark wiborgite is lower than in the more silicic rapakivi varieties. The concentration of volatiles towards the less basic differentiation products is reflected in, e.g., the amounts of fluorite as an accessory mineral. In the dark varieties, it is met with only exceptionally, while in other varieties it is an essential accessory constituent of the rock, often in as high concentrations as up to 2 percent by volume. The occurrence of fluorite in the miarolitic druses and in the scantily present pegmatites is marked.

In the histogram of Fig. 19, all the even-grained granites of group I are combined. Table 2 clearly shows that the thermal state of the potash feldspar is slightly higher in the Ia-subgroup than in the Ib-subgroup granites. Mostly, the Ia-subgroup granites have potash feldspar with the reflection type *I*, their contact varieties against the non-rapakivitic country rock lower thermal state, while the Ib subgroup is characterized by the reflection types *I—IV*.

The data on the hornblende granites (group II in Table 2) are so scanty that they cannot be treated statistically. The two specimens of Lappee granite represent the *I/II—III* structural types, and the potash feldspar from the Suomenniemi massif indicates a clearly lower thermal state (reflection types *IV—V*). The same is true of the hornblende rapakivi from the Jaala—Iitti dike. Attention is called to the observation that the Lappee granite grades over to Ia-subgroup tirilite and that the hornblende rapakivi of the Jaala—Iitti dike also grades over to tirilite. In both cases, the more basic tirilitic variety contains an alkali feldspar with a higher thermal state than the hornblende rapakivi.

The dark and darkish wiborgites reveal a comparatively even occurrence of the reflection types *I—IV*. The phenocryst alkali feldspar is statistically characterized by a slightly higher thermal state than the groundmass alkali feldspar.

The groundmass alkali feldspar of the normal wiborgite clearly shows a lower thermal state than that of the dark and darkish wiborgite. Reflection type *IV* now prevails. The phenocryst alkali feldspar is in a remarkably higher thermal state than the groundmass alkali feldspar. Reflection types *II* and *II/III* represent the approximate center of gravity.

In pyterlite and coarse porphyritic rapakivi, no essential difference is noticeable with respect to the distribution of the reflection types. Both varieties are characterized by potash feldspar with a rather low thermal state. The groundmass potash feldspar

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1) Based on 40 silicate analyses of different rapakivi granite varieties from the Wiborg massif.

is seen to have the same reflection types as the normal wiborgite. Both the angular and the ovoidal alkali feldspar phenocrysts in the pyterlite and porphyritic rapakivi are characterized by a markedly lower thermal state than in the wiborgite.

The Vb subgroup of porphyritic rapakivi granites (Table 2) does not appear in the histogram, Fig. 19, forming as they do a highly inhomogeneous group. The alkali feldspar in the Sinkko granite, in respect to both phenocryst and groundmass alkali feldspar, corresponds in the thermal state to that of the Lappee granite.

The alkali feldspar of all the even-grained biotite rapakivi granites is characterized by a low thermal state. The pyterlitic ovoids, which occur sporadically, have a slightly higher thermal state than does the groundmass potash feldspar in the corresponding sample.

The porphyry aplites (group VII) contain a groundmass alkali feldspar with a similarly low thermal state than the foregoing biotite granites. The thermal state in the ovoids is higher than in the groundmass.

The potash feldspar in the dike rocks is mostly in a low thermal state. No essential difference between the phenocryst alkali feldspar and the groundmass alkali feldspar is found, the quartz porphyry dike rocks being the exceptions (see pp. 47—48 and 66—67).

The triclinicity of rapakivi granite potash feldspar had been previously investigated by Neuvonen in 1957. As reported by him, the different rapakivi varieties differ but little with regard to the distribution of the obliquity. In wiborgite, a monoclinic or weakly triclinic potash feldspar is the most common. In porphyritic varieties, all the degrees of triclinicity are equally present. In the pyterlitic and even-grained varieties, there is a weak distribution maximum of 0.0—0.3 and another maximum of 0.75. In the quartz porphyry and granite porphyry dikes, there prevails a potash feldspar with a high degree of triclinicity (0.7—1.0).

According to Neuvonen (oral communication), the triclinicity of the phenocryst potash feldspar alone was measured in wiborgite, pyterlite, porphyritic rapakivi and dike rocks with phenocrysts. Thus the data given by Neuvonen do not include groundmass potash feldspar. In comparing Neuvonen's findings with the data in Fig. 19, one must remember that the figure is a distribution histogram of the reflection types, and not a distribution histogram of the triclinicity values $\triangle$, and that in the present study the even-grained rapakivis have been represented in three different histograms, each representing a petrographic rapakivi variety, while Neuvonen treated them together.

In their study on the hornblende rapakivi granite dike at Jaala—Iitti, on the northwest border of the Wiborg massif, Lehijärvi and Lonka (1964) determined the triclinicity of the potash feldspar in different rapakivi varieties belonging to the dike. The reddish brown hornblende granite has a potash feldspar with $\triangle = 0.2—0.7$ (specimen No. 751/ML/54 in the present study being from this hornblende granite). The dark green (tirilitic) marginal variety of this rapakivi has a potash feldspar with a lower triclinicity, $\triangle = 0.0—0.2$ (specimen No. 759/ML/54 in the present study being

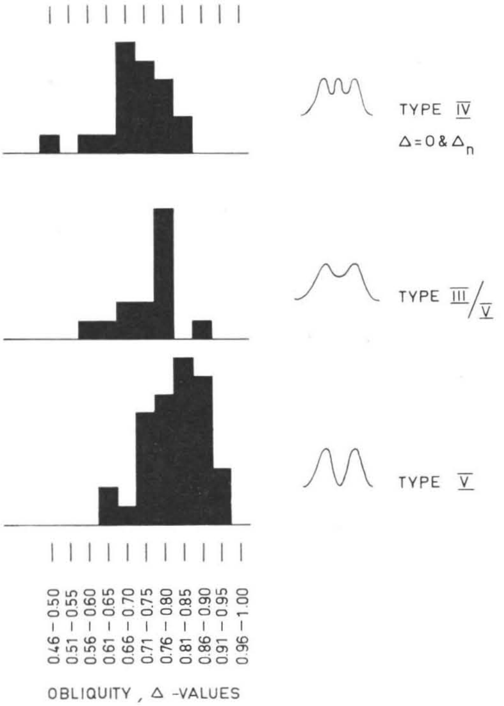

FIG. 20. The obliquity frequency histograms in the three reflection type groups *IV*, *III/V* and *V*. See the text.

from this marginal variety). The even-grained biotite granite in the same area showed a potash feldspar with a triclinicity of 0.2—0.7. In the rapakivi series, dark and darkish even-grained granite—dark and darkish wiborgite—normal wiborgite—pyterlite/coarse porphyritic rapakivi—biotite rapakivi/porphyry aplite, a small but significant gradual change is observed (Table 2, Fig. 19). In the first member of this series, the groundmass alkali feldspar has the same thermal state as the phenocryst alkali feldspar. From »tirilite» towards more silicic varieties, the difference in thermal states between the phenocryst alkali feldspar and the groundmass alkali feldspar becomes more and more pronounced. The phenocryst alkali feldspar is, on the average, in a slightly higher thermal state than the groundmass alkali feldspar. No clear difference between the thermal state in alkali feldspar in wiborgitic ovoids, pyterlitic ovoids and angular phenocrysts can be found. Table 2 surely suggests that the alkali feldspar in wiborgitic ovoids is in a slightly higher thermal state than the pyterlitic ovoids from the same sample.

The quartz porphyry samples 99/AV/58 and 18/AS/56 are of special interest because of the difference in thermal states between the phenocryst and the groundmass alkali feldspar. In both cases, the phenocrysts are almost maximum microcline, the

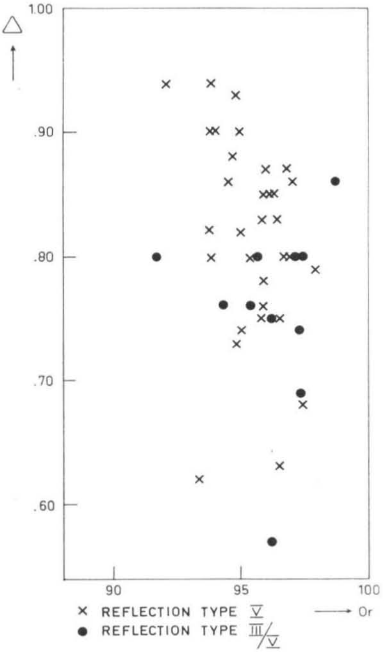

FIG. 21. Obliquity of the triclinic rapakivi granite alkali feldspars having the reflection types *V* and *III/V* plotted against the composition.

groundmass is represented by structural types *II/III* and *III*, i.e., by an alkali feldspar in a clearly higher thermal state than the phenocrysts. The phenocryst alkali feldspar is an almost homogeneous (non-perthitic) potash feldspar, which in places exhibits a very thin polysynthetic twinning. The groundmass potash feldspar has a spherulitic structure indicating a sudden crystallization (for the conclusions and interpretation see pp. 66—67).

When the potash feldspar is characterized by the reflection types *IV*, *III/V* and *V*, it is possible to measure the obliquity. Figure 20 shows a △-frequency histogram for each of the three reflection types. These diagrams show that when a less ordered potash feldspar is transformed into a more ordered one, the degree of triclinicity — as long as there are domains of orthoclase present — cannot reach the state represented by nearly maximum microcline.

Figure 21 shows the composition plotted against the triclinicity of the microcline (types *III/V* and *V* only included). Most of the compositions are between $Or_{94}$ and $Or_{98}$. Goldsmith and Laves (1961) emphasized that most microclines have exsolved virtually all their albite, and have 5 percent or less $NaAlSi_3O_8$ in solid solution. The plot in Fig. 21 bears a similar relation. A curious feature, however, emerges from the graph. At high triclinicity values, i.e., $\triangle = 0.9$ or more, there is a group of points indicating an increasing Ab-content with increasing obliquity. Most of these specimens have too high an Ab-content to be reasonable with their obliquity.¹) In the author's view, the discrepancy is due to the somewhat different cooling history of the potash feldspars in question from that in most of the other microclines investigated. Most of the samples with an anomalous composition are either granite porphyritic contact varieties of rapakivi or granite porphyry dikes cutting the country rocks or quartz porphyry dikes or, as in the case of 223/AV/59, a thin porphyritic rapakivi intrusion between the granodioritic country rock and tirilitic rapakivi. A common feature of most of these rocks is the fact that the groundmass is fine-grained, indicating rapid crystallization.

## A single-crystal study of the sodic phase of perthite

An X-ray single-crystal study was made of 37 rapakivi granite alkali feldspar samples applying the method of Smith and MacKenzie (1955). The results of the study are given in Table 3. It gives data on the Na-phase of the perthite and also data on the nature of the K-phase, the bulk chemical composition and the optical axial angle of the K-phase.²) In Fig. 22, $\alpha^*$ of the Na-phase is plotted against $\gamma^*$.

As early as 1957 Neuvonen studied the rapakivi granite perthite using the X-ray single-crystal methods. Neuvonen reported his finding in a lecture given at a meeting of the Geological Society of Finland; he did not present any numerical data. Neuvonen concluded that the albite phase in cryptoperthite is exceedingly poor in potassium and that the albite twin-type superstructure is common. Further, the albite phase of microperthite is generally twinned according to both the pericline and the albite laws. It probably crystallized in the high temperature form. In some of the specimens studied, a high-albite structure has been found. This albite contains about 10 % $KAlSi_3O_8$.

In the present study, the Ia-subgroup tirilite is characterized by an orthoclase cryptoperthite where the sodic phase is high-temperature anorthoclase (about $Ab_{80}Or_{20}$). Anorthoclase is twinned according to both the pericline and the albite law. The phase twinned according to the albite law in many instances and the phase twinned according to the pericline law only exceptionally shows a superstructure. In addition to anorthoclase, some samples contain low-temperature plagioclase as

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¹) Dietrich 1962 p. 410: »Most Ab-content must be exsolved before $\triangle$-values of greater than ca. 0.85 can be fixed (of the approximately 80 checked, the Ab-content in solid solution is less than six per cent in microclines with $\triangle$-values greater than 0.85).»

²) As far as ovoid or angular phenocrysts are concerned, the 2V value and reflection type *(I—V)* were measured by the powder X-ray method from the same part of the grain as that from which the crystal splinter for the single crystal study was taken. As for the groundmass feldspar, its 2V values were measured with a U-stage from thin sections, the reflection type by the powder method using feldspar separated from the crushed rock by heavy liquids, and the single crystal work using separate grains from this feldspar separate.

TABLE 3.

Character of exsolved sodic phase in rapakivi granite crypto-

| Rock type | Specimen number | Single crystal from | Sodic phase | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Albite twinning | | | | Pericline | |
| | | | $\alpha^*$ | $\gamma^*$ | Thermal state | Remarks | $\alpha^*$ | $\gamma^*$ |
| Tirilite (Ia) .... | 35b/AS/54 | Pyterlitic ovoid | 86°26′ | 88°51′ | H—L | Superstr. | faint | |
| | | Groundmass | 87°29′ | 88°59′ | H | » | 87°12′ | 88°44′ |
| | | » | 87°14′ | 88°58′ | H | » | 87°12′ | 88°43′ |
| | 258/AV/59 | » | 86°19′ | 89°42′ | L | » (very well developed) | 86°52′ | 89°50′ |
| | | » | 86°25′ | 89°52′ | L | | 86°52′ | 89°34′ |
| | 245/KM/55 | » | faint | | | | faint | |
| | 223/KM/55 | » | 87°22′ | 89°11′ | H | Superstr. | 88°01′ | 89°06′ |
| | | » | 87°34′ | 89°06′ | H | | very faint | |
| | 321/KM/55 | » | 87°45′ | 89°35′ | H | Superstr. | 88°02′ | 89°08′ |
| | | » | | | | » strong | faint | |
| | 132/RL/55 | » | faint | | | | 87°45′ | 88°55′ |
| | | » | faint | | | | faint | |
| | | » | faint | | | | faint | |
| Tirilite (Ib) .... | 644/55/MLa | » | 86°27′ | 89°41′ | L | | faint | |
| | | » | 86°20′ | 89°49′ | L | | faint | |
| | 678/55/MLa | » | 86°26′ | 89°32′ | L | | faint | |
| | | » | very faint | | | | faint | |
| Wiborgite (IIIa) | A1 | Pyterlitic ovoid | 86°24′ | 90°05′ | L | | very faint | |
| | | Groundmass | 86°14′ | 90°00′ | L | | | |
| | 3/AV/69 | Angular phenocryst | 86°53′ | 90°28′ | L | Superstr. | | |
| | 102/54/MLa | Groundmass | | | | | 87°40′ | 88°38′ |
| | | » | | | | | 87°43′ | 88°51′ |
| | 192/54/MLa | Wiborgitic ovoid | 86°38′ | 89°49′ | L | | 86°30′ | 89°03′ |
| | | Pyterlitic ovoid | 86°27′ | 89°44′ | L | Superstr. | 87°09′ | 88°55′ |
| | | » | 86°34′ | 90°04′ | L | | faint | |
| | | Groundmass | 86°21′ | 90°04′ | L | | faint | |
| Wiborgite (IIIb) | A2 | Wiborgitic ovoid | 86°17′ | 89°31′ | L | Superstr. | 87°31′ | 89°03′ |
| | | » | 86°24′ | 89°43′ | L | | very faint | |
| | | Pyterlitic ovoid | 86°33′ | 89°35′ | L | | 86°42′ | 89°52′ |
| | | Angular phenocryst | 86°30′ | 89°53′ | L | | 87°53′ | 88°55′ |
| | | Groundmass | 86°35′ | 90°00′ | L | | very faint | |
| | 136/LL/59 | Wiborgitic ovoid | 86°15′ | 90°12′ | L | | | |
| Pyterlite (IV) .. | A3 | Pyterlitic ovoid | 86°27′ | 90°16′ | L | | | |
| | | » | 86°30′ | 90°13′ | L | | 86°37′ | 90°23′ |
| Even-grained (VI) ........ | A4 | Groundmass | 86°22′ | 89°52′ | L | | faint | |
| Porphyry aplite (VII) ....... | A6 | Wiborgitic ovoid | 86°31′ | 90°21′ | L | | 86°48′ | 89°49′ |
| | | Groundmass | 86°11′ | 90°00′ | L | | faint | |

Thermal state: H = high, L = low

and microperthites as well as of the host potassic phase.

| twinning | | Potassic phase | | | Bulk composition % by wt. |
|---|---|---|---|---|---|
| Thermal state | Remarks | Nature of potassic phase | 2Vα(°) | Reflection type from powder data | |
| | | O | 57 | *I* | 1) $\mathrm{Or}_{72\cdot 9}$ |
| H | | O | 54—63 | *I* | 2) $\mathrm{Or}_{76\cdot 37}\mathrm{Ab}_{21\cdot 46}\mathrm{An}_{2\cdot 17}$ |
| H | Superstr. | O | | | |
| L | | O | | | |
| | | | 60—62 | *I* | $\mathrm{Or}_{72\cdot 5}$ |
| H—L | | O | | | |
| | | O | 60—61 | *I* | $\mathrm{Or}_{76\cdot 0}$ |
| H | | O | 62—66 | *I* | $\mathrm{Or}_{78\cdot 4}$ |
| | | O | | | |
| H | | O | 56—64 | *I* | $\mathrm{Or}_{72\cdot 4}$ |
| | | O | | | |
| H | | O | 48 | *I* | $\mathrm{Or}_{76\cdot 5}$ |
| | | O | | | |
| | | O | | | |
| L | | O—M (ab-twinning) | 64—76 | *II* | $\mathrm{Or}_{79\cdot 7}$ |
| | | O+M (ab-twinning) | | | |
| | Superstr. | O | 60—68 | *I* | $\mathrm{Or}_{76\cdot 9}$ |
| | | O | | | |
| | | O—M (ab-twinning) | — | — | — |
| | | M (ab-twinning) | 65—68 | *IV* | — |
| | | O+M (diagonal association) | 74 | *III* | — |
| H | Superstr. | O | 45—47 | *I* | $\mathrm{Or}_{81\cdot 1}$ |
| H | » | O | | | |
| H—L | | O—M (ab-twinning) | — | — | — |
| H | | O | — | — | — |
| | | O | — | — | — |
| | | M (ab-twinning) + O | 68—72 | *II/III* | $\mathrm{Or}_{74\cdot 6}$ |
| H | Superstr. | O | — | *I/II* | $\mathrm{Or}_{68\cdot 29}\mathrm{Ab}_{30\cdot 19}\mathrm{An}_{1\cdot 52}$; ($\mathrm{Or}_{71\cdot 9}$) |
| | | O—M (ab-twinning) | | | |
| L | | O—M (ab-twinning) | 64 | *I/II* | $\mathrm{Or}_{69\cdot 78}\mathrm{Ab}_{29\cdot 09}\mathrm{An}_{1\cdot 13}$ |
| H | Superstr. | O—M (ab-twinning) | 66 | *III* | — |
| | | M (ab-twinning) + O | 66—69 | *IV* | $\mathrm{Or}_{73\cdot 42}\mathrm{Ab}_{24\cdot 99}\mathrm{An}_{1\cdot 59}$ |
| | | M (ab-twinning) | — | — | — |
| | | O—M (ab-twinning) + M (pericl. tw.) | — | *IV* | $\mathrm{Or}_{69\cdot 65}\mathrm{Ab}_{29\cdot 31}\mathrm{An}_{1\cdot 04}$ |
| L | | M (ab-twinning) + O | — | *IV* | |
| | | M (diagonal association) | 72—75 | *III/V* | $\mathrm{Or}_{67\cdot 81}\mathrm{Ab}_{30\cdot 99}\mathrm{An}_{1\cdot 20}$ |
| L | | O—M (ab-twinning) | — | *I/II* | $\mathrm{Or}_{65\cdot 9}$ |
| | | M (ab-twinning) | 66—80 | *IV* | — |

O = orthoclase; M = microcline; centered on sharp reflections
O—M = short diffuse streaks with monoclinic symmetry
1) by $\bar{2}01$ method used on homogenized sample
2) by wet chemical analysis

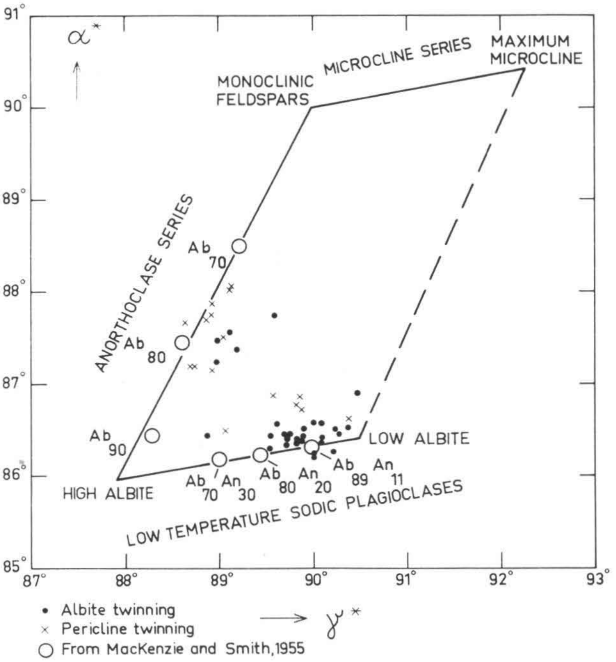

FIG. 22. The plot of reciprocal $\alpha^*$ against $\gamma^*$ of the sodic phase of rapakivi granite micro- and cryptoperthites.

exsolutions (evidently also cryptoperthite). The plagioclase in question is either a pure albite the thermal state of which deviates slightly from the low albite or a plagioclase with a low thermal state.

The Ib-subgroup tirilites, i.e., the dark and darkish, even-grained rapakivi granites from the islands of the Gulf of Finland, are characterized by both micro- and cryptoperthites in which the sodic phase is a low plagioclase (or intermediate albite) and is twinned according to the albite law. The pericline twinned sodic phase produces such diffuse reflections that it is not possible to measure the $\alpha^*$ and $\gamma^*$ accurately. In one of the samples, which is twinned according to the pericline law, the pericline twin-type superstructure was observed. The potassic phase of the perthites contains, besides the monoclinic orthoclase, also triclinic domains twinned according to the albite law.

Between the dark and the normal wiborgite, no essential difference was detected. Microscopically, the perthite is orthoclase microperthite, which contains patches consisting mainly of cryptoperthite. In the light of the single crystal study, the sodic phase twinned according to the albite law is a low-temperature plagioclase or intermediate albite, whereas the sodic phases twinned according to the pericline law are in some cases anorthoclases, in other cases low plagioclases. Both albite twin-type and pericline twin-type superstructures have been encountered in both in the mantled and the unmantled ovoids. A pericline twin-type superstructure has been observed in the groundmass alkali feldspar of dark-coloured wiborgite with sparsely scattered ovoids. As a whole, the albite twinned phase is better developed than the pericline twinned phase. The high-temperature pericline twinned sodic phase occurs only in orthoclase. The pericline twin-type superstructure is found only in anorthoclase exsolved in orthoclase. In all the phenocrysts of wiborgite studied, with one exception, the potassic phase is orthoclase. In many instances, however, besides the orthoclase reflection, there are diffuse tails in the direction of the *b*-axis, indicating the presence of triclinic domains. In one case (see Table 3), in addition to the orthoclase reflections, there are sharp reflections of microcline in a position indicating a diagonal association (see, Smith and MacKenzie, 1959). The potassic phase of the alkali feldspar crystals from the wiborgite groundmass, which was investigated by the single crystal method, is either orthoclase or microcline twinned according to the albite law. Here, a weak reflection in many instances indicates the presence of monoclinic potash feldspar.

Likewise, attention was given to only a few alkali feldspar single crystals from pyterlite, even-grained biotite granite and porphyry aplite. Common to all of these is the fact that the sodic phase occurs in the low thermal state, when twinned according to both the pericline law and the albite law. The latter twin-type is better developed than the former. There are no superstructures. A marked inhomogeneity characterizes the potassic phase. Each sample contains microcline, some also orthoclase; and in the wiborgitic ovoid of porphyry aplite, orthoclase prevails over microcline. In the only single crystal of the biotite granite investigated, the potassic phase was microcline in diagonal association.

Combining the microscopical observations of rapakivi perthites (pp. 30—37) with the data yielded by the single crystal studies, it can be regarded as obvious that the film- and string perthites (1—5 $\mu$) of the alkali feldspar grains without cross-hatching correspond to anorthoclase cryptoperthite and the sodic phase in the vein perthite corresponds to low-temperature plagioclase or intermediate albite. This view is supported also by the fact that the cross-hatched potash feldspar in the rapakivi granites is never characterized by string- or film perthite textures but by vein perthite and patch perthite textures. Correspondingly, in the single crystals, in which the triclinic potassic phase is prominent, only low plagioclase (or intermediate albite) is met with as exsolutions.

MacKenzie and Smith (1962) made a compilation of data from X-ray single crystal determinations on $\alpha^*$ and $\gamma^*$ of micro- and cryptoperthites occurring in different geological environments. They established a cooling sequence based on the thermal state of alkali feldspars from igneous rocks:

(a) Potassic phase monoclinic, sodic phase anorthoclase
(b) Potassic phase monoclinic, sodic phase anorthoclase+plagioclase

(c) Potassic phase monoclinic, sodic phase two plagioclases
(d) Potassic phase monoclinic, sodic phase one plagioclase
(e) Potassic phase monoclinic+triclinic, sodic phase one plagioclase.

According to MacKenzie and Smith (1962, p. 101), »the conditions under which the feldspars exsolved, viz., cooling rate, temperature, pressure and concentration of volatiles, may all be important factors in determining the type of pattern produced» (types (a)—(e) above). By analogy, the different rapakivi varieties in the Wiborg rapakivi massif may be arranged in a cooling sequence that slightly deviates from that by MacKenzie and Smith.

(1) Potassic phase monoclinic, sodic phase two anorthoclases. To this group belong the dark and darkish-coloured, even-grained rapakivis of group Ia, i.e., the tirilites in the Lappeenranta area. It seems that these crystallized from a dry magma at a high temperature in a narrow temperature range. In the cooling system cited, no counterpart exists. This combination, however, was later described by Scharbert (1966) as exhibited by specimens from microsyenite dikes in the northern part of the Ílimaussaq peninsula in southern Greenland. Scharbert suggests a rather rapid cooling of the syenitic magma in question.

(2) Potassic phase monoclinic, sodic phase anorthoclase+plagioclase. Some of the wiborgites may be grouped into this association. This is the same as MacKenzie and Smith's type (b), represented by the Tertiary ring dikes (porphyritic felsite and granophyre) of Slieve Gullion, Ireland, and the marginal specimens of the Beinn and Dubhaich granites in Isle of Skye (MacKenzie and Smith, *op.cit.*, pp. 75—81 and p. 99). As interpreted by the authors referred to (p. 99): »either the exsolution is accomplished in two distinct stages with the anorthoclase appearing at the highest temperature and the plagioclase later, or that the two phases are exsolved simultaneously at one temperature but the anorthoclase does not achieve significant order at this temperature because of its potassium content whereas the plagioclase phase orders readily because of its relatively high calcium content and low potassium content.» Common to all these igneous rocks is the fact that none of them, the rapakivi granites included, can be regarded as deep-seated plutonic intrusions, but they are more or less hypabyssal and unmetamorphosed.

(3) Potassic phase monoclinic+triclinic, sodic phase two or one plagioclase. Part of the tirilites and of the wiborgites belong to this type. This in certain respects corresponds to MacKenzie and Smith's types (c)—(e). The rapakivi granites cannot be divided into the detailed cooling sequence of MacKenzie and Smith, because in a single specimen the wiborgitic ovoids, the pyterlitic ovoids and the groundmass alkali feldspar do not necessarily represent the same exsolution type as seen in Table 3. MacKenzie and Smith's (c) type is represented, e.g., by specimens from the Tertiary granites of Arran and Mourne (Ireland), the Kûngnât syenite (SW Greenland); type (d) by specimens from the Dartmoor granite

(SW England), the Finnmark igneous complex (Oslo region) and the Tatoosh pluton, a shallow intrusion of granodiorite—quartz monzonite in Washington (Wright 1964); type (e) by some of the specimens of the Dartmoor granite and Kûngnât syenite and most of the specimens from the Tugtudôq complex in SW Greenland (MacKenzie and Smith 1962).

(4) Potassic phase triclinic±monoclinic, sodic phase two or one plagioclase. To this type belong the alkali feldspars of the few investigated specimens of pyterlite, even-grained biotite rapakivi and porphyry aplite as well as a substantial part of the groundmass alkali feldspar from wiborgites.

Considering the areal distribution of different rapakivi varieties in the Wiborg massif — normal wiborgite 76.2 %, dark wiborgite 4.9 %, pyterlite 6.1 %, porphyritic rapakivi 1.2 %, tirilite 3.1 %, even-grained granite 7.8 %, etc. (Simonen and Vorma 1969), — it may be concluded that the types (2) and (3) characterize the Wiborg rapakivi massif.

Even though Table 3 is based on quite limited data, it does give a picture of an association in disequilibrium. Table 3 further supports the assumption suggested from the powder data that the potassic phase of the ovoids has a slightly higher thermal state than that of the groundmass (see also Table 2 for their compositions and the differences between them). It also shows that the sodic phase in the ovoids evidently has a slightly higher thermal state than that of the groundmass microperthite.

A weak, often diffuse, albite twin-type superstructure characterizes most of the albite twinned anorthoclases. 321/KM/55 and 258/AV/59 — tirilites — are exceptions, where the superstructure is well developed. In three cases, the albite twin-type superstructure is met with in the low-temperature plagioclase phase: in two cases the host potassic phase of the ovoids is orthoclase, one mantled by plagioclase, the other unmantled, while in the third case — 3/AV/69 — the host is an angular phenocryst consisting of orthoclase with microcline, the latter in diagonal association. A pericline twin-type superstructure, also weakly developed, is present in about every other pericline twinned anorthoclase. In each case, the host potassic phase is orthoclase.

According to MacKenzie and Smith (1955, p. 721): »The tendency to form superstructure is probably highest at the beginning of the unmixing process. - - - It is thus reasonable to suppose that the formation of a superstructure is an intermediate step in the formation of twinned crystal.»

The dependence of the superstructure type on the bulk composition of alkali feldspar and its thermal state (deducted from 2V$\alpha$) was discussed by Smith and MacKenzie in 1959. Fig. 7 in their paper shows that anorthoclases with pericline twin-type superstructure occur in the most potassium-rich alkali feldspar with the lowest values of 2V among the specimens studied by them. The specimens containing a superstructure of albite-oligoclase occupy an adjacent area with slightly greater values of 2V and more sodium-rich compositions. The third group, mainly albite twinned, sometimes pericline twinned, albite-oligoclase, covers the largest area including all the sodium-rich specimens and most of the microcline perthites. Some overlapping occurs between the areas occupied by the groups.

Because of the uncertainty of the exact bulk chemical composition of the rapakivi granite alkali feldspars listed in Table 3, no diagram corresponding Fig. 7 in Smith and MacKenzie's paper of 1959 was compiled. Generally taken, the pericline superstructures occur in the same area as in Smith and MacKenzie's diagram. The same can be said also of the albite superstructures. The only difference is that part of the sodic phase with albite twin-type superstructure is represented by anorthoclase, while in the material investigated by Smith and MacKenzie the albite twinned superstructure occurred in association with albite-oligoclase. This strongly indicates that both the albite twinned and pericline twinned sodic phases in rapakivi originally exsolved as anorthoclase, the superstructure state being produced at the beginning of exsolution. Evidently, the anorthoclase with pericline twin-type supersturcture was preserved during the cooling of the rock better than that with albite twin-type superstructure, in which the potassium possibly diffuses more readily during the reorganization of the perthites, and transforms into albite-oligoclase.

## CHEMICAL COMPOSITION

### Composition of the potassic phase of perthite

The Or contents of the potash feldspars listed in Table 2 were determined by the X-ray powder method measuring the $2\theta$ for the $\bar{2}01$ reflection using a Philips wide range diffractometer. Smear mounts calibrated with quartz were used. The average was measured for the separation between $2\theta(10\bar{1}0)_{\text{quartz}}$ and $2\theta(\bar{2}01)_{\text{potash fp.}}$ from 4 to 8 runs. $\text{Cu}K\bar{\alpha}$ radiation was used. The results were calculated on the $\text{Cu}K\alpha_1$ radiation. The Or content of orthoclase was determined using the equation of Wright and Stewart (1968) and the Or content of microcline using Orville's equation for the maximum microcline—low albite series (in Stewart 1968, p. 97). Only those specimens in Table 2 were measured that show either the reflection types *I*, *I/II*, *II* and *II/III* (treated as orthoclases) or *III/V* and *V* (treated as maximum microclines). The alkali feldspars with reflection types *III* and *IV* were not measured because of the presence in them of different intermediate thermal states. Further, the cases where the resolution of alkali feldspar $\bar{2}01$ peak from the quartz $10\bar{1}0$ peak would not allow a numerical estimation to be done on the Or content were excluded. In these cases, either the alkali feldspar $\bar{2}01$ peak was very broad, indicating a range of compositions, or, owing to the high Or content, the resolution was poor.

The composition of the potassic phase (Table 2) of the microperthite can be related to the rock type in question. Relating the thermal state determined by the obliquity to the rock type makes it obvious that the thermal state and the composition are interdependent. High thermal state (orthoclase) — composition near $Or_{90}$, low thermal state (microcline) — composition around $Or_{95}$.

## The bulk chemical composition of perthite

All the specimens in Table 2 were homogenized for three hours at 1 000°C, and subsequently their Or content was determined by the X-ray powder method, measuring the $2\theta$ angle for the $\bar{2}01$ reflection of alkali feldspar. The bulk chemical composition thus derived is given in Table 2. From twenty of the homogenized samples, polished thin sections were made to check microscopically and in some cases also by microprobe analyser the perfection of the homogenization. The results show that in the case of orthoclase cryptoperthite, the homogenization process in quite complete, in the case of orthoclase microperthite less so, and in the case of microcline microperthites poor.

Partial wet chemical analyses were made of ten alkali feldspar samples. For this, the alkali feldspar was separated by heavy liquids. While only $K_2O$, $Na_2O$ and CaO were determined, the quartz was tolerated as an impurity. It is presumable that, besides the perthitic albite, small plagioclase inclusions were present in the alkali feldspar because the grinding could not be continued to the point where also loss of perthitic albite would have taken place. The results of the wet chemical analyses are given in Table 4. The Or+Ab+An is calculated as 100 %, thus eliminating the influence of quartz.

TABLE 4.

Partial chemical analyses and compositions (% by weight) of rapakivi granite alkali feldspars from the Wiborg rapakivi massif. Anal. Pentti Ojanperä.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $K_2O$ | 11.51 | 12.11 | 11.32 | 11.99 | 11.37 | 10.95 | 11.84 | 11.20 | 11.37 | 10.74 |
| $Na_2O$ | 2.26 | 2.76 | 3.14 | 2.85 | 3.31 | 3.38 | 3.48 | 3.62 | 3.01 | 3.46 |
| CaO | 0.39 | 0.24 | 0.23 | 0.31 | 0.22 | 0.29 | 0.21 | 0.07 | 0.24 | 0.32 |
| Or | 76.37 | 74.46 | 70.72 | 73.42 | 69.78 | 68.29 | 69.65 | 68.12 | 67.81 | 67.27 |
| Ab | 21.46 | 24.30 | 28.08 | 24.99 | 29.09 | 30.19 | 29.31 | 31.52 | 30.99 | 31.04 |
| An | 2.17 | 1.24 | 1.20 | 1.59 | 1.13 | 1.52 | 1.04 | 0.36 | 1.20 | 1.69 |

1. Alkali feldspar from tirilite, 35b/AS/54.
2. Groundmass alkali feldspar from hornblende rapakivi, 28/AS/53.
3. Pyterlitic ovoid from » » »
4. Groundmass alkali feldspar from wiborgite, A2.
5. Pyterlitic ovoid » » »
6. Core of wiborgitic ovoid » » »
7. Pyterlitic ovoid from pyterlite, A3.
8. Angular phenocryst from porphyritic rapakivi, 714/ML/54.
9. Alkali feldspar from even-grained biotite rapakivi, A4.
10. » » » » » » , A5.

For localities see Table 1.

The figures in Table 4 and Table 2 (see, tirilite No. 35b/AS/54, hornblende rapakivi 28/AS/53 and wiborgite A2) show that in the tirilite the Or contents determined by both the X-ray and the wet chemical methods agree, while in the other two cases — microperthites — the X-ray method gives a somewhat higher Or content than the wet chemical method.

Owing to the incomplete homogenization of the alkali feldspar samples, the petrogenetic conclusion that can be drawn are limited. The high Or content of the alkali feldspar in tirilite is in agreement with the assumed crystallization of the rock at higher temperatures than the other rapakivi varieties listed in Table 4. The table likewise shows that in hornblende rapakivi and wiborgite, the groundmass alkali feldspar has a higher Or content than the ovoids have. This evidently is due to the removal of sodium from the melt by continued disequilibrium crystallization of plagioclase.

The alkali feldspar compositions in Table 4 remarkably deviate from those of the East Fennoscandian rapakivi granites reported by Holmquist (1939), Wahl (1925) and Sviridenko (1968), as recorded in Table 5. Most of these analyses are considerably richer in $NaAlSi_3O_8$ and $CaAl_2Si_2O_8$ than the new analyses in Table 4. This the present author attributes to incomplete separation of the inclusions in the alkali feldspars listed in Table 5. The results in Table 4 agree well with those of Neuvonen (1957), based on X-ray powder data on the Finnish rapakivi granites, as well as with those of Stewart (1959), based both on X-ray powder data and on chemical analyses of the rapakivi granite alkali feldspars from different localities.

TABLE 5.

Composition of alkali feldspars from the east Fennoscandian rapakivi granites. Data from literature; Nos. 1—6 from Wiborg massif (% by weight), Nos. 7—13 from the Salmi massif (molecular per cent).

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Or ... | 52.3 | 48.3 | 65.7 | 75.0 | 57.8 | 72.9 | 61.8 | $57.0_5$ | 61.0 | 56.1 | 61.0 | 49.0 | 59.3 |
| Ab ... | 43.9 | 39.4 | 30.1 | 20.9 | 34.7 | 25.1 | 36.1 | 40.7 | 37.0 | 41.4 | 35.2 | 49.0 | 38.7 |
| An ... | 3.8 | 12.3 | 4.2 | 4.1 | 7.5 | 2.0 | 2.1 | $2.2_5$ | 2.0 | 2.5 | 3.8 | 2.0 | 2.0 |

1. Wiborgitic ovoid, wiborgite. Muhutlahti, Säkkijärvi (Holmquist 1939).
2. Wiborgitic ovoid(?), wiborgite (Holmquist 1939).
3. Wiborgitic ovoid, wiborgite. Pikiruukki, Monrepos, Wiborg (Wahl 1925).
4. Pyterlitic ovoid, wiborgite. Muhutlahti, Säkkijärvi (Holmquist 1939).
5. Pyterlitic ovoid(?), pyterlite (Holmquist 1939).
6. Pyterlitic ovoid, pyterlite. Pyterlahti, Hämeenkylä (Wahl 1925).
7. Alkali feldspar from wiborgite (Sviridenko 1968).
8. » » » » ( » » ).
9. » » » pyterlite ( » » ).
10. » » » » ( » » ).
11. » » » coarse-ovoid porphyritic granite (Sviridenko 1968).
12. » » » even-grained granite (Sviridenko 1968).
13. » » » » » ( » » ).

## ON THE CRYSTALLIZATION OF RAPAKIVI MAGMA

Quite many of the recent explanations of the origin of ovoids are based on the assumption that the potash feldspar and quartz began to crystallize from the melt before the plagioclase (Savolahti 1956, pp. 83—93, 1962, pp. 70—77; Tuttle and Bowen 1958, pp. 93—98; Sviridenko 1968, pp. 82—92; Elders 1968, p. 44). These explanations are based on experimental granite systems where the influence of the An content has been omitted.

The explanations which take the An content into consideration give a different picture for the order of crystallization from rapakivitic magma. Stewart (1959, p. 308), e.g., convincingly showed that it is the plagioclase that first begins to crystallize from rapakivitic magma. The same conclusion was drawn by Richter (1966) from his study of feldspars of the marginal porphyry which exhibits a rapakivi texture, of the Eisenkappel granite, Austria. It is noteworthy that the bulk composition of this granite deviates considerably from the rapakivitic composition; especially the $K_2O/Na_2O$ ratio is smaller than in the Fennoscandian rapakivis. After comparing its composition with other rapakivis, Richter (p. 447) states »Der Vergleich der sechs Analysen zeigt, dass die chemischen Unterschiede aller Granitproben sehr beträchtlich sind. Dass trotzdem alle Rapakiwi Textur entwickelt haben, scheint also in erster Linie nicht auf die Aufgangszusammansetzung der Granitschmelzen zurückzugehen.»

According to a third view, the potash feldspar ovoids are either autometasomatic or metasomatic in origin. Replacement by microcline of the minerals previously secreted was proposed, e.g., by Budanov (1963, 1965). Dawes (1966) in his study of rapakivi granites in the Tasiussak area in South Greenland, described basic rocks intruded as dikes and small bodies into the rapakivi granite. The critical fact is that the basic rocks pre-date the formation of the feldspar megacrysts of the granite. Hawkes (1967) interprets the rapakivi texture observed in the Dartmoor granite as a result of autometasomatic, potassium-feldspathization of large plagioclase crystals. Dimanche and Michot (1966), in their study on the Flamaville granodiorite, suggest a similar explanation of the origin of the rapakivi texture present in the rock. Allaart, Bridgwater and Henriksen (in press) interpret the potash feldspar megacrysts of the rapakivi suite of South Greenland as a late growth.

The rapakivi texture, marked by a plagioclase mantle around a potash feldspar ovoid, is explained in newer publications either as a product of magmatic crystallization of plagioclase around potash feldspar (Savolahti 1956, 1962; Tuttle and Bowen 1958; Sviridenko 1968; Elders 1968; Stewart 1959; Stewart and Roseboom 1962) or as a metasomatic or autometasomatic replacement of plagioclase phenocrysts by potash feldspar (Hawkes 1967; Dimanche and Michot 1966) or as an autometasomatic replacement of potash feldspar by plagioclase (Sobolev 1947; Velikoslavinskiy 1953).

This diversity of opinion, to which should be added the ones based on exsolution of the plagioclase of the mantle from the potash feldspar of the ovoid (Gates 1953;

Hutchinson 1956; Neuvonen 1957) shows that the origin of the wiborgitic ovoids in rapakivi has not yet received a generally acceptable explanation. A further complication is that wiborgitic ovoids occur also as intratelluric phenocrysts in fine-grained dike rocks belonging to the rapakivi suite (cf., Savolahti 1962, p. 74) and also that intratelluric wiborgitic ovoids have been described from the effusive quartz porphyry, comagmatic with rapakivi, of Suursaari (Hogland) (Wahl 1925, p. 20).¹) On the other hand, wiborgitic ovoids occur in xenoliths in rapakivi granite. These ovoids certainly have grown metasomatically. Härme (1954, pp. 27—28) described wiborgitic ovoids grown metasomatically in both basic rocks and in gneisses penetrated by granitic material, also other than rapakivitic. This diversity of environments shows that the evolution of wiborgitic ovoids is not bound to any single process or to one specific stage during the magmatic crystallization of rapakivitic or granitic magma. In some circumstances the development of wiborgitic ovoids may take place at a rather late stage (autometasomatic or metasomatic process) as, e.g., in South Greenland, where, according to a personal communication from Dr. Bridgewater, the rapakivi granites are quite deep-seated: Rocks more mafic than granitic predominate in the rapakivi suite. The present erosion niveau of the eastern Fennoscandian rapakivi evidently represents a quite shallow intrusion level of the rapakivi massifs. For the Salmi rapakivi massif, Sviridenko (1968, pp. 93—94) tentatively gives an intrusion depth of from 2 km to 3.5 km. There, the more mafic rocks of the rapakivi suite are missing. The same is true as regards the other eastern Fennoscandian rapakivi massifs, where mafic rocks, possibly co-magmatic with rapakivi granite, occur to only a limited extent.

If the estimated thickness of the Wiborg rapakivi massif, from 8 to nearly 19 km, as computed from gravity data by Lauren (1968, 1970), is correct, then the rocks at the present erosion level actually are contact varieties of granites, possibly during the crystallization of granite with a continuous migration of aqueous fluid rich in potassium taking place upwards. Thus the rapakivi texture actually may originate by the same process as the mantled ovoids in marginal porphyritic varieties of many smaller granite massifs.

The assumption of a shallow intrusion also receives some support from the petrology, petrography and tectonic environment of the small massifs of Sederholm's (1934) third group of granites. These small granite massifs occur in southern Finland between the Ahvenanmaa (Åland) rapakivi massif and the Wiborg massif; their age is the same as that of rapakivi (Kouvo 1958), and in chemical composition the magma from which they crystallized was rapakivitic. Some of them are associated in many places with more basic rocks (Lemland granite, Mosshaga granite, Åva granite). The basic rocks have been brecciated at many points by granite, and potash feldspar phenocrysts and quartz phenocrysts have metasomatically grown in them. Rapakivi

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¹) Ehrreich and Winchell (1969) described a volcanic rock, a Miocene rhyolite in California, with a rapakivi texture.

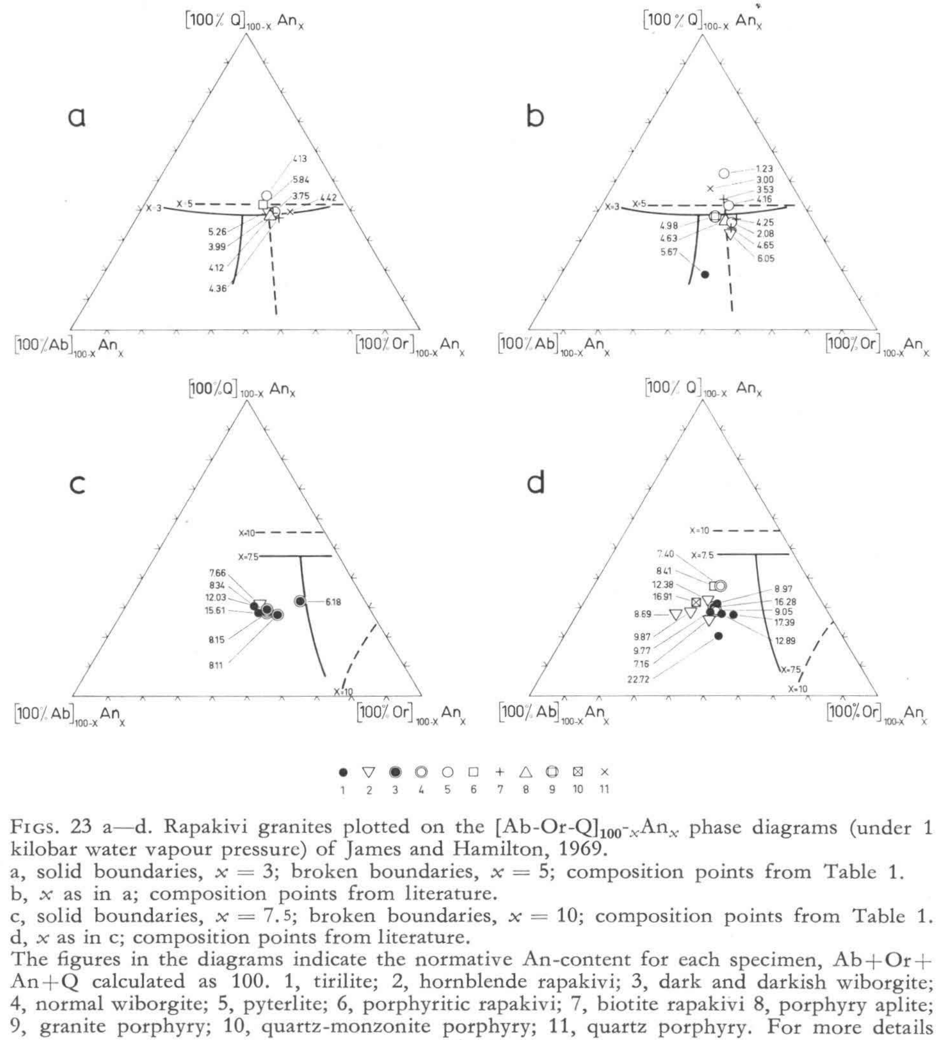
texture is very seldom observed; but occasionally the porphyritic varieties contain scattered potash feldspar ovoids mantled by plagioclase, e.g., in the Bodom granite. The potash feldspar — microcline microperthite — often has a marked alignment. The massifs occur tectonically in lines, which are connected with remarkable joints (Edelman 1949, pp. 36—37).

According to the current view the granites of Sederholm's third group are comagmatic with rapakivi. The textural differences are, in the opinion of the present author, mainly due to the difference in intrusion depth or in erosion niveau between the granites of Sederholm's third group (deep seated) and the rapakivis (Sederholm's fourth group): Block movements, presumably after the emplacement of these granites, raised some of the block so that also certain of the deep-seated granites of the rapakivitic magma are now to been seen on the present erosion niveau.

The various granites with a rapakivi texture evidently developed under quite different circumstances: shallow or deep-seated intrusions, anorogenic or orogenic rapakivis. It is highly improbable that the evolution leading to the rapakivi texture in each case was thoroughly identical. Thus also the interpretation hypotheses presented for the rapakivi texture of the South Greenland rapakivi cannot be applied as such to the rapakivi texture in the Wiborg massif. In the Wiborg massif the ovoidal potash feldspar crystallized before the groundmass was completely solidified (see Fig. 7). Thus the different hypotheses, so far as the ovoid potash feldspar is concerned, necessarily do not all contradict but, at least partly, supplement each other. In shallow intrusions, perhaps, the potash feldspar crystallized quickly at a comparatively early magmatic stage. This does not imply that the replacement phenomena should be absent. At deeper levels, where the deep-seated »rapakivis» lie, the stage at which the potash feldspar crystallized as ovoids possibly shifts gradually to a later stage during the consolidation of the magma, conceivably at last as a submagmatic crystallization from residual solutions, either in situ or in xenoliths, in the country rock, or in the already consolidated parts of the granite; thus the formation of the potash feldspar phenocrysts is metasomatic or autometasomatic. Certainly these processes — crystallization from granitic melt and autometasomatic replacement — both act during the crystallization of a single rapakivi magma body. At shallow levels, the residual liquids and, especially, the aqueous phase have a better change to escape during the crystallization than from magmas crystallizing at deeper levels in the earth's crust.

## *Application of experimental studies*

The texture of the rapakivi (wiborgite) shows that no overall equilibrium had been reached during the crystallization. Thus also the application of experimental phase-equilibrium relations in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-$CaAl_2Si_2O_8$-$SiO_2$-$H_2O$ (James and Hamilton 1969) imposes restrictions. The experimental work cited was



FIGS. 23 a—d. Rapakivi granites plotted on the $[Ab\text{-}Or\text{-}Q]_{100-x}An_x$ phase diagrams (under 1 kilobar water vapour pressure) of James and Hamilton, 1969.
a, solid boundaries, $x = 3$; broken boundaries, $x = 5$; composition points from Table 1.
b, $x$ as in a; composition points from literature.
c, solid boundaries, $x = 7.5$; broken boundaries, $x = 10$; composition points from Table 1.
d, $x$ as in c; composition points from literature.
The figures in the diagrams indicate the normative An-content for each specimen, Ab+Or+An+Q calculated as 100. 1, tirilite; 2, hornblende rapakivi; 3, dark and darkish wiborgite; 4, normal wiborgite; 5, pyterlite; 6, porphyritic rapakivi; 7, biotite rapakivi 8, porphyry aplite; 9, granite porphyry; 10, quartz-monzonite porphyry; 11, quartz porphyry. For more details see the text.

made under 1 kilobar water vapour pressure. Figs. 23a and b show the phase diagrams for the joins $[Ab\text{-}Or\text{-}Q]_{97}An_3$ and $[Ab\text{-}Or\text{-}Q]_{95}An_5$, Figs. 23c and d for the joins $[Ab\text{-}Or\text{-}Q]_{92.5}An_{7.5}$ and $[Ab\text{-}Or\text{-}Q]_{90}An_{10}$ at 1 kilobar $P_{H_2O}$. The composition points from the chemically analysed samples in Table 1 are plotted in Figures 23a and c, and those from the literature ¹) of the Wiborg massif in Figures 23b and d. The figures show that:

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¹) Hackman 1905, 1934; Wahl 1925, 1938; Savolahti 1956.

- The composition points representing the wiborgites, the typical rapakivi, lie in the plagioclase field (with one exception), indicating that the plagioclase in the wiborgite began to crystallize before the potash feldspar. A corresponding conclusion was drawn by Stewart (1959).
- Tirilite, hornblende rapakivi, Sinkko granite, quartz-monzonite porphyry, granite porphyry, all with scattered wiborgitic and/or pyterlitic ovoids fall into the plagioclase field.
- Pyterlites, i.e., rapakivis without plagioclase mantles around the potash feldspar ovoids fall into the quartz field or near the quartz-potash feldspar boundary in the potash feldspar field. The margination texture in the pyterlite evidently is due to the beginning of crystallization of the quartz before the potash feldspar.
- Porphyritic granites fall into the plagioclase field near the isobaric minimum.
- Even-grained biotite granites fall into the potash feldspar field, in one case in the quartz field.
- Porphyry aplites, represented only by two analyses, fall into the potash feldpar field, near the isobaric minimum.
- Quartz porphyries, also represented by two specimens, fall 1, into the quartz field, and 2, into the potash feldspar field quite close to the quartz-potash feldspar boundary.

Practically all the rapakivis with a rapakivi texture (with wiborgitic ovoids) are plotted in the plagioclase field (the two porphyry aplites and one dark wiborgite being exceptions); i.e., the crystallization of the plagioclase started before that of the potash feldspar. Practically all the rapakivis without a rapakivi texture fall into either the quartz field or the potash feldspar field. This convincingly proves that the rapakivi texture in the Wiborg massif does not originate through the simple mechanism proposed by., e.g., Savolahti (1956, 1962), Tuttle and Bowen (1958) and Sviridenko (1968), but has a more complicated origin. The relations presented in Figs. 25a—d are in agreement with Stewart's theory (1959).

Studying the granitic system, v. Platen (1965) experimentally demonstrated that in the system Or-Ab-Q at 2 000 bar $P_{H_2O}$ pressure with a constant Ab/An ratio, the eutectic point changes towards the Or corner when the acidity of the fluid phase increases. At the same time, both the eutectic temperature and the potash feldspar field descrease. The rapakivi granites are unusually rich in fluorite (see, e.g., the analyses in Table 1 for F). An HF content in the magma moves the Or-Ab-Q minimum in Figs. 25 a—c nearer to the Or corner, thus decreasing the potash feldspar field. This also brings it about that possibly all the pyterlite composition points fall into the quartz field.

A feature regarded as characteristic of rapakivi granites has been their assumed crystallization from a dry magma. This is, e.g., reflected in the scantiness of rapakivi pegmatites. But this theory of crystallization from a dry magma cannot be taken for granted. The presence of miarolitic cavities in rapakivi granites proves that the consolidating magma contained a volatile phase: presumably at a considerably low confining pressure. The high concentration of fluorine in itself gives a clue to the fact that at least certain rapakivi varieties have crystallized from melts rich in volatiles. Sahama (1945) reports that the standard mixture of eastern Fennoscandian rapakivi granites contains 0.36 % F, 0.06 % Cl, 0.05 % S and 0.05 % $CO_2$. Sahama also emphasizes (*op.cit.*, p. 63) that: »When compared with other granitic rocks the rapakivi granites — as already previously known — contain more $SiO_2$ and $K_2O$, and less MgO, CaO, as well as $Al_2O_3$.» This scantiness of $Al_2O_3$ is reflected also in the weight norms of Table 1 of the present paper. There are more analyses showing wollastonite in their norms than those showing corundum. This means that, on the average, rapakivi granites contain an excess of alkalies as against that of feldspar. This excess of alkalies as alkali silicate is concentrated with volatiles in the liquid phase during crystallization. Tuttle and Bowen (1958, pp. 85—87) investigated the system $K_2O$-$Al_2O_3$-$SiO_2$-$H_2O$ in the presence of water vapour at a pressure of 1 000 kg/cm². The orthoclase-quartz eutectic appears in the system as a maximum on the boundary between the quartz and orthoclase fields (760°C). The boundary between the quartz and orthoclase fields falls on the potassium side to temperatures below 400°C, and reaches compositions of nearly pure potassium silicate, the liquid probably containg more than 30 % water. The system $Na_2O$-$Al_2O_3$-$SiO_2$-$H_2O$ is probably similar to the foregoing. Also in it the presence of water will give rise to very low melting mixtures if more sodium is present than is required to combine with all the alumina to form albite (Tuttle and Bowen 1958, p. 87).

Thus, theoretically, the rapakivitic magma should produce a hydrous liquid, which would continue to crystallize at temperatures below 400°C, and also be able to produce autometasomatic processes in the rapakivi granite itself and metasomatic processes in the country rocks and in the xenoliths. The replacement of plagioclase by alkali feldspar in even-grained rapakivi granites, as described on p. 38, presumably is an example of this process. Another example of this process evidently is the micrographic intergrowth of quartz with alkali feldspar in the groundmass of certain rapakivi varieties and also in the marginal parts of some phenocrysts and ovoids. The graphic texture is restricted to only some rapakivi varieties. This texture is absent from e.g., the tirilite—Lappee granite—Sinkko granite series.

The graphic texture of the rapakivi granites has been interpreted as a eutectic fabric originating from a simultaneous growth of potash feldspar and quartz (Eskola 1928). Sloemer (1962) obtained a graphic texture by crystallizing glass (75%Or, 25 % Q) under hydrothermal conditions between 300° and 450° at pressures up to 450 atm $H_2O$. His experiments also show that it is possible to generate structures similar to those of graphic granite by metasomatosis (orthoclase with metasomatic quartz infiltration).

In different rapakivi granite varieties, there is a correlation between the occurrence of porphyritic or ovoidal texture and graphic texture (*cf.*, Eskola 1928, p. 13). The action of volatiles favours both the growth of a porphyritic texture i.e., rapid crystallization when the diffusion rate is increased by volatiles, and the growth of a graphic texture, i.e., a simultaneous crystallization of potash feldspar and quartz from the water-rich liquid phase. Also a correlation is easily found between the action of volatiles and the perthitic texture as well as the ordering of alkali feldspar, to be discussed later.

### *Intrusive phases*

The first intrusion phase is represented by the rapakivi varieties in the surroundings of Lappeenranta, i.e., the series tirilite (Ia)—Lappee granite (II)—Sinkko granite (Vb). Potash feldspar ovoids are only rarely encountered. Micrographic texture is not met with. The intrusion evidently involved a comparatively dry magma. Rapid crystallization at high temperature in a narrow temperature range is conjectured. Perhaps the process approached isothermal polybaric crystallization. This intrusion phase was characterized by a very small amount of residual volatile-rich liquid.

The second intrusion phase is represented by the major rapakivi granites: dark and darkish wiborgite—normal wiborgite—hornblende rapakivi—pyterlite/porphyritic rapakivi—biotite rapakivi/porphyry aplite—dike rocks. This series is characterized by rapakivi texture in the Ca-rich members. Graphic texture is often present. A moderately rapid crystallization from a magma containing more volatiles than the foregoing at quite high temperatures took place in a quite broad temperature range. The crystallization was evidently more isobaric polythermal than in the first phase. This one was evidently characterized by quite large amounts of residual liquids, from which the graphic groundmass crystallized.

The third intrusion phase is represented by, e.g., the Jaala—Iitti dike (pp. 7 and 10; Ic and II), possibly also by the tirilites (Ib) in the islands in the Gulf of Finland. During the crystallization, the magma presumably was quite variable with respect to the water-vapour pressure and that of other volatiles. At certain stages the crystallization was quite rapid. The whole crystallization process evidently took place in a broad temperature range. Graphic texture pervades the Ib-type tirilites with scattered ovoids, as also the rocks of the Jaala—Iitti dike. At the stage when the magma producing the Jaala—Iitti dike rocks intruded, some of its extensions might have reached the earth's surface. If so, the dike acted as a ventilator for over-pressure. As long as this action lasted, the crystallization was isobaric polythermal. When the gases could no longer escape, owing to the increasing viscosity of the magma, which was capable of plugging the channel, the pressure increased and the crystallization halted until the temperature dropped sufficiently to allow further crystallization to take place. It may be that the pressure increased to the extent that it was able to work a new over-pressure valve: a new, sudden escape of volatiles, triggering a sudden increase in the crystallization rate. This process could be repeated several times and

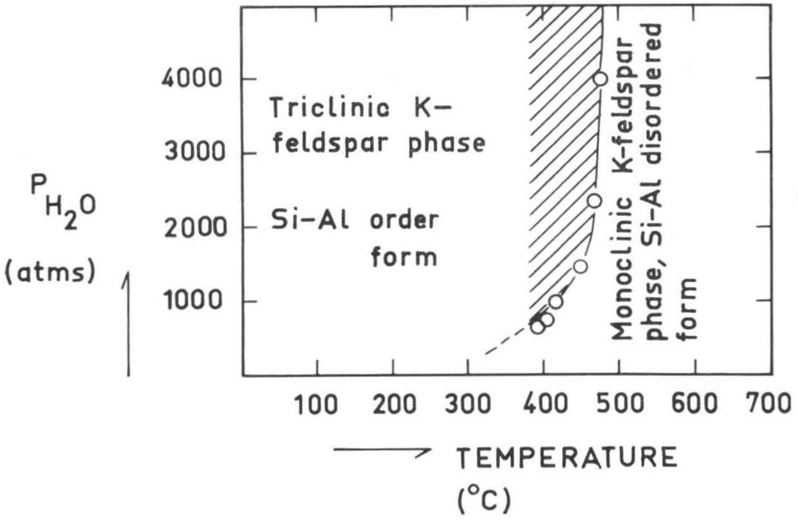

FIG. 24. The temperature-pressure diagram showing the stability relations of monoclinic-triclinic potassium feldspars according to Tomisaka (1962). The hatched area represents the P—T range where the transition from the triclinic to the monoclinic phase is possible. No appreciable transition takes place when there is no water vapour, although the high would be a thermodynamically stable one.

produce both corona textures (e.g., hornblende seams around idiomorphic quartz phenocrysts), resorption and all the other signs of mineral disequilibrium present in these rocks.

The quartz porphyry dikes (see p. 13), both in the rapakivi area and also cutting the country rocks, belong either to the third intrusion phase or, more likely, represent even a later stage. Quartz, alkali feldspar and plagioclase grew as phenocrysts either before the emplacement of the quartz porphyry or, then, crystallized from a hydrous melt after the emplacement. The latter case seems less plausible. In the first case, the temperature should have fallen sufficiently before the emplacement to enable the transformation of the orthoclase into microcline. Since the comparatively low temperature required in this event can be reached only in systems rich in $H_2O$ (and deficient in $Al_2O_3$), one should assume a water-vapour pressure of 1—3 kilobar. Tomisaka (1962) demonstrated that the microline-orthoclase inversion under a water-vapour pressure of 4 000 atm takes place at about 470°C, of 2 400 atm at about 460°C and of 1 500 atm at about 450°C (see Fig. 24). The second case is that a completely molten hydrous magma filled the joint but at the very beginning of crystallization the volatiles were prevented from escaping. Orthoclase, quartz and plagioclase phenocrysts crystallized. The temperature dropped close to 400°C and the orthoclase inverted into microcline. If the volatiles were prevented from escaping, the water-vapour pressure increased. At last, the pressure exceeded the level needed for the volatiles to break an »over-pressure valve». A sudden decrease in volatile pressure ensued. In both cases, the groundmass either crystallized suddenly at temperatures below the orthoclase microcline inversion temperature or vitrified at a somewhat higher temperature. Owing to the rapid crystallization or devitrification, the potash feldspar grew in the disordered form. Evidently, the spherulitic groundmass orthoclase developed in this way and was preserved metastably because the crystallization or devitrification producing spherulitic alkali feldspar took place below the temperature at which ordering can take place. The proposed mechanism also explains the lower thermal state of the phenocrysts as compared with the groundmass alkali feldspar.

## SUMMARY ON THE FACTORS AFFECTING ORDERING IN RAPAKIVI GRANITE ALKALI FELDSPARS

Even though the crystallization of rapakivi melt is not yet fully known in detail, it is possible to correlate the obliquity of potash feldspar, the grade of exsolution in alkali feldspar and the difference in thermal state between the alkali feldspar in ovoids and in the groundmass to the crystallization scheme outlined in the preceding chapter.

The ordering of Al/Si in alkali-feldspar and the exsolution are two simultaneous processes in rapakivi granites. If one assumes the presence of volatiles as being the catalyzing agent at the stage when ordering and exsolution take place, it fits perfectly in the crystallization scheme. The rocks of the first intrusion phase, especially the tirilites, possibly formed by isothermal polybaric crystallization at high temperatures in a dry magma. When the temperature dropped low enough for orthoclase-microcline inversion (c. 400°C), the whole rock presumably was already solidified. Most of the volatiles had escaped before this stage, and the ordering of the potash feldspar was thus exceedingly sluggish and only locally reached a higher degree. The weakly developed perthite texture, especially in the tirilitic varieties, evidently also can be attributed to the scantiness of volatiles and to the absence of their catalyzing action from the exsolution process.

The occurrence of both the albite-twinned and the pericline-twinned sodic phase in perthite in the high thermal state (anorthoclase) also can be attributed to the scantiness of catalyzing volatiles at temperatures when the segregation took place.

In the complex second phase, the major intrusion phase, also the interdependence between the action of the vapour phase and the ordering and the exsolution in alkali feldspar can be noticed. The obliquity of alkali feldspar increases in the series dark-coloured wiborgite—wiborgite—porphyritic rapakivi/pyterlite—biotite rapakivi simultaneously with the increase of the coarseness of the perthite texture. In the same series, the albite phase of perthite also changes from a high thermal state to a low one. On the average, the potash feldspar in the ovoids shows a slightly higher thermal state than in the groundmass. At least part of the ovoids are assumed to have grown during the magmatic stage, the potash feldspar in the groundmass — especially when graphically intergrown with quartz — having presumably crystallized from a hydrous magma. The groundmass potash feldspar certainly had originally been monoclinic, but the ovoid potash feldspar, crystallizing at higher temperatures, was presumably more disordered (sanidine) than the groundmass potash feldspar. Under the catalyzing influence of the volatiles, the ordering process was longer in the ovoids than in the groundmass potash feldspar. When the rock was so cool that no further ordering could take place, the groundmass potash feldspar had reached a higher order than the potash feldspar in the ovoids. This is all in accordance with the proposition of a moderately rapid crystallization of the alkali feldspar beginning at high temperatures and taking place in a quite broad temperature range. The action of volatiles is stronger in the more acid members of this intrusion phase.

In both the dark wiborgite and the normal wiborgite, the typical rapakivi texture is well developed. The dark wiborgite, on the average, has crystallized from a somewhat more basic magma than the normal wiborgite, possibly owing to the contamination of the former. Both the phenocryst alkali feldspar and the groundmass alkali feldspar in the dark wiborgite have preserved their monoclinic disordered state better than have those of the normal wiborgite. The bulk chemical composition of the alkali feldspar in the dark wiborgite may be richer in sodium than that of normal wiborgite (see Table 2). Yet, the analytical results do not necessarily reflect the original bulk composition, because of the possibly imperfect homogenization of the more triclinic alkali feldspar. If these do, however, reflect the original bulk composition, it may be readily seen that the groundmass alkali feldspar and the phenocryst alkali feldspar in the dark wiborgites are similar to both the composition and the thermal state. In the normal wiborgite, the bulk composition of the ovoids is the same as in the dark variety but the thermal state is slightly lower. The groundmass alkali feldspar is considerably richer in the Or component than the ovoids, and also the thermal state in the groundmass alkali feldspar is lower.

It may be that one of the agents regulating the ordering of Al/Si during the cooling of the rapakivi granite is the bulk chemical composition of the alkali feldspar. In the alkali feldspar richer in Or, the ordering thus should take place more easily than in the alkali feldspar richer in Ab, as discussed by, e.g., Smith and MacKenzie 1961. This relation was found to exist in nature by, e.g., Wright 1964 in the Tatoosh Pluton (Washington) alkali feldspars. In plutons with suggested complex histories, the situation can be the reverse, as in Rader Greek Pluton, Boulder Batholith, Montana (Tilling 1968) where the bulk compositions of alkali feldspar are more potassic in the orthoclase zone than elsewhere, e.g., in the intermediate microcline zone. During the formation of normal wiborgite, the volatile pressure evidently was higher than during the formation of dark and darkish wiborgites. This difference is clearly marked in the accessory mineral composition. Fluorite is very seldom met with in dark wiborgite, but, in normal wiborgite it is an invariable constituent. This strongly indicates that volatiles have been the catalyzing agent in the ordering process of potash feldspar during the cooling of the crystallizing magma, and the difference in the potash feldspar bulk composition thus plays only a minor role in the process.

The third intrusion phase can be interpreted by analogy with the second phase. The ordering process in the dike rocks calls for some attention. All the dike rocks show high triclinicity values, both in the groundmass potash feldspar and in the phenocrysts. Evidently, they crystallized from a water-rich melt, some from hydrous residual liquids. The crystallization produced monoclinic alkali feldspar. At the stage of the dike rock intrusions, the country rocks, both rapakivitic and older nonrapakivitic ones, were still warm; conceivably the temperature in the nonrapakivitic country rocks likewise exceeded 400°C. A sudden release of the vapour phase and a more rapid crystallization of the groundmass was more probable in the dikes than in the rapakivi proper. Thus ther thermal history of the potash feldspar of the dike rocks also in some cases is different from that of the feldspar in massive rapakivi. A good example of this is the quartz porphyry dike described on p. 66. In addition, the groundmass potash feldspar in quartz porphyry samples 99/AV/58 and 18/AS/56 is the only one, among the samples investigated, whose thermal state was originally, during the event of crystallization, somewhat lower than that represented by the reflection type I, in Table 2. Moreover, at the stage when the quartz porphyry dikes were emplaced, presumably both the rapakivitic and the nonrapakivitic country rocks were cooler than they had been at the stage of the granite porphyry and aplite intrusions.

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