5. The Hällefors dolerite dike and some problems of basaltic rocks.

By

Torsten Krokström.

(With Pl. I.)

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Preface.

The field investigations for this paper were carried out mainly in the summer of 1932 and during a few shorter visits to the area in 1931 and 1933. The laboratory research was done in the Mineralogical and Geological Institution of the University of Upsala during the winters of 1933—1934 and 1934—1935. The final preparation of the paper was made in the autumn of 1935.

In presenting the results of my investigation I wish to express my gratitude to all those who have promoted my work. In the first place my most sincere thanks are due to my teacher and friend Professor H. G. BACKLUND, Director of the Upsala institution. During the years I have been working there, employed most of the time as assistant, he has displayed a never failing interest in my investigations and has greatly facilitated my work by placing at my disposal the excellent equipment of his institution, At any time ready to enter into a discussion, he has further by his vast experience been able to make valuable suggestions concerning the problems encountered in the course of my research. Finally, I am indebted to him for publishing my paper in the Bulletin of which he is the editor.

Dr. J. E. RICHEY and Dr. W. Q. KENNEDY of the Geological Survey of Scotland have most obligingly undertaken the tedious task of revising the manuscript from a linguistic point of view. It is a great pleasure to me to express my gratitude to them for this kind helpfulness and further to Dr. RICHEY for the great hospitality that I enjoyed in his home during a visit to Scotland in 1932. In that respect my thanks are also due to Professor E. B. BAILEY and Dr. G. W. TYRRELL of Glasgow University, who gave much valuable advice in planning my excursions to the tertiary intrusives of N.W. Scotland.

I am also indebted to my friend Dr. S. G. W. WAHLUND, Director of the Statistical Office of Stockholm, for a discussion in connection with the statistical treatment attempted on p. 151 ff.

The chemical analyses presented in this paper were executed with great skill by Dr. NAIMA SAHLBOM. The microscopical slides — about 200 in number — were prepared by Mr. A. R. ANDERSSON, Mr. E. KARLS-

SON, and Mr. W. PLAN. Finally, my wife helped to read the proof-sheets. To them all I wish to express my best thanks.

For financial support I am further indebted to the LILJEWALCH and LÄNGMAN foundations.

In the text below the numbers within round brackets refer to the list of references on p. 258 and to the page of the paper quoted respectively. The numbers within square brackets refer to specimens.

I. Methodological remarks.

A. Laboratory methods.

The refractive indices were determined on optically oriented thin sections by means of standardized liquids of immersion, the indices of which were, immediately after every determination, checked by the method of total reflection. The intervals of the liquid series were generally about 0.005, and, as the index to be determined could always be enclosed between two successive liquids, the error of measurement does not surpass ± 0.003.

The determinations of birefringence were made with the aid of a BEREK compensator, the thickness of the thin sections being directly measured with an ocular screw micrometer.

For works with the universal methods a FEDOROFF stage of LEITZ' construction was used. The determinations of optic axial angles were always carried out according to the universal methods, and, when not otherwise stated, the feldspar determinations were based on complete FEDOROFF stage measurements.

For the microphotographs, which were all made by the author, a micro-polarising apparatus of LEITZ' construction was used. Only for the photographs of Figs. 4 and 18 a Leica camera mounted directly on the microscope was made use of.

The specific gravities of the rocks analysed were determined with the aid of a WALKER-LA TOUCHE balance.

B. Some remarks concerning the interpretation of plagioclase determinations.

In estimating the modal mineral composition of a rock from its chemical analysis and by aid of the microscopical investigations, the plagioclase generally forms a very important basis for the calculation, as in most cases its chemical composition may be ascertained closely by the optical methods. There are, however, some difficulties in respect even to that method and they are connected with the potassium content of the plagioclase which must not be neglected. This potassium content cannot, so far, be determined by optical methods, but ALLING (1921, p. 249) on the basis of a comprehensive statistical study deduced the probable orthoclase content in plagioclases of different compositions. According to his results the average orthoclase percentage should be: in albite 6 %, in oligoclase 8 %, in andesine 7 %, in labradorite 6 %, in bytownite 4 %, and in anorthite 3 %. ALLING emphasizes that these values are not exact, but he considers — and rightly so — that they give a better approach to the real composition than would result if the potassium component were ignored altogether. The determinative curves of the plagioclases are, however, based on two components only, *viz.* anorthite and albite, and the question arises as to how the probable orthoclase content is to be fitted in. There are three possibilities:

1: The *anorthite* content indicated by the curves is accepted as the actual one. In that case the albite content is obtained by subtracting the probable orthoclase content from the remainder.

2: The *proportion* $Ab:An$ indicated by the curves is accepted as the actual one and the percentages found are recalculated on a sum = 100 minus the probable orthoclase content.

3: The *albite* content indicated by the curves is accepted as the actual one. In that case the anorthite content is obtained by subtracting the probable orthoclase content from the remainder.

It may appear that these details are of no practical importance, but an example will show that such an opinion cannot be justified. Suppose that a plagioclase has been determined as $Ab_{50}An_{50}$ by the aid of some optical method. According to ALLING it is likely to contain 6 % orthoclase silicate, and its actual composition will then be $Ab_{44}An_{50}Or_6$, $Ab_{47}An_{47}Or_6$ or $Ab_{50}An_{44}Or_6$ depending on which of the three methods of calculation is adopted. The consequence of such a difference in calculating a rock analysis will be readily realized, if we consider that in the two extreme cases the quotient $Ab:An$ will come out as *0.88* resp. *1.14*, that is, a difference of no less than *26 %* of the mean value.

From these considerations we find that it is quite necessary to decide how the calculation is to be made. ALLING points out emphatically that only the method given as no. 3 above is correct and, consequently, is of the opinion that the curves give an indication of the actual *albite* content. His reasons for this opinion are stated as follows: »An important fact, which needs to be emphasized, is that in using the conventional extinction curves of the text-books to determine the percentage of the soda component in a plagioclase, it is not possible to determine the percentage of the lime and potash members with anywhere near the same accuracy. The reason for this fact is that the isogonic lines are nearly parallel to the potash-soda side of the triangle» (*loc. cit.* p. 251). I must confess that I am at a loss to understand this argument. The very fact that the isogonic lines are parallel to the potash-soda side of the feldspar triangle must in my opinion lead to a conclusion contrary to that arrived at by ALLING, *viz.* that the extinction angles are almost entirely controlled by the anorthite content, whereas the mutual proportions of the alkali silicates are of very little influence.

As a matter of fact, however, a solution of this problem can hardly be arrived at by theoretical considerations. The point is simply to find on which basis the current determinative diagrams are founded. If they are constructed according to the anorthite content the values derived from them must indicate the actual anorthite percentage and *vice versa.* It has been pointed out by REINHARD (1931, p. 105) that these curves are often rather inaccurate, owing to the variable and unknown orthoclase content, but this fact does not affect the question now under consideration. The only way out is to scrutinize the original plagioclase analyses, upon which the curves are based, and in table I the most important of these are brought together. The table consists of four different parts. In the uppermost one the analyses are given and immediately below the proportions of feldspar silicates derived from them in using all CaO, Na_2O and K_2O available. In the third part these proportions are recalculated to a sum of 100, and, finally, at the bottom of the table the rests and deficiencies, that result from the calculation are listed. Notwithstanding a few minor irregularities, which will be considered below, it is quite evident that the anorthite percentages, with which the different feldspars have been plotted in the diagrams, are those actually found by analysis and not the sums of the anorthite and orthoclase contents, as argued by ALLING. Thus the fact should be stressed that the results gained from the common plagioclase curves indicate the *anorthite* percentage. If allowance shall be made for a certain orthoclase content it must be considered as replacing the albite.

A glance at the analytic material, listed below, is sufficient to bring out its heterogeneity, and in several cases it seems not to be quite reliable — a fact that was already emphasized by REINHARD (1931, p. 106). Nor does it appear that the anorthite percentages have been calculated in a uniform way, for one may observe that the »official» value may sometimes be in accordance with the value of the upper part of the table, sometimes with that of the middle part. It is true that this inconsistency, and also the fact that there is sometimes a slight deviation of the »official» value from that actually derived from the analysis, will hardly introduce any great error, as the deviations are, as a rule, fairly small. Nevertheless these details should be taken into consideration. The analysis XI of the table is of special interest, as its deviation from the theoretical feldspar com-

Table I.

Analyses and feldspar silicate proportions of the plagioclases on which the current curves of plagioclase determinations are based. See text above.

% An	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.
	0.5	5	12.5	13.5	20	25	35	51	56	73/75	97
SiO_2	68.41	68.96	64.75	64.75	62.60	62.58	59.98	56.18	54.55	48.94	43.34
Al_2O_3	19.80	20.26	22.25	23.56	23.52	24.15	24.67	27.33	28.68	33.26	35.31
CaO	0.08	1.05	2.67	2.84	4.47	5.05	7.26	10.33	11.23	15.20	19.93
Na_2O	11.17	9.89	10.17	9.04	8.62	8.42	7.04	5.17	4.62	3.30	0.39
K_2O	0.21	0.11	0.37	1.11	0.56	0.56	—	0.36	0.42	—	0.36
MgO	—	0.22	—	—	—	—	—	—	—	—	0.17
Fe_2O_3	—	0.23	—	—	0.08	1.10	0.54	1.38	1.03	—	0.65
	99.67	100.72	100.21	101.30	99.85	101.86	99.49	100.75	100.53	100.70	100.15
An	0.5	5.0	13.0	14.0	22.0	25.0	35.5	51.0	56.0	75.5	98.5
Ab	94.5	84.0	86.0	76.5	73.0	71.0	60.0	43.5	39.0	27.5	3.0
Or	1.0	0.5	2.0	6.5	3.5	3.5	—	2.0	2.0	—	2.0
An	0.5	6.0	13.0	14.5	22.5	25.0	37.5	53.0	57.5	73.0	95.0
Ab	98.5	93.5	85.0	78.5	74.0	71.5	62.5	45.0	40.0	27.0	3.0
Or	1.0	0.5	2.0	7.0	3.5	3.5	—	2.0	2.5	—	2.0
SiO_2	+2.64	+8.70	−1.38	+1.73	+0.78	+1.02	+3.60	+2.76	+2.46	−2.64	−2.88
Al_2O_3	+1.00	+1.90	+0.40	+2.20	+0.50	+0.60	—	−0.30	+0.30	+0.30	−1.63
Fe_2O_3	—	+0.23	—	—	+0.08	+1.10	+0.54	+1.38	+1.03	—	+0.65
MgO	—	+0.22	—	—	—	—	—	—	—	—	+0.17

I. Albite from Morro Velho. Analyst G. TSCHERMAK (TSCHERMAK 1903).
II. Albite from Amelia. Analyst ERBEN and CEIPEK (ERBEN and CEIPEK 1901).
III. Oligoclase-albite from Soboth. Analyst SMITA (BECKE 1901 p. 68).
IV. Oligoclase-albite from Wilmington. Analyst TECLU (BECKE 1901 p. 56).
V. Oligoclase from Bakersville. Analyst SPERRY (PENFIELD and SPERRY 1888 p. 325).
VI. Oligoclase from Twedestrand. Analyst TERTSCH (TERTSCH 1903 p. 169).
VII. Andesine from Hohenstein. Analyst GROSSPIETSCH (BECKE 1922 p. 32).
VIII. Labradorite from Labrador. Analyst CLEMENT (SCHUSTER 1881 p. 183).
IX. Labradorite from Kamenoi-Brod. Analyst SCHUSTER (*Ibidem* p. 184).
X. Bytownite from Naerödal. Analyst LUDWIG (*Ibidem* p. 203).
XI. Anorthite from Vesuvius. Analyst ROST-HOFFMAN (KRATZERT 1921 p. 487).

position is very conspicuous. The value *97 % An,* which is allotted to it in the text-books, was obtained by KRATZERT as a mean of the values which result, when the different oxides of the analysis are taken as basis for the calculation. These values vary from *94 %* to *100 %*, and KRATZERT gives the mean value of *97 %*. As, in the middle part of the table the analysis shows an albite percentage of *3.0*, this is the only case where one might suspect that the anorthite value was obtained by subtracting the albite percentage from 100. However, KRATZERT points out emphatically that in the calculation Na_2O and K_2O were taken together as one component in contrast to the lime molecule.

II. **Introduction. Earlier investigations in the area.**

The Hällefors dike is situated in the province of Södermanland in the southern part of Middle Sweden. It extends from the neighbourhood of Lake Nedingen in the parish of L. Mellösa in a westerly direction to the immediate vicinity of the great Lake Hjälmaren. Its total length is no less than 40 km., and its average width about one km. The western end of the dike is situated about 30 km. in a north-east direction from the eastern end of the Breven dike which has previously been investigated by me (KROKSTRÖM 1932 a). Both dikes strike east-west and are thus parallel to the great fault-lines of central Sweden. For about $^2/_3$ of its total length the dike falls within the geological map-sheet Hällefors (KUGELBERG 1864), the remaining westernmost part being found within the map-sheet Säfstaholm (SIDENBLADH 1864).

The part of the dike falling within the Hällefors sheet is everywhere very well exposed and also stands out fairly well in the topography. On the Säfstaholm sheet the exposures are generally rather scanty and, with the exception of the easternmost parts, they project only slightly above the general level of the country.

The dike was first mentioned in the literature by KUGELBERG and SIDENBLADH in the description of the above-mentioned geological map-sheets. They gave a rather summary description of the megascopical character of its rocks, stating only that they consisted mainly of augite, labradorite and chlorite with some titaniferous iron ore and sometimes apatite. A chemical analysis was given in each paper. KUGELBERG (*loc. cit.* p. 20) pointed out that the rock was generally coarse-grained, but that it sometimes exhibited a fine-grained development leading to a porphyritic texture, as the feldspars often retained their large size. He also recorded a characteristic jointing in some of the rocks.

In 1877 TÖRNEBOHM (1877, pp. 15—17) gave a somewhat more detailed description of the rocks and proposed the name »Helleforsdiabas». He seems to have paid attention only to the coarse types with abundant secondary chloritic matter, which are referred to below as Hällefors dolerite, and explicitly states that the name proposed should be attached only to these types. He seems to have considered the dike to be of a rather uniform composition and made no reference to the porphyritic types — nor did he mention the rather wide distribution of olivine dolerites of the Åsby type. On the contrary, he mentioned the discovery of a specimen with fresh olivine in such terms that it must be concluded that he considered it rather an exceptional occurrence. The microscopic description of the types studied is excellent, and in many cases I have only been able to confirm his statements. In a later paper (1882) he again mentioned the Hällefors dike, and spoke also of the porphyritic rocks, which he regarded as occupying marginal positions in the dike. This statement is altogether at variance with the actual relations and, as a matter of fact, one gets the impression from TÖRNEBOHM's treatise that he gained his experience mostly by microscopic investigations, but had very little opportunity of studying the field relations.

III. General petrological structure of the dike.

When trying to give a petrological description of the Hällefors dike, great difficulties are met with. As a matter of fact, only one of its many rock types may be considered as sufficiently well defined from a petrological point of view, *viz.* a typically ophitic dolerite of about the same characters as the Åsby dolerite of Dalecarlia. This type of rock, with a few exceptions, occupies the whole western part of the dike and farther eastwards it forms a fairly broad and surprisingly constant and unbroken zone, which always represents the outer boundaries of the dike (see map, Pl. I). Inwards it is almost everywhere substituted by a narrow zone of coarser grain, the rocks of which show unmistakeable affinities to those of the outer zone and in spite of some minor deviations (see p. 143) must be considered as belonging to the same main group. At a few localities (see p. 144) the actual boundary between the two types is exposed, and the contact is so sharp and well defined that we are forced to postulate two different intrusions having taken place in rapid succession. Quantitatively these two types of marginal dolerites may occupy about ²/₃ of the present area of the dike.

The area inside these rocks is extremely complicated in structure. In the easternmost parts it is almost exclusively occupied by a rock that I have named Hällefors dolerite — which is quite in accordance with TÖRNEBOHM's proposal — and which in spite of great variations may well be dealt with as a unit. In the middle parts, however, a great many transitional types come in, leading in their extreme development to markedly porphyritic rocks. The mutual relations of these — the Hällefors porphyrites — and the Hällefors dolerites are practically impossible to decipher, as will be evident from the detailed description. In all probability, however, the porphyrites and the Hällefors dolerites represent extreme members of the same rock series. The relations are still further obscured by strong alterations of a late magmatic kind that have mainly affected the porphyrites, giving rise to albitic rocks, but which may be traced sometimes also in the Hällefors dolerites.

In accordance with the general structural arrangement outlined above, the results of the investigation are presented as follows. Firstly, the marginal dolerite together with its contact modifications and some exceptional types belonging to the same group are described. Secondly, a general description of the Hällefors dolerites and porphyrites is attempted, and the effects of late magmatic alterations are discussed. After a description of some peculiar rocks of more restricted occurrence the mutual field relations of the main types are outlined and a few conclusions are drawn as to the probable mode of intrusion of the dike. With reference to the petrological and chemical data a general discussion of the magmatic evolution is given and further a comparison of the Breven and Hällefors dikes is attempted. The treatise is concluded by a chapter on faulting zones within the dike and a few words on the age relations of the great dike-intrusions of Middle Sweden.

IV. **Petrological description.**

A. **The marginal series.**

a. **The mottled dolerite.**

1. Normal development.

Megascopically the predominant type of the marginal dolerite shows a very characteristic black-and-white mottling (Fig. 1) caused by the strong contrast between the dark mafic minerals and the plagioclase which has in these rocks lost its fresh greenish colour and assumed a dull white one.

The following minerals are encountered: *Labradorite, olivine* or *olivine pseudomorphs, pyroxene, diabantite, titaniferous iron ore, amphibole, biotite, apatite, alkali-feldspar, chlorite, quartz, prehnite, zoisite, sericite.*

In order to get an estimate of the mutual proportions of the main minerals, several geometrical analyses were executed, but the results were very different in different slides. The only proportion that seems to be fairly constant is that of *plagioclase: mafic minerals*, which always comes out about *2:1*. The proportion *olivine: pyroxene* on the other hand varies within very wide limits and in several thin sections no olivine or olivine pseudomorphs whatever can be detected although olivine is readily distinguished by the naked eye in the corresponding hand specimens. This must, however, be considered almost as a characteristic of all typically ophitic dolerites. As the pyroxene forms large plates, often extending over the area of an entire thin section, the olivine grains cluster outside the pyroxene areas and thus they display a somewhat irregular distribution in the rock. This dualism between pyroxene and olivine may be observed in most slides made from these rocks and is most probably the cause of the extremely varying proportions of the dark minerals obtained in the geometrical analyses. It should be pointed out that exactly the same phenomenon was described by me in the case of the Breven olivine dolerite (KROKSTRÖM 1932 a, p. 253—254).

Plagioclase.

The plagioclase forms radially divergent laths, the dimensions of which may vary a little in different thin sections, but on an average they attain a length of 2—3 mm. Occasionally some larger feldspar laths (6—8 mm.) may occur, giving the rock a somewhat porphyritic appearance.

A polysynthetic twinning according to the Carlsbad and Albite laws is always prominent and in some cases also pericline twins are observed. Zoning is very inconspicuous, and when present it is rarely of the discontinuous type but is, as a rule, represented by an undulose extinction, indicating a continuous variation within the crystal.

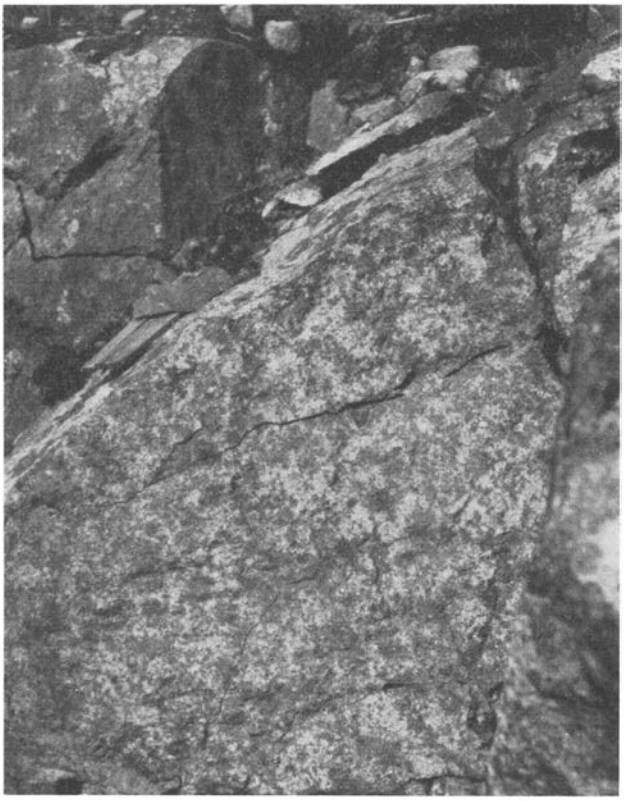


Photo by the author.

Fig. 1. Exposure of mottled dolerite, S. of Hälleforsnäs. The outcroup has a height of about 2 m.

The composition of the plagioclase has been ascertained from the mean value of a large number of measurements in several slides to be:

$$Ab_{35}\,An_{65}.$$

The porphyritic crystals referred to above, however, generally show a somewhat higher anorthite content, attaining values of *70—75 % An.* A fuller treatise of the compositional variations of the feldspar is given on p. 151 ff.

The plagioclase has very often been subjected to several kinds of alteration, giving rise to the dull white colour observed in hand specimen. The alterations consist mainly of a strong zoisitization, generally accompanied by less marked sericitization. Alteration to *prehnite* is less common, but where it occurs it may have a very wide distribution. The intensity of the saussuritic alteration varies from place to place and, apparently, the variation is quite irregular. Moreover, in the same thin section one portion of the slide may show an entirely limpid plagioclase of great freshness, whereas in adjoining areas the same mineral may be intensely altered to an aggregate of *zoisite* and *sericite.* Of course, the zoisitization implies a considerable lowering of the anorthite content, but it was not possible to ascertain to what extent, as only the fresh sections allow of quantitative measurements. It is very difficult to find any regularity in the distribution of the altered portions over the thin sections. Very often, however, it seems as if the alteration has proceeded further within the areas dominated by pyroxene than in the olivine-bearing parts (*cf.* above). One possible explanation of this fact may be that the olivine-plagioclase portions of the rock represent the earliest consolidation, whereas the plagioclase of the pyroxene fields was surrounded for some appreciable time by the melt from which the pyroxene was generated. The plagioclase laths associated with the olivine were, therefore, protected from the influence of the melt at a rather early stage. In some cases, however, not even this rule of distribution seems to hold good.

Prehnitization to any appreciable extent was observed only in four slides [20, 86, 195, 271]. In a way it seems to be a substitute for the sericitization and generally it is confined to the vicinity of certain veins that penetrate the rock and are themselves filled with prehnite. Within these parts the alteration is often so strong that practically all plagioclase is replaced by prehnite individuals, attaining a diameter of as much as 2 mm. These large prehnite grains very often show a beautiful fan-structure. In one of the veins mentioned above the prehnite shows well-developed spherulitic structure. It seems very probable that the formation of prehnite, in contrast to the more general and irregularly distributed sericitization, is caused by some late solutions or gases percolating through the rock during the hydrothermal period, and that its distribution is controlled by the paths of these solutions or gases.

Still another type of plagioclase alteration will be described later on (p. 134) in connection with the iron ore.

Pyroxene.

Only clinopyroxene is observed. It is colourless or of a faint brownish gray hue. The variation of its optical properties will be treated on pp. 154—156 and in Table II only the extreme and mean values are given:

Table II.

Optical properties of the pyroxene of the mottled dolerite.

	$2V_\gamma$	c/γ	$N_\gamma - N_\alpha$	$N_\gamma - N_\beta$
Extreme values	41°—59°	36°—46°	0.019—0.029	0.015—0.023
Mean	49°	42°	0.025	0.020

The refractive indices of one individual were also measured, the complete result of the optical determination being:

$2V_\gamma = 47°$
$c/\gamma = 43°$
$N_\gamma = 1.695 \pm 0.003$
$N_\alpha = 1.670 \pm 0.003$
$N_\beta = 1.674$ (calculated)
$N_\gamma - N_\alpha = 0.025 \pm 0.006$ (calculated)
$N_\gamma - N_\beta = 0.021$ (calculated)

In order to get a view of the general chemical character of the pyroxene the results of those optical determinations that yielded both $2V_\gamma$ and c/γ were superimposed upon the determinative diagram devised by WINCHELL (1935 p. 567). The number of measurements available was 36. Six of them do not fit the curves of the diagram — probably because of errors in the determination of c/γ. Of the remaining 30 no less than 28 fall within the area indicated in Fig. 2, with a very strong concentration (25 observations) in the hatched part of it. One observation falls some distance outside the area in the hedenbergite direction, while the last one falls exactly on the diopside-hedenbergite line close to the diopside end. To judge from the projected points the pyroxene of this rock tends to approach the composition of the pigeonitic types. As will be seen later on (p. 137), however, there is reason to doubt the validity of this conclusion.

In most cases the pyroxene is remarkably fresh, only a narrow amphibole fringe, bordering a few grains, being generally observed. This amphibole, which surrounds the pyroxene in a homoaxial position, represents an actinolitic hornblende with the following optical properties:

$c/\gamma = 17°$
γ *pale green*
β *paler green*
α *colourless.*

Sometimes the amphibole may be associated with some colourless or faintly green chlorite and in one case (specimen 261) it shows pleochroism in brown colours, no more detailed investigation being possible on account of the small size of the grains.

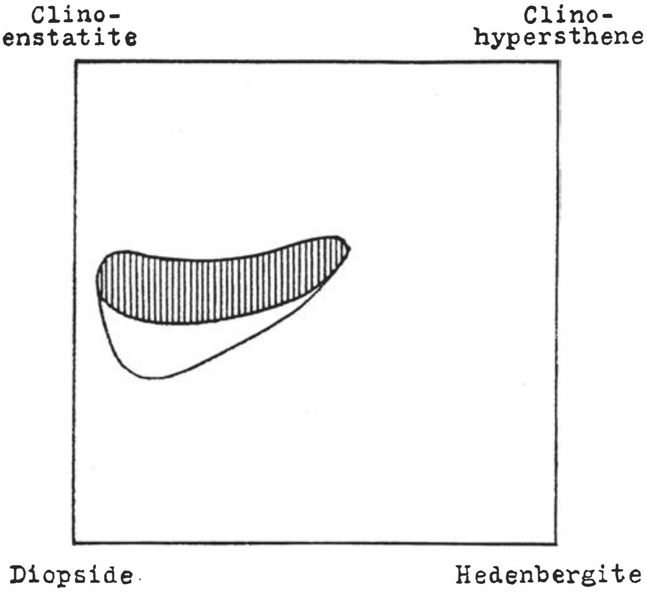


Fig. 2. For explanation see text.

Concerning some problematic secondary products which may have originated partly from pyroxene, the reader is referred to the discussion of the olivine pseudomorphs on p. 131.

Olivine.

Olivine is a characteristic mineral of the marginal dolerite. Its optical variations are treated on pp. 153—154 and here only the extreme and mean values are given:

$2V_\alpha = 72° - 82°$. *Mean value:* $2V_\alpha = 78°$.

The composition indicated by these angles is *49—29 % fayalite* according to BACKLUND (1909) or *54—26 % of fayalite* according to WINCHELL (1927 p. 168), the mean being *37* and *40 %* respectively.

The irregular distribution of olivine in the rock has already been discussed. Concerning the occurrence of the mineral it need only be added that it may sometimes exhibit ophitic relations to the plagioclase (Fig. 3). In these cases, however, the boundaries between the two minerals show very seldom, if ever, the distinct rectilinear shape, characteristic of the corresponding intergrowths of plagioclase and pyroxene. On the contrary, they exhibit a slight convexity against the plagioclase, giving the impression that the two minerals crystallized in a struggle for space. Furthermore the plagioclase laths enclosed by olivine are smaller than those which penetrate the pyroxene plates, and when a lath enters into an adjacent olivine it is, as a rule, seen to wedge out towards the central portion of the enclosing mineral. This phenomenon is very seldom observed in the pyroxenes. We may infer from these facts that the olivine, as a rule, crystallized in advance of the plagioclase, but that sometimes part of the latter might have solidified even before the olivine had begun its crystallization. For the most part the two minerals, however, crystallized simultaneously and later on the olivine was succeeded by pyroxene as a representative of the mafic crystallization.

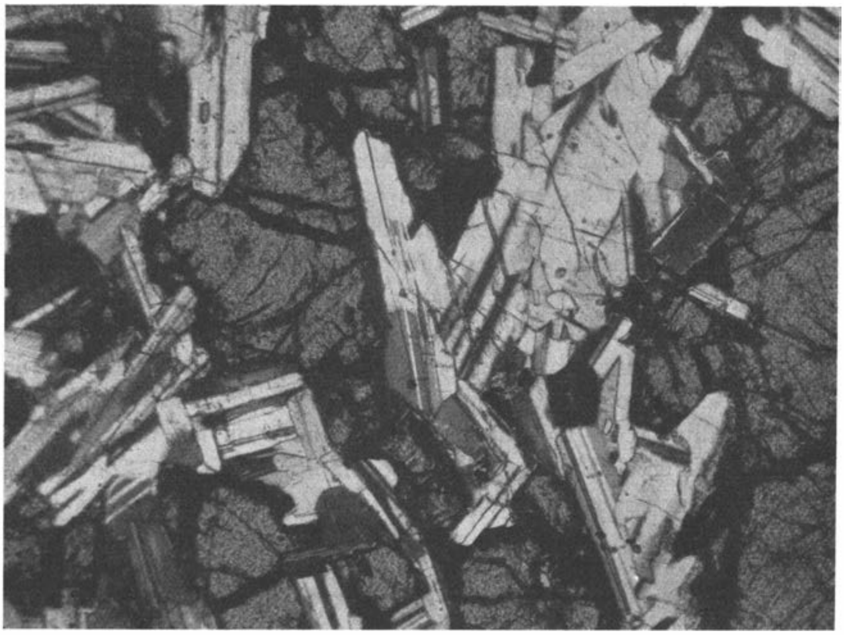


Fig. 3. Olivine and plagioclase with ophitic relations. Specimen 196, nicols +. Magnification 40 diameters.

The olivine is generally rather strongly altered and one can hardly find a single thin section where it has not given rise to secondary products of various kinds. It may be observed comparatively well preserved in those marginal portions of the dike where strong alteration has not been caused by assimilation (see p. 138 ff.). The secondary processes seem to proceed in several different stages, the first always being represented by aggregates of *talc* crowded with small grains of *iron ore*. Possibly some *chlorite* may also enter into these aggregates. Very soon, however, numerous needles and plates of a colourless *actinolitic hornblende* are developed at the expense of the talc and part of the iron ore. They are scattered irregularly throughout small rounded patches. These aggregates constitute the commonest pseudomorphs of olivine in these rocks and have been described by me already from the Breven dike (KROKSTRÖM 1932 a, p. 266 and fig. 11 on p. 268). They seem to be identical with the *pilite* described by BECKE (1893, p. 163) and as in the latter case some chlorite may often be observed between the amphibole needles. These pseudomorphs are sometimes, although not invariably, crowded with grains of iron ore. Such variations are not surprising, as the type of alteration depends on several different factors (the iron content of the original olivine, the iron content of the amphibole, the relative quantities of amphibole, chlorite *etc.*). It presents no great difficulty, however, to picture the process stoichiometrically. The first simple alteration of olivine to talc and iron ore is readily effected by the aid of the omnipresent silica and an oxidation process, which is a necessary condition for the formation of iron ore from olivine. The process may be represented by the following equation:

$$\underset{\text{olivine}}{6\ \mathrm{MgFeSiO_4}} + 2\ \mathrm{SiO_2} + 2\ \mathrm{H_2O} + 3\ \mathrm{O} = \underset{\text{talc}}{2\ \mathrm{H_2Mg_3\,(SiO_3)_4}} + \underset{\text{iron ore}}{3\ \mathrm{Fe_2O_3}}$$

In this equation, for the sake of simplicity, the fayalite content of the olivine is assumed to be 50 %. Any other composition adopted will only affect the relative quantities of talc and iron ore produced and the amount of silica necessary to effect the reaction.

The later stages of the alteration — the formation of actinolite — require the presence of a component that is not so easily obtained as silica, *viz.* lime. The only available source of CaO is the surrounding plagioclase and in the vicinity of the actinolite aggregates this mineral is everywhere dissected by numerous chlorite-filled veins, indicating an exchange of material between the feldspars and the pseudomorphs. As chlorite is rather ill-defined, chemically, and is, moreover, of a very complex constitution, it is not easy to illustrate stoichiometrically the course of this exchange. Following WINCHELL we will assume that chlorite represents an isomorphous mixture of the four components antigorite, iron-antigorite, amesite, and daphnite, and on that assumption a general equation may be derived as follows:

$$\underset{\text{olivine}}{(m+3\,n)R_2SiO_4} + \underset{\text{anorthite}}{m\,CaAl_2Si_2O_8} = \underbrace{\underset{\text{amesite, daphnite}}{m\,(2\,RO\cdot SiO_2\cdot Al_2O_3)} + \underset{\text{(iron-)antigorite}}{2\,n\,(3\,RO\cdot 2\,SiO_2)}}_{\text{chlorite}} + m\,CaO + (2\,m-n)\;SiO_2;$$

Thus by interaction between olivine and plagioclase the anorthite content of the latter is utilized in the formation of chlorite and simultaneously lime and silica are set free. By a change in the coefficients of the equation the composition of the chlorite as well as the relative quantities of the liberated elements may be varied within certain limits.

Lime is therefore readily accessible, and there are no further difficulties in the way of explaining the formation of actinolite:

$$\underset{\text{olivine}}{3\,R_2SiO_4} + 2\,CaO + 5\,SiO_2 = \underset{\text{actinolite}}{2\,Ca(R)Si_2O_6\cdot RSiO_3};$$

It will be easily understood from the equations that a very marked variation in the mutual quantitative relations of the different secondary products must arise, when the different processes of alteration happen to interfere with each other.

It appears, however, that in this series of alteration processes still another stage may be detected, leading to the formation of a rather problematic mineral which occurs abundantly in all these rocks. In all probability it should be classed as an iron-rich chlorite. Before discussing the mutual relations between this mineral and olivine it seems appropriate to give a description of its occurrence and properties.

As a rule the mineral occurs in fairly large individuals (up to 2 mm. in size) which are sometimes of a rounded form, but very often their outer boundaries are completely determined by the plagioclase laths, the mineral exhibiting exactly the same textural relations as the ophitic pyroxene. The optical properties vary rather widely from one slide to another, but the variation appears to be continuous and it can hardly be doubted that the different individuals belong to the same mineral series. The most conspicuous feature of the mineral is a very marked watered or creasy structure appearing in practically all individuals. It is difficult to give an adequate description, but very often one gets the impression that the mineral was formed by recrystallization of some fibrous mineral aggregate, the structure of which may still be traced in the pseudomorph. This impression is further accentuated by numerous thin needles of amphibole which are usually scattered all over the mineral and which, by reason of their curved shape, tend to emphasize still more the peculiar structure referred to above.

The mineral shows a good micaceous cleavage and exhibits the usual optical orientation of the micas. Thus the extinction is parallel, with α perpendicular to the cleavage. The optic axial angle is small and negative, often practically nil and very seldom exceeding 10°. The pleochroism is always distinct though of varying strength, α being always *colourless*, γ varying between a very *faint green* and a *deep green* colour, and β occupying an intermediate position. The double refraction, too, varies within wide limits. Often it hardly exceeds 0.005 whereas in some sections it may attain values of 0.020 and more. In one slide [no. 20] the following optical properties were found:

$$N_\gamma = 1.634 \pm 0.002 \quad N_\alpha = 1.621 \pm 0.002 \quad N_\gamma - N_\alpha = 0.013 \pm 0.004$$

$$\varrho > v,\ \textit{strong};\quad 2\,V_\alpha\ \textit{small};\quad \gamma\ \textit{deep green},\ \alpha\ \textit{colourless}.$$

In most respects the mineral corresponds fairly well with delessite but the high double refraction which is sometimes observed and also the high refractive indices are not compatible with that species. No doubt the mineral under discussion must be classed with the chlorites. In the rocks of the central parts of the dike it occurs still more abundantly and shows a still greater variation for which reason a full discussion ist postponed to a later occasion (p. 182 ff.). At present only the result of this discussion need be quoted, *viz.* that the mineral is identified as *diabantite.*

The diabantite is a characteristic mineral of the rocks under discussion and is very often associated with the olivine pseudomorphs previously described. In the specimen 339, for instance, one may observe a continuous zoning of these pseudomorphs, the different »zones» from the centre and outwards consisting of: 1) *olivine,* 2) *talc + iron ore,* 3) *actinolite + ore,* 4) *diabantite + a little actinolite.* Thus it can hardly be doubted that at least some of the diabantite is derived from olivine. Most probably, when the supply of lime became too scant to permit the formation of actinolite, iron and magnesia were bound to enter into some lime-free compound and the result was the formation of diabantite.

On the other hand, the general habit of the diabantite individuals often seems to suggest a primary origin. Not seldom they form large plates with a sub-ophitic relation to the plagioclase, in this respect resembling the pyroxene. Of course the possibility cannot be absolutely precluded that part of the mineral was derived from pyroxene, but such an interpretation meets with some difficulties. As already mentioned, the pyroxene is practically everywhere quite fresh, and if there were a direct genetic relation between it and the diabantite it would be rather surprising that no intermediate stages with pyroxene relics are observed. On the other hand there seems to be no objection agaist the assumption of a primary origin for part of the diabantite, the mineral simply representing a low-temperature continuation of the mafic crystallization, which at higher temperatures led to the formation of olivine and pyroxene. Thus, from extensive study of the rather complicated relations of the diabantite I have become convinced that it is of twofold origin, partly a secondary or deuteric product of olivine and partly a low-temperature primary product of crystallization. In all probability the two processes of formation were operating simultaneously.

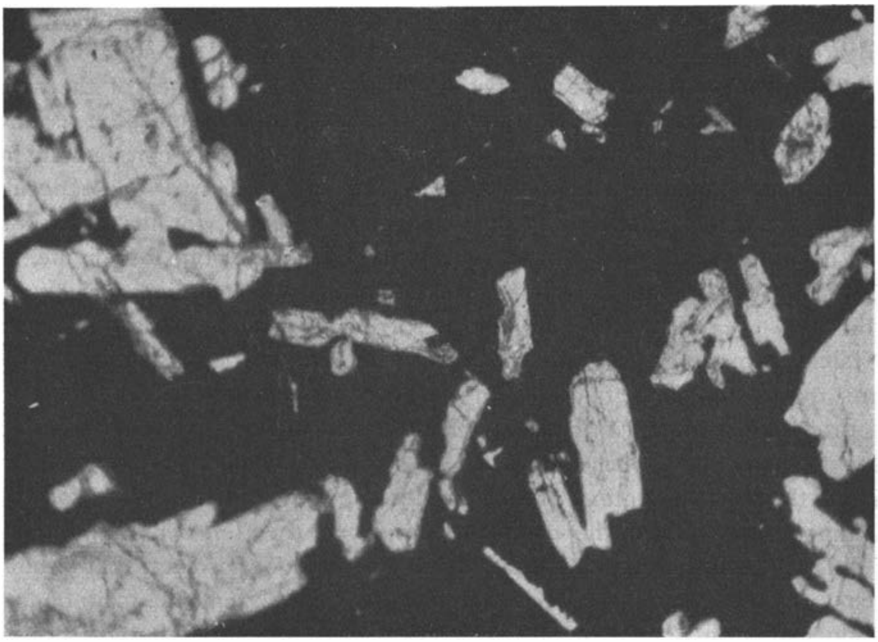


Fig. 4. Plagioclase and iron ore with ophitic relations. Specimen 337, one nicol. Magnification 35 diameters.

When an ophitic relation between plagioclase and diabantite is developed, the former is generally altered to a very fine, scaly aggregate with high double refraction, apparently consisting of *actinolitic hornblende*. This fact may be regarded as additional evidence for the above conclusion that the formation of actinolite or diabantite is controlled by the lime-supply.

In some cases (*e.g.* specimens 195 and 199) the earliest olivine pseudomorphs are not composed of talc and iron ore only, but, especially in the central parts of the pseudomorph, one may observe a biotite-like mineral with high birefringence, parallel extinction, and strong pleochroism in yellowish brown and reddish brown. This mineral which may sometimes be associated with small quantities of actinolite, most probably belongs to the ill-defined *iddingsite* group, but it appears as if there were a continuous transition between this group and the diabantite series. This question, however, will be considered later on (p. 166).

Iron ore.

In most specimens of this rock the iron ore has a mode of occurrence similar to that of the pyroxene. It forms large — sometimes very large — plates enclosing the divergent plagioclase laths in a typically ophitic manner (Fig. 4). It must be inferred that this iron ore was deposited at a rather late stage, but as a rule there are also a few small ore-grains of early crystallization. It is certainly surprising to find that solutions of so high an iron-content were circulating during the last stages of the solidification of the rock, and the question arises whether it must be assumed that in the normal course of crystallization the melt was enriched in iron to such an unusual extent, or if any other explanation of these peculiar textures can be found. The question may be asked, for instance, if the iron could not have been made free by the decomposition of olivine, and as a matter of fact, the olivine pseudomorphs are sometimes so charged with iron ore that their origin is betrayed only by very narrow ribbons of talc. Sometimes (*e. g.* in specimen 102) the ore dust is aggregated to form quite compact grains which can hardly be distinguished from those of probably primary origin. It cannot be entirely ruled out that the late ore may have been deposited by solutions which had previously obtained their iron content from the decomposing olivine by a process of leaching. The rest of the olivine material was then left behind in the form of different silicates of magnesia. It is my opinion, however, that although such a process may have been operating to some extent, the main quantity of the late iron ore should be interpreted as normally deposited from the melt at a late stage.

The ore seems to be rather highly titaniferous, as it is very often subjected to extensive *leucoxene* alteration, which may sometimes affect the mineral to such a degree that only grate-like skeletons are left.

In the ophitic intergrowths between iron ore and plagioclase a reaction zone between the two minerals is often — though not always — developed, and may sometimes devour an entire plagioclase lath. This zone is composed of a very fine scaly aggregate, almost always containing some light-green *chlorite* but generally dominated by small *biotite-* or *chlorite*-scales of green or brown colour. Also, some fibrous *amphibole* may be found in these aggregates.

Besides these fine scales, *biotite* of a brown colour is sometimes observed in association with the iron ore in the form of fairly large flakes.

Orthoclase, generally without a pronounced perthitic structure is found in small quantities in the interstices between the plagioclase laths and sometimes is associated with some *quartz*, forming small micropegmatite areas. Otherwise the interstices are usually filled with aggregates of spherulitic light-green *chlorite*, some scaly green *biotite* and occasional small bunches of *amphibole*.

Apatite always occurs in moderate quantities. It forms inclusions in all the other minerals except the plagioclase and always shows a good idiomorphic development. Some *epidote* may also be found among the accessories.

Table III.

Analysis 1.

Mottled dolerite, S. of Lake Holmsjön. Specimen 113. Spec. gr. $\frac{17^\circ}{4^\circ}=2.881$.

Analyst: N. SAHLBOM.

	Weight-%	Mol. Prop.	Norm			
SiO_2	45.80	763		Or	6.12	
TiO_2	1.99	25		Ab	20.18	
Al_2O_3	15.62	153		An	28.63	
Fe_2O_3	3.34	21		Ne	0.14	Σ sal 55.07
FeO	11.35	158	di	$CaSiO_3$	8.47	16.67
MnO	0.16	2		$MgSiO_3$	4.50	
CaO	9.99	179		$FeSiO_3$	3.70	
MgO	7.42	186	ol	Mg_2SiO_4	9.80	18.57
Na_2O	2.43	39		Fe_2SiO_4	8.77	
K_2O	0.96	11		Mt	4.87	
P_2O_5	0.11	1		Ilm	3.80	
H_2O+	0.75			Ap	0.34	Σ fem 44.25
	100.01					H_2O+ 0.75
						100.07

III : 5 : 4—5 *Auvergnose.*

Or : Ab : An = 11.1 : 36.8 : 52.1

OSANN's System.

s50.8 a2.5 c5.0 f22.5 n7.8

S : Al : F = 16.0 : 3.0 : 11.0

Al : C : Alk = 12.0 : 14.0 : 4.0

k = 0.83

NIGGLI values.

qz	−29	si	99
al	20	ti	3.3
fm	50	mg	0.48
c	23	k	0.22
alk	7	p	0.13

In table III a chemical analysis of the mottled dolerite is given, the specimen analysed being a very fresh representative of this rock. On close study some discrepancies between the norm and the result of the microscopic investigation are seen and, as they are of some general interest, it seems appropriate to give them somewhat detailed consideration.

The most conspicuous fact is the appearance of nepheline in the norm.

This is a rather common feature of rocks of this type, but as far as my experience goes no quite satisfactory explanation has ever been offered. It is true that the amount of normative nepheline in the present case is very small, but even so its existence is rather enigmatic and, moreover, as the rock contains small quantities of interstitial quartz, the nepheline value would be still higher if this quartz had to be represented in the calculation. As a matter of fact, the silica required for quartz formation must necessarily be taken from the feldspar, as a decrease of silica in the mafic minerals would imply an increase of the olivine quantity and, consequently, of the ratio $CaO:(MgO + FeO)$ of the pyroxene, while to match the probable modal composition quite the opposite change is desirable (*cf.* below).

To explain the occurrence of normative nepheline three ways present themselves. Either some lime may enter the olivine, or the proportion $CaO: (Mg, Fe)O$ of the pyroxene exceeds the theoretical value of 1 : 1, or, finally, some of the alkalies may enter into compounds less rich in silica than the normal alkali-feldspars. Of these three explanations the first may not be entirely precluded though it seems very improbable, and the second, as already hinted at above, is hardly compatible with the results of the optical examination. There remains, then, the third possibility — an alkali-compound poorer in silica than the alkali-feldspars — but no mineral whatever is observed which might fulfil this requirement. Thus, if it exists, it must be assumed to combine with the normal feldspars and in this way evade direct observation. It is readily realized that here we approach a problem discussed for several years, *viz.* the anemousite problem.

It is a well-known fact that in 1910 WASHINGTON and WRIGHT claimed to have proved the existence of a variety of plagioclase in which part of the anorthite component was replaced by soda-anorthite or *carnegieite*, $Na_2Al_2Si_2O_8$. The new feldspar was named *anemousite* and ever since its recognition it has often been referred to in petrologic literature. It appeared to be present in certain basalts from the Hawaiian Islands and for these rocks a new name, *pacificite*, was introduced (BARTH 1930). In other cases the existence of anemousite was supported from a theoretical point of view (BELIANKIN 1929, SHAND 1935).

Already in 1912, however, BOWEN, in an experimental investigation of the system carnegieite-anorthite, found that the solubility of carnegieite in anorthite amounts to 2 % only, whereas the anemousite of WASHINGTON and WRIGHT requires a solubility of 5.5 % in Ab_8An_{10} (BOWEN 1912, p. 571). Moreover, quite recently ERNST and NIELAND (1934) as the result of a fairly exhaustive investigation of the original material of WASHINGTON and WRIGHT, concluded that the supposed anemousite was just a normal plagioclase, and that the term as well as the name pacificite should be discarded.

It is no affair of mine to offer an opinion concerning these contradictory results, but although the investigation by ERNST and NIELAND seems fairly convincing, it must be pointed out that their results cannot set aside the theoretical possibility of carnegieite entering the plagioclase in minor quantities.. On the contrary, in many cases this assumption seems to be the only explanation available (*cf.* the papers by BELIANKIN and SHAND quoted above) and it is my opinion that it must be accepted for the rock here under discussion.

Returning now to the analysis of table III, the next conspicuous feature of the norm is the composition of the pyroxene. As there is no normative hypersthene the pyroxene comes out as a member of the diopside-hedenbergite series, whereas the optical data were found to be:

$$2\,V_\gamma = 43^\circ \qquad c/\gamma = 38^\circ.$$

The great uncertainty of optical determinations in the case of pyroxenes is well known to every petrologist but it seems to be a fairly well established fact that a decrease in the lime content implies a decrease in the axial angle, too. Now, in the present case, there is no other mineral, in which the lime may be placed — as any considerable lime-content of the olivine is precluded — nor are there any indications of an alkali-content in the pyroxene or in any other mineral, which would allow some more lime to enter the plagioclase. Thus there seems to exist an inexplicable incompatibility between the optical determinations and the chemical data.

One possible explanation is offered on the assumption of a titanium content of the pyroxene. BARTH has recently (1931) described a titanium-rich pyroxene with $2\,V_\gamma = 46^\circ$, but as this specimen is also rather poor in lime, nothing may be inferred with certainty from this fact. A pyroxene described by DIXON and KENNEDY (1933) seems to give a better indication of the influence of TiO_2 upon the optical properties. The species in question shows *5.27 %* TiO_2 together with *24.06 %* CaO and is optically uniaxial. Consequently, it might be considered as supporting the assumption that titanium tends to lower the value of $2\,V_\gamma$. The evidence is however, not altogether conclusive, for, as pointed out by the authors, the alumina content is also abnormally high (14.29 %) and its effect on the optics of the mineral cannot be determined. Moreover, in the present case, the optical properties of the pyroxene, especially the refractive indices (see page 127) do not suggest a remarkably high titanium content (*cf.* DIXON and KENNEDY 1933, p. 114). Indeed, the pyroxene of the central dolerite which shows an optic axial angle of about 50° is, most probably, considerably richer in TiO_2 (see p. 162).

As a conclusion I must admit that I am at a loss to give an adequate solution of this problem. It would seem, however, that although a low lime-content of the pyroxenes tends to decrease the optic axial angle, a small axial angle may also be found in lime-rich types, being caused by some factor or factors unknown. Attention should be drawn to this possibility, as pyroxenes of fairly small axial angles are very often found in basaltic rocks. (*Cf.* BACKLUND and MALMQVIST, 1932.)

Concerning the analysis of table III it may further be pointed out that it agrees remarkably well with the analysis of the Breven olivine dolerite (WINGE 1896, quoted in KROKSTRÖM 1932 a, p. 302). The NIGGLI values of the two analyses are practically identical — only the alkali distribution is a little different with $k = 0.11$ in the Breven rock and $k = 0.22$ in the Hällefors rock.

Finally, the normative anorthite content of the plagioclase is a little lower than that determined optically. That, of course, is accounted for by the small amounts of interstitial alkali-feldspars.

2. Contact modifications.

The mottled dolerite has never been found in immediate contact with the wall rock, although the outer boundary line of the dike is exposed at several localities. At some distance from the contact the rock takes on a uniform greenish-gray colour because the plagioclase, the dull white colour of which caused the mottled appearance, turns fresh and greenish. Microscopically, too, one finds that the only difference between the two types lies in the state of freshness of the feldspar. In the outer type it is quite limpid and fresh, whereas in the mottled dolerite more or less strong saussuritization is almost invariably observed, especially in the pyroxene-rich areas, as already mentioned. The difference is most probably accounted for by more rapid cooling in the outer parts, which has greatly hampered the secondary processes.

As a matter of fact, however, not even this fresh type is seen to border immediately upon the wall rock, but is always separated from it by a zone up to some ten metres in width, the rocks of which show unmistakeable indications of assimilation and strong mineral alterations that will be described below. It may seem odd that between two zones of altered rocks such a remarkably fresh zone should appear, but the facts cannot be denied, and most probably it may be explained as follows. The secondary processes that have led to saussuritization in the inner parts, must decrease in intensity on approaching the contact with its high temperature gradient. On the other hand the alterations brought about by assimilation are restricted, by the low velocity of diffusion, to the vicinity of the contact and so it may happen that an intermediate zone appears to which neither of the two processes may gain access. In other words: the fresh appearance that should appropriately have belonged to the outer part of the dike is spoilt by assimilation in the outermost zone. BOWEN (1921) has shown that the rate of diffusion of temperature in silicate melts is at least 4000 times as great as the rate of diffusion of substance. Moreover, it must be borne in mind that the assimilation need not necessarily — not even probably — have been effected at the present junction between the dike and the wall rock. On the contrary, we must assume that the magma, forcing its way upwards, has been contaminated in its marginal portions by incorporating material from the adjacent rocks at lower levels. Consequently, when it came to rest in its present position and began to congeal there, there was already a certain chemical difference between the outermost and the more central portions. We will now proceed to see how that difference has manifested itself in the character of the contact proper.

The most conspicuous feature of the contact rocks as compared with the main dolerites is their texture, which is not ophitic but markedly doleritic according to the nomenclature proposed by me (KROKSTRÖM 1932 b, p. 199). It is a most remarkable fact that nowhere is a typically ophitic dolerite found in contact with the wall rock.

As to their mineral composition, the contact rocks are, like the normal ones, dominated by divergent plagioclase laths, which as a rule, however, show an extremely irregular patchy or undulose zoning, indicative of rapidly changing conditions during the period of crystallization. In most specimens the plagioclase is intensely saussuritized. A great number of measurements seems to establish that the average composition of the plagioclase is about the same as in the normal dolerite, *viz.*

$$Ab_{40}\,An_{60}\,.$$

Olivine in a fresh state is never met with and even olivine pseudomorphs are, at least in the outermost rocks, very scarce if not entirely wanting. When they do appear they belong to the amphibole or diabantite stage of alteration (*cf.* p. 132).

Pyroxene is always found, sometimes in fairly large quantities, although it is never so abundant as in the main dolerite. Attention has already been called to its textural relation to the plagioclase, but it must be borne in mind that there is a continuous transition from the contact rocks to the ophitic dolerite. Thus at some distance from the contact the texture is something between ophitic and doleritic, just as the olivine pseudomorphs are more numerous there than close to the contact. At any rate, however, the tendency of idiomorphic development of the pyroxene — that is, the tendency of attaining a doleritic texture — on approaching the contact is sufficiently pronounced to allow of a rather close estimate of the distance from the boundary by guidance of the texture only. As a rule the pyroxene tends to assume the shape of rather long prisms and very often shows a twinning on (100).

Another conspicuous feature that is encountered in the contact zones only, is a very strong alteration of the pyroxene, and this alteration seems to deserve a somewhat detailed description. The first sign of instability is seen in the development of a very marked and quite irregular patchy structure. As alteration proceeds, the originally quite limpid mineral becomes turbid or clouded and, simultaneously, a distinct striation parallel to the basal plane becomes prominent. This striation is caused by an almost sub-microscopically fine decomposition and at a later stage the decomposition products become clearly distinguishable, rendering the pyroxene distinctly streaky with alternating stripes of fresh and altered material. Eventually, the alteration begins to break through even those stripes that were hitherto unaffected, and the last stage before the pseudomorph is completed shows long parallel strings of small pyroxene drops traversing the secondary material. Very often this alteration begins in the centre of the mineral, and one may observe an outer border of fresh pyroxene with the same optical orientation as the drop-like relics of the interior. The resulting products of alteration are sometimes made up of an *actinolitic hornblende,* sometimes of *serpentine.* The hornblende is of the same character as that observed in the main dolerite (see p. 128) and often it shows irregular patches, probably caused by an intricate twinning.

As a very peculiar fact it must be pointed out that in a single specimen of the contact rock [189 a] an *ortho-pyroxene* is encountered. In other respects the rock is altogether similar to the normal contact type. The ortho-rhombic pyroxene is colourless and not perceptibly pleochroic. Its optical axial angle was determined with the same result in two separate grains:

$$2\,V_{\alpha} = 64^{\circ}.$$

This value, according to WINCHELL, indicates a content of $FeSiO_3$ of *38 %.*

I am not able to offer an explanation of this isolated occurrence of a mineral that is otherwise completely wanting in the rock series treated.

A very good representative of the contact rocks is found in specimen 245 b, whereas the gradual changes of the pyroxene are particularly well illustrated by specimens 66 and 193. In more or less advanced stages, however, they are met with at almost every locality in the vicinity of the dike boundaries.

As has previously been hinted at, these contact rocks are, no doubt, to be interpreted as varieties of the mottled dolerite, generated by assimilation, and even the observations now related are very strongly in favour of this opinion. By assimilation from the wall rock during the upward rise of the magma — probably containing some suspended solid matter of early crystallization — the melt was made more acid, the olivine already deposited was to a great extent resorbed, and the crystallization of pyroxene was able to begin at an earlier stage than would have been possible if the melt had retained its initial composition. Consequently, the relation of plagioclase and pyroxene became one of almost simultaneous crystallization and a doleritic texture was developed. The continued assimilation of acid material — quartz and alkali feldspars being the minerals of the wall rock most easily remelted — caused instability in the pyroxene deposited and, in consequence of its well-established reaction relation to amphibole, the mineral became subjected to a marked amphibolization which has not at all or very slightly affected the same mineral at some distance from the contact.

There is also, however, some evidence of a more tangible kind, proving the correctness of the assimilation hypothesis. North-east of Lake Lidsjön the contact zone is exposed at several places and at two localities there are found as inclusions in the contact rock rather large relics of granitic composition microscopically displaying a very beautiful micrographic texture (specimen 148 c, *cf.* Fig. 5). Furthermore, at this locality coarse quartz-bearing veins are seen to dissect the contact rock, and although it was not possible to ascertain whether they represent segregation veins or whether they should be interpreted as emanations from the mobilized wall rock, they also speak in favour of assimilation. Along the main road just S. of Lake Tallsjön and close by the southern dike boundary, an exposure is observed in which dolerite and a leptitic rock occur together with very

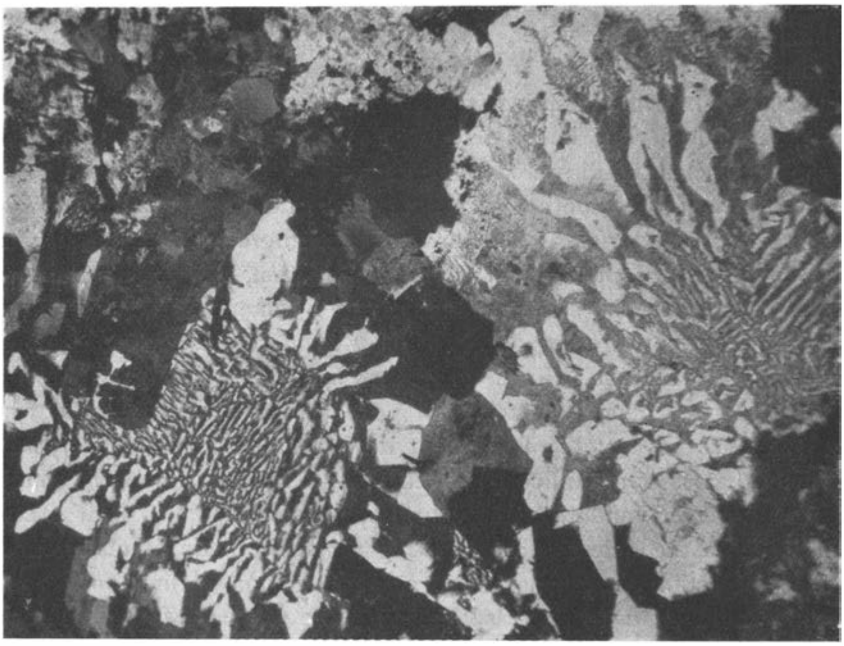


Fig. 5. Micropegmatites in a granitic inclusion in the marginal dolerite. Specimen 148 c, nicols +. Magnification 40 diameters.

intricate mutual relations, impossible to explain otherwise than as the result of assimilation. Microscopically one finds within a contact rock of the type previously described, patches of granitic composition with well-developed mortar texture.

Finally, almost everywhere close to the contact the dike rock is immensely enriched in *quartz* and *alkali-feldspar* forming large micropegmatitic intergrowths. This phenomenon is sometimes so strongly accentuated that the dike rocks may be said to merge continuously into the wall rock, eliminating every possibility of tracing a distinct boundary. In these cases the alkali-feldspar often forms large plates, ophitically enclosing the plagioclase laths and sometimes surrounded by micropegmatite zones.

Most frequently, however, there is no such transitional zone; instead the contact rock develops a narrow chilled margin of considerably finer grain than in the other parts of the zone. In these fine-grained types the pyroxene is, as a rule, completely replaced by *serpentine* and *amphibole,* and the plagioclase is dissected by numerous *chlorite* veins.

In some of the contact rocks great quantities of a *delessitic chlorite* of abnormal blue interference colours are encountered. This delessite forms rather large rounded plates with a wavy extinction, enveloping the plagioclase laths in much the same manner as the pyroxene of the ophitic types, and is probably to be interpreted as a low-temperature continuation of the pyroxene crystallization. In a couple of specimens [67, 139 b, 189 b] a few fairly large rounded patches of yellowish glass are observed which, as a rule, are in a state of incipient devitrification yielding a crystalline substance that is very difficult to identify. It reminds one very much of delessite, however, and the glassy portions themselves also bear a strong resemblance to the delessite areas as regards their mode of occurrence.

The objection may arise that an assimilation of lime-poor gneissic material would tend to decrease the anorthite content of the plagioclase, whereas the optical determinations show that the plagioclase of the contact rocks is of about the same composition as that of the main dolerite. In order to get an idea of the probable effects of assimilation upon the plagioclase composition, table IV was constructed. In column 1 the main oxides of the mottled dolerite of analysis I are recalculated to the sum 100, in column 2 the same recalculation is made for a theoretical rock obtained as a mean of the 5 analyses of garnet gneiss included in LARSSON's tables (LARSSON 1932). In column 3 the composition of a rock is given that would result if the dolerite is assumed to assimilate the rock of column 2 in the proportion of 40 % of its own weight. Finally, the columns 4 and 5 show the molecular proportions of the feldspar-forming components of the main dolerite and the assumed contaminated rock respectively. A calculation of the normative plagioclase composition gives the results entered in the last column; it is seen that practically no change in this value is brought about by the assimilation. It is true that the normative relations may not necessarily be the same as the modal ones, but it is thought that the result is likely to give a general indication, at least, of the extent to which the composition of the plagioclase is affected by the assimilation. Furthermore the quantity of assimilated material forming the basis of the above calculations must be considered to represent a rather generous maximum value. Consequently, the fact that the plagioclase of the contact rocks is of much the same composition as that of the main dolerite does not in any way disprove the hypothesis of assimilation. In this connection attention should once more be drawn to the considerable inaccuracy of the optical feldspar determinations which are most probably reliable only within an interval of ± 5 % (*cf.* p. 119).

Table IV.

	1	2	3	4	5	6
SiO_2	47.22	66.38	52.72	787	879	Normative plagioclase composition of rock 1 $Ab_{42} An_{58}$.
Al_2O_3	16.10	17.51	16.51	158	162	
Fe_2O_3	3.44	2.76	3.25			
FeO	11.70	4.21	9.56			Normative plagioclase composition of rock 3 $Ab_{41} An_{59}$.
CaO	10.30	2.21	7.99	184	143	
MgO	7.65	2.08	6.06			
Na_2O	2.51	1.88	2.33	40	37	
K_2O	0.99	2.98	1.56	16	25	
	99.99	100.01	99.98			

For explanation of the table see text.

The most conspicuous result of assimilation is the increase of the silica percentage and I have previously pointed out that the textural relations of basic rocks are chiefly governed by the silica content (KROKSTRÖM 1932 b, pp. 209—210), a view which was later again emphasized by NORIN (1934, pp. 136—144). For a fuller treatment of these problems, however, the reader is referred to p. 241 below.

b. **The coarse-grained dolerite.**

1. **Normal development.**

Inside the two zones of mottled dolerite, at each side of the central rocks, a coarse-grained rock of somewhat different type is encountered. This rock occupies two rather narrow zones generally not exceeding a width of 50—100 metres, but occasionally it may increase in bulk so as to displace the central rocks entirely. (*Cf.* below p. 145).

At two localities the actual boundary line between the mottled and the coarse-grained types is exposed, *viz.* immediately north of Lake Kvarnsjön and immediately south of Lake Tallsjön. At these two places one may observe a sharp and well-defined contact line between the rocks. This seems to indicate that the mottled rock is not simply a chilled marginal facies of the coarse-grained one, but that two different intrusions have taken place. In neither of the two rocks, however, does the grain diminish on approaching the contact, the inner rock being quite as coarse at the actual contact line as elsewhere. Thus one must conclude that the two intrusions took place in rather rapid succession, the earlier rock not having cooled down entirely before the intrusion of the later one. It is not possible to make a definite statement as to the mutual age-relations of the two types, but it seems reasonable to assume that the extremely coarse grain of the inner rock is a result of its congealing in a *milieu* already warm, in fact, within an earlier intrusion. As will be seen later on, however, this explanation is not altogether adequate. Another fact of great importance, however, is that the coarse-grained rock, at several localities, displays an unmistakeable fluidal arrangement of its feldspar laths, indicating that a great part of them had crystallized already before intrusion. Thus we may conclude that the generating magma passed a rather long period of crystallization at a deep level, and during that stage had ample opportunity to develop the coarse degree of crystallization finally found in the resulting rock. Consequently, the coarse rock should represent the later intrusion,

In its normal development the coarse rock, except for its coarseness, differs but slightly from the mottled variety. Fresh olivine is, however, never met with, its place being taken by numerous pseudomorphs of *diabantite* of the type already described. This difference is of no importance from a purely magmatic point of view, as it merely indicates that the processes of alteration have proceeded further in the coarse rock, which is indeed to be expected from the longer duration of its period of crystallization.

Another difference is found in the development of the interstitial matter. Whereas in the mottled dolerite the plagioclase interstices are filled with aggregates of alkali feldspar and quartz, in the coarse-grained dolerite they are occupied by a very fine-grained mass, possibly representing a devitrified glass or at any rate the result of very rapid cooling. This fine-grained mass, which is practically identical with the groundmass of the porphyritic rocks to be described later on (p. 175 ff.) is composed mainly of *alkali-feldspar,* small *pyroxene* margarites partly amphibolitized, bunches of a faintly *bluish-green amphibole,* small rosettes of a brown *chlorite of ferrite-type* (see p. 184) and rather large quantities of *apatite.* It was not possible to ascertain the character of the alkali-feldspar, but most probably both *orthoclase* and *albite* are present. The feldspar is generally developed as narrow rods with a fan-like mutual arrangement and even the minute chlorite scales often show forms that remind one of dendritic structures. The feldspar mass fills the interstices in a wholly plastic manner strongly contrasting with the interstitial aggregates of the mottled dolerite, and quantitatively it seems, as a rule, to make up a greater part of the rock than the latter. The plagioclase is often surrounded by an outer lime-poor zone, passing directly into the interstitial mass, and, moreover, it has been subjected to zoisitization, which seems to increase in proportion to the quantity of the latter.

This difference in the development of the interstitial material in the two rock types is most probably closely connected with the different state of preservation of the olivine. Both rocks are undersaturated in silica and — as stressed by BOWEN (1928) — the condition for the production of quartz-bearing residua is that olivine was precipitated in excess of its stoichiometrical amount, and afterwards failed to react with the melt. In the holocrystalline coarse-grained types all olivine is converted into secondary products and, consequently, the conditions necessary for the generation of quartz-bearing residua are not fulfilled. In the mottled types, on the other hand, it is rather probable that the alteration was checked by cooling before the stoichiometrical proportions were re-established. Moreover, as will be discussed on p. 238 there seems to be reasons for assuming that some quantity of olivine was carried away from its original *milieu,* thus escaping conversion.

Good opportunities for studying the fine-grained mass just described are offered by the specimens 102, 301 and 337.

2. Glassy development.

At one locality, *viz.* immediately E. of Jacobsberg, a rather peculiar variety of the coarse-grained dolerite is met with. In this neighbourhood the zones of mottled dolerite are rather narrow and the central rocks are absent; the coarse-grained rock, therefore, occupies almost the whole width of the dike, which is about 500 metres.

Megascopically the rock [235, 236] does not differ materially from the normal type and it is seen to merge into it laterally, but microscopically a very interesting picture is presented.

The rock may be described as a coarse, olivine-bearing, typically ophitic dolerite in which the place of the pyroxene is to a great extent taken by a brownish mass representing a more or less completely devitrified glass (Fig. 6).

Pyroxene is in many specimens practically absent but in others some rather large areas of it are developed, displaying an excellent ophitic relation to the feldspar, — in this respect texturally identical with the devitrified areas. The following optical properties were determined on three different pyroxene grains:

1. $2V_\gamma = 49^\circ$ $c/\gamma = 42^\circ$ $N_\gamma - N_\alpha = 0.019$ $N_\beta - N_\alpha = 0.003$.
2. $2V_\gamma = 52^\circ$ $c/\gamma = 40^\circ$.
3. $2V_\gamma = 53^\circ$ $c/\gamma = 45^\circ$.

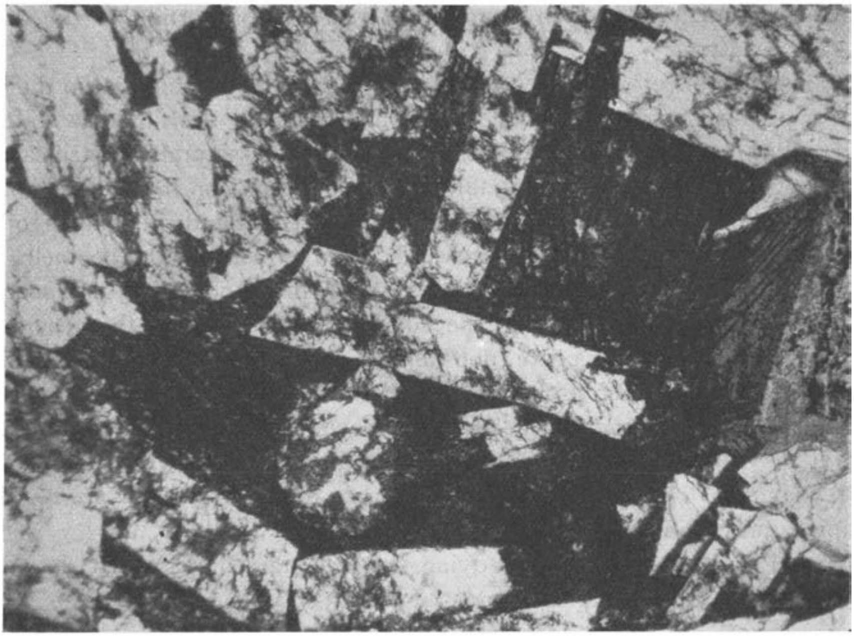


Fig. 6. Microphotograph of the glassy marginal dolerite showing plagioclase laths embedded in a partly devitrified mesostasis. Specimen 236, one nicol. Magnification 40 diameters.

From these values it may be concluded that the pyroxene belongs to the same type as that of the mottled dolerite *viz.* to a group, the optical properties of which seem to indicate pigeonitic affinities. (*Cf.* however, p. 137). The mineral is generally quite fresh.

Olivine is always present and, as a matter of fact, this rock-type is the only one within the coarse-grained group that may show fresh olivine. Even here, however, the mineral is altered to a great extent and the pseudomorphs are in most cases made up of *talc* and *iron ore,* only seldom of *diabantite.* Both types of pseudomorphs reproduce very distinctly the idiomorphic form of olivine, especially when enveloped by the devitrified mass, and curiously enough the pseudomorphs show crystallographic outlines that are better developed than those of the olivine crystals still completely preserved. Most probably this is a consequence of changing composition during crystallization. Three measurements on olivine in one of these specimens gave the following results:

1. Fresh olivine $2V_\alpha = 73^\circ$: 47 % *fayalite* (BACKLUND 1909).
2. Olivine strongly altered $2V_\alpha = 78^\circ$: 37 % *fayalite* » »
3. » » » $2V_\alpha = 79^\circ$: 35 % *fayalite* » »

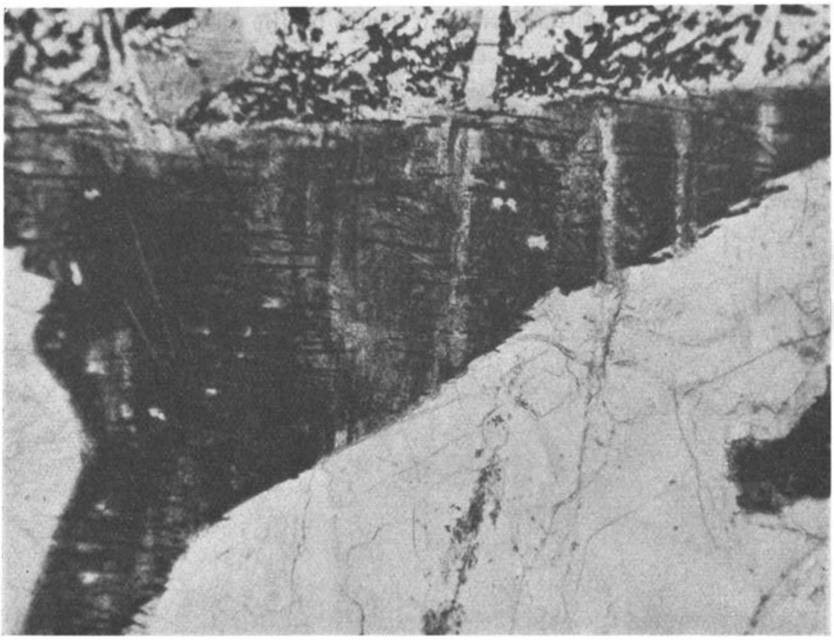


Fig. 7. Groups of parallel iron-ore rods traversing the mesostasis of the glassy marginal dolerite. Specimen 237, one nicol. Magnification 100 diameters.

As the general trend of crystallization will cause a successive increase in the fayalite content of the olivine, the values obtained seem to indicate that the altered crystals are of somewhat earlier origin than the fresh ones, and thus the idiomorphism mentioned above is readily explained. Furthermore, we infer that the alteration — which no doubt belongs to the magmatic period — affected in the first instance the earlier crystals which were not in equilibrium with the surrounding melt.

The *plagioclase* is generally quite fresh. Sometimes it may display a slight continuous zoning. As a mean result from several measurements its composition was found to be:

$$Ab_{35}An_{65}$$

The *devitrified areas* are of a greenish brown colour and envelop all the main minerals in a completely plastic or ophitic manner. They are composed of a rather scant matrix, which is difficult to identify but is most probably of feldspathic composition and possibly still partly glassy. In this matrix beautiful crystallites of *pyroxene* and *iron ore* are abundant. The iron ore forms minute rods traversing the matrix and the pyroxene crystallites in strictly parallel groups. (Fig. 7). The pyroxene forms very delicate margarites (Fig. 8), which may also often exhibit a parallel or subparallel arrangement. The amount of pyroxene in the devitrified portions varies a little from one specimen to another, and where the pyroxene crystallization has proceeded a little further it leads to the development of narrow laths with a fan-like arrangement, or even to small isometric skeleton crystals.

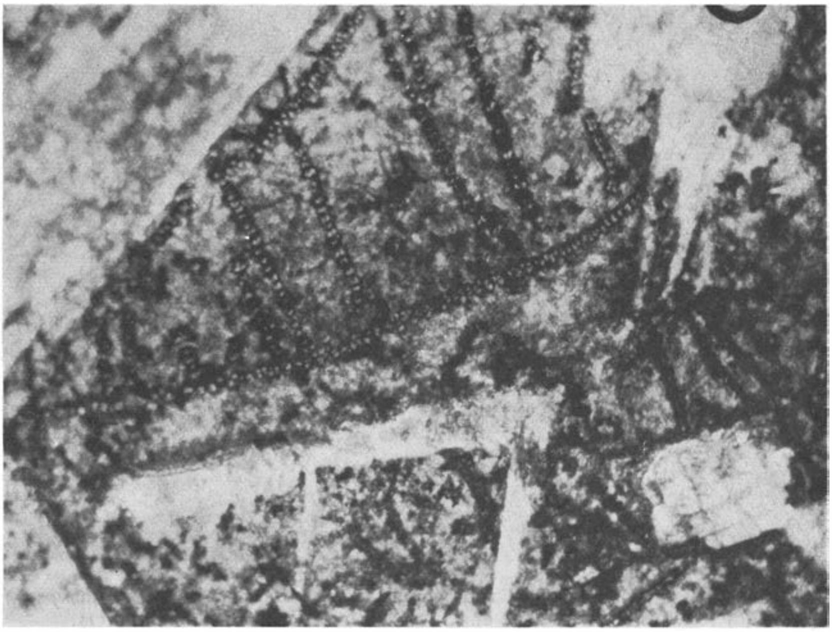


Fig. 8. Pyroxene margarites in the mesostasis of the glassy marginal dolerite. Specimen 239, one nicol. Magnification 100 diameters.

The quantity of devitrified material is generally considerable and in most specimens it may be estimated to make up about 25 % of the whole rock.

In table V a chemical analysis of this rock-type is presented. As is seen from a comparison with table III on p. 135 it agrees fairly well with the analysis of the mottled dolerite, and this agreement is still more emphasized by Table XXIV on p. 229 where all the Hällefors analyses available are plotted. As it is beyond doubt that the »glassy» rock is chemically identical with the normal coarse-grained dolerite the excellent conformity

Table V.

Analysis 2.

Glassy coarse-grained dolerite, S.E. of Jacobsberg. Specimen 236.

Spec. gr. $^{17^\circ}_{4^\circ} = 2.853$. Analyst: N. Sahlbom.

	Weight-%	Mol. Prop.
SiO_2	47.69	795
TiO_2	2.20	28
Al_2O_3	17.04	167
Fe_2O_3	3.77	24
FeO	9.39	131
MnO	0.20	3
CaO	9.17	164
MgO	4.56	114
Na_2O	2.89	47
K_2O	1.50	16
P_2O_5	0.20	1
H_2O+	1.20	
	99.81	

Norm

	Or	8.90	
	Ab	24.63	
	An	28.91	Σ sal 62.44
di	$CaSiO_3$	6.61	13.08
	$MgSiO_3$	3.30	
	$FeSiO_3$	3.17	
hy	$MgSiO_3$	3.00	5.77
	$FeSiO_3$	2.77	
ol	Mg_2SiO_4	3.64	7.31
	Fe_2SiO_4	3.67	
	Mt	5.57	
	Ilm	4.26	
	Ap	0.34	Σ fem 36.33
		H_2O+	1.20
			99.97

(III) II : 5 : 3(4) : 4(4—5)
Andose
(Hessose)
(Camptonose)
(Auvergnose)

Or : Ab : An = 14.3 : 39.4 : 46.3

Osann's System

$s_{54.5}\ a_{3.5}\ c_{6.0}\ f_{20.5}\ n_{7.5}$

S : Al : F = 17.0 : 3.5 : 9.5

Al : C : Alk = 12.5 : 12.5 : 5.0

k = 0.89

Niggli values

qz	—21	si	115
al	24.0	ti	4.0
fm	43.0	mg	0.39
c	24.0	k	0.25
alk	9.0	p	0.15

of the two analyses seems to indicate that the two main types of marginal dolerite, although representing different intrusions, belong practically to the same stage of evolution of the magma. As opposed to the central rocks to be treated later on, they may be regarded as a unit.

From the peculiar development of the »glassy» rocks some conclusions may be drawn. The contrast between the big crystals of plagioclase and olivine on the one hand and the originally glassy portions on the other seems to allow of one explanation only, *viz.* that a period of low-level crystallization of rather long duration was followed by very rapid intrusion into higher and cooler regions of the crust. Now, from the mutual quantitative relations between pyroxene and »glass», as well as from the type of devitrification displayed by the latter, it is quite evident that the residual melt existing at the time of intrusion would, in the course of normal crystallization, have yielded mainly pyroxene, iron ore, and a little feldspar, and would thus have completed the crystal assemblage already existing so as to form a normal ophitic dolerite of coarse grain.

Consequently, whereas in the normal holocrystalline dolerites the final result of crystallization is pictured, the »glassy» types give evidence of an earlier stage in the course of crystallization of the same magma. We find that at this stage all olivine and by far the greater part of the plagioclase had crystallized, whereas the crystallization of pyroxene had only just begun. These observations seem to afford strong confirmation for the views previously expressed by me (KROKSTRÖM 1932 b, p. 210) concerning the order of crystallization in basaltic magmas of this type.

We may get a still better view of the processes operating in the magma by studying the alteration of the olivine. In the »glassy» types the alteration is rather strong and mostly of the talc-iron-ore type, whereas in the mottled dolerite we have endeavoured to show the existence of a series of alteration processes, starting with talc and iron ore and ending with diabantite. In spite of all these processes the olivine of the mottled types is, on an average, far better preserved than that of the »glassy» rocks. These facts must be explained as follows. During long-extended deep-level crystallization the olivine was subjected to the changes required by the temperature prevailing, resulting mainly in the formation of talc and iron ore, and these changes had ample time to be completed. On the subsequent intrusion chemical processes in the magma were very effectively checked by rapid cooling, and the later stages of alteration were able to come into operation only to a very limited extent. The magma, giving rise to the mottled rocks, on the other hand, was cooling down more slowly, and the alteration processes were at work until the very last stages, adapting themselves continually to the changing conditions of temperature *etc.* In spite of that, much of the olivine was left in a fairly well-preserved state because, as the temperature of the magma had decreased to a certain point, the massive olivine grains were less susceptible to change than the secondary products previously formed from them.

These considerations seem to prove beyond doubt that the secondary changes of the olivine in the rocks under discussion belong to the magmatic stage of evolution and that the alteration to talc and iron ore is the primary and the highest temperature process.

The composition of the devitrified areas also confirms the opinion given on p. 134 that the residual melt was rather rich in iron and is most probably to be made responsible for the deposition of the peculiar ophitic ore of the mottled dolerite.

c. Chemical variation of the chief minerals.

During the past few years I have been much interested in the question of the variability of the main rock-forming minerals within seemingly homogeneous intrusive bodies. In my description of the Breven dolerite dike (KROKSTRÖM 1932 a, p. 257) a considerable variation in the optical properties of the olivine was indicated, although the extent of the variation was not investigated in detail. Now, the marginal dolerite of the Hällefors dike seems to offer an excellent opportunity for studying this problem further and, consequently, a somewhat extensive series of quantitative determinations has been carried out. Special attention has been paid to the pyroxene, but plagioclase and olivine have been also to some extent included in the investigation, the results of which are given in the following pages. All measurements were carried out with the aid of the FEDOROFF stage. In the case of plagioclase a complete investigation of the position of the twin elements with regard to the optical axes of symmetry was made and the result was interpreted according to the diagrams of BEREK (1924). On olivine and pyroxene the axial angles were determined according to the method of NIKITIN (BEREK 1924, p. 103 ff.). On each grain two measurements were made, one in each of the two accessible planes of symmetry, and the mean values were accepted only when the difference between the two results did not exceed 1°. The extinction angle of the pyroxene was measured when possible, but in most cases it had to be obtained from the stereographic projection by indirect construction and, consequently, these values are not as accurate as those of the axial angles.

1. Plagioclase.

The plagioclase was determined optically in 27 individuals belonging to 13 different specimens. The results are given in Table VI below.

Table VI.

Anorthite-percentage of the plagioclase of the marginal dolerite.

Percentage of anorthite	50	55	56	59	60	64	65	68	70	72	74	75
Number of individuals . .	2	2	1	1	9	1	4	1	2	1	1	2

Of course, it is not possible to treat statistically so limited a number of observations, but nevertheless it might be of some interest to construct a frequency curve on the basis of the numbers arrived at. Now the accuracy of the FEDOROFF method of feldspar determination can hardly be considered to exceed ± 5 % of anorthite (*cf.* REINHARD 1931, p. 108). In order to eliminate to some extent the ambiguity arising from this inaccuracy the results of measurement are conveniently referred to the nearest multiple of five per cent, and even so the requirements of strict accuracy are not fully complied with. For the present purpose, though, this mode of calculation is thought to be satisfactory. In table VII below, the statistical elements are calculated so as to allow the series of observations to be plotted as a frequency curve in direct comparison with the GAUSS curve of normal distribution (Fig. 9). The reader who is not initiated

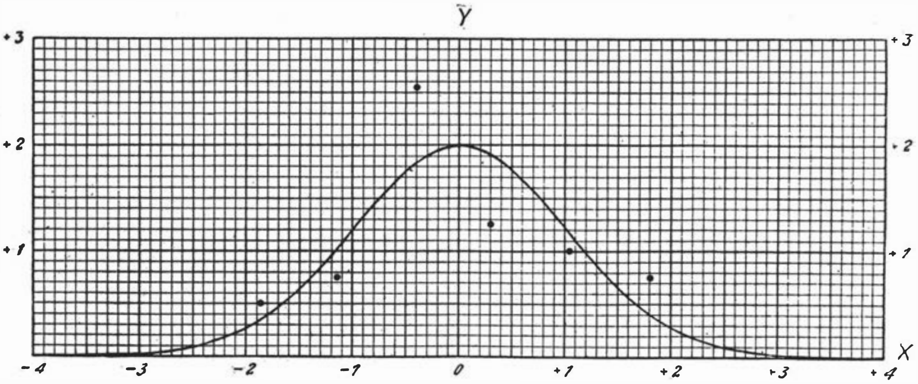


Fig. 9. A series of plagioclase determinations plotted in comparison with the GAUSS curve.

Table VII.

Statistical elements of a series of plagioclase measurements in the marginal dolerite.

$N = 27$ $M_0 = 60$
$M = 62.8$ $b = +2.8$
$\sigma = 6.85$ $w = 5$

% An	x	$F(x)$	$x^2 F(x)$	X	Y
50 ± 2.5	−2	2	8	−1.87	0.50
55 ± 2.5	−1	3	3	−1.15	0.75
60 ± 2.5	0	10	0	−0.40	2.55
65 ± 2.5	+1	5	5	+0.30	1.25
70 ± 2.5	+2	4	16	+1.05	1.00
75 ± 2.5	+3	3	27	+1.80	0.75

in the first principles of mathematical statistics is referred to any elementary treatise on the subject (*e.g.* CHARLIER 1920).

Because of the very small number of observations no conclusion can of course be drawn with certainty from fig. 9. It is remarkable, however, that the projected points show a certain tendency to group themselves in the vicinity of the normal curve. As a matter of fact a replacement of only two measurements from the group 60 % into the group 65 % — which would only imply a replacement within the limits of observational errors — would cause quite close coincidence. As it is known that an insufficient number of observations will tend to increase the deviations from the normal curve, the conclusion may be ventured that the feldspars of the present rocks as regards their chemical composition vary within fairly wide limits but that their distribution is satisfactorily described by the central value $M = 62.8$ and the variation value $\sigma = 6.85$. The probable significance of such a distribution will be discussed later on (p. 156 ff.).

2. **Olivine.**

The optical determination of the olivine was carried out in 33 individuals belonging to 13 different hand specimens. The results are given in table VIII below.

Table VIII.

Optic axial angles of olivines of the marginal dolerite.

$2V_\alpha$	72°	73°	74°	75°	76°	77°	78°	79°	80°	81°	82°	87°	89°
Number of individuals	1	2	1	4	3	6	2	7	1	2	2	1	1

In table IX below, the axial angle values are arranged in the same manner as the feldspar values of table VII, each group, however, compri-

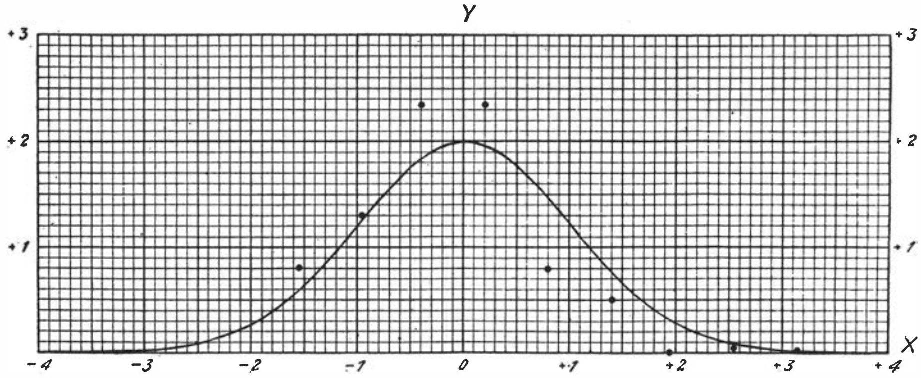


Fig. 10. A series of olivine determinations plotted in comparison with the GAUSS curve.

Table IX.

Statistical elements of a series of axial angle measurements on olivines of the marginal dolerite.

$N = 33$ $M_0 = 78.5$ $w = 2$

$b = 0.36$ $M = 77.8$ $\sigma = 3.41$

$2 V_\alpha$	x	$F(x)$	$x^2 F(x)$	X	Y
72—73°	−3	3	27	−1.55	0.80
74—75°	−2	5	20	−0.95	1.30
76—77°	−1	9	9	−0.40	2.35
78—79°	0	9	0	+0.20	2.35
80—81°	+1	3	3	+0.80	0.80
82—83°	+2	2	8	+1.40	0.50
84—85°	+3	0	0	+1.95	0.00
86—87°	+4	1	16	+2.55	0.25
88—89°	+5	1	25	+3.15	0.25

sing an interval of only two degrees. The accuracy of the measurement may be estimated to ± 1°. The statistical elements are calculated as before.

In fig. 10 the series is plotted in comparison with the Gauss curve. It is seen that in this case the coincidence is perhaps a little better than in fig. 9 and for the same reasons we may conclude that the olivines of the rocks under discussion in regard to their optic axial angles vary within fairly wide limits but that their distribution is satisfactorily described by the central value $M = 77.8$ and the variation value $\sigma = 3.41$. For further discussion the reader is referred to p. 156.

3. Pyroxene.

The optical determination of the pyroxene was carried out on 63 individuals belonging to 35 different hand specimens. The axial angle determinations are to be considered accurate to within ± 1°, whereas the extinction angle measurements are less reliable, although the limit of error is not easily estimated. Because of this, only the former values have been subjected to more detailed treatment. In fig. 11, however, are plotted the axial angles and the extinction angles of those individuals in which both values could be determined. As will be immediately recognized, the two values seem to vary quite independently of each other.

In table X below, the axial angle values are given, and in table XI they are arranged as before in groups each of which comprises an interval

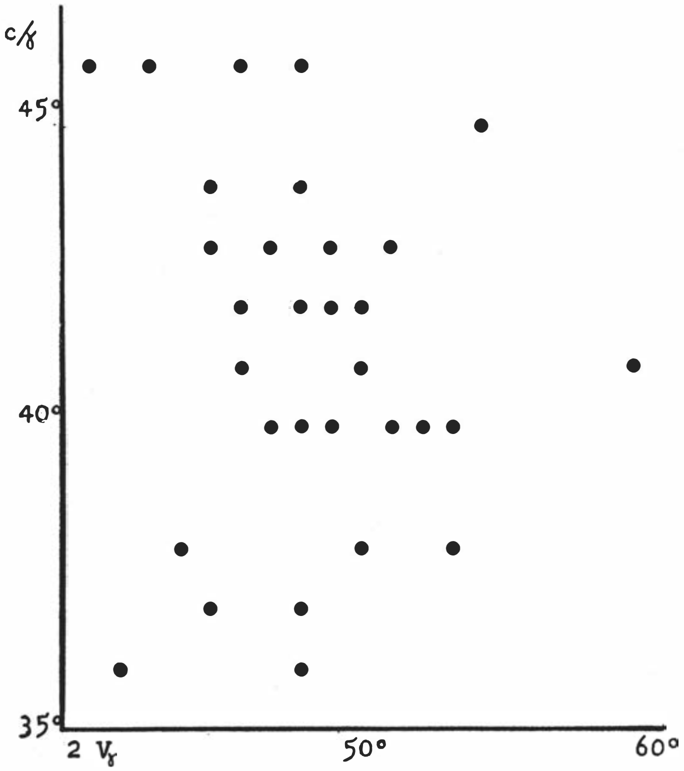


Fig. 11. Optic axial angles and extinction angles of pyroxenes of the marginal dolerite.

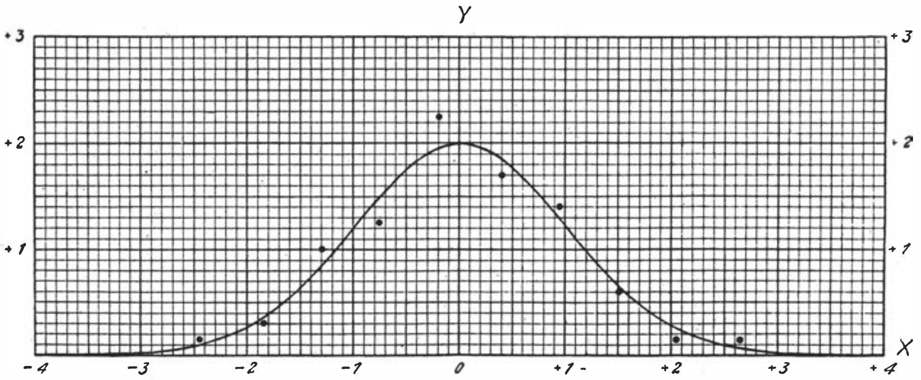


Fig. 12. A series of pyroxene determinations plotted in comparison with the GAUSS curve.

of two degrees. The statistical elements are calculated as usual and the resulting values *X* and *Y* are plotted in the diagram fig. 12. In this case almost complete coincidence between the projected points and the GAUSS curve is found, and as the number of observations is considerably greater than before we may with some confidence conclude that the pyroxenes of the present rocks as regards their optic axial angles vary within fairly wide limits but that their distribution is satisfactorily described by the central value $M = 49°.1$ and the variation value $\sigma = 3.56$.

Table X.

Optic axial angles of pyroxenes of the marginal dolerite.

$2 V_\gamma$	41°	42°	43°	44°	45°	46°	47°	48°	49°	50°	51°	52°	53°	54°	57°	59°
Number of individuals	1	1	1	1	6	4	5	10	6	5	7	4	6	4	1	1

Table XI.

Statistical elements of a series of optic axial angle measurements on pyroxenes of the marginal dolerite.

$N = 63$ $M_0 = 48°.5$ $w = 2°$

$b = 0.32$ $M = 49°.1$ $\sigma = 3.56$

$2 V_\gamma$	X	$F(x)$	$X^2 F(x)$	X	Y
40—41°	−4	1	16	−2.45	0.15
42—43°	−3	2	18	−1.85	0.30
44—45°	−2	7	28	−1.30	1.00
46—47°	−1	9	9	−0.75	1.25
48—49°	0	16	0	−0.20	2.25
50—51°	+1	12	12	+0.40	1.70
52—53°	+2	10	40	+0.95	1.40
54—55°	+3	4	36	+1.50	0.60
56—57°	+4	1	16	+2.05	0.15
58—59°	+5	1	25	+2.65	0.15

4. Discussion of the results.

This statistical investigation was attempted because the marginal dolerite, owing to its very uniform composition and rather fresh condition, seemed to offer a good opportunity of studying rather extensively the mode of variation of the rock-forming minerals, and it is thought that the results may not only apply to the rocks investigated, but very probably may also give some hints concerning mineral formation in general.

From the above tables and figures we have gathered that the optical properties and, consequently, the chemical composition of the chief minerals vary within surprisingly wide limits. Now it should be emphasized that, with one single exception, no difference in *habitus*, occurrence *etc.* could be observed between individuals of very different optical properties, nor can there be traced any relation between the latter and the geological position of the rocks. The one exception is represented by the plagioclase, which may form in some cases a few exceptionally large, porphyritic grains that contrast rather strongly with the feldspar of the »groundmass». Always, when such a grain is measured, it shows an anorthite content considerably higher than the majority of the feldspars and the very high values of more than 70 % An are as a rule found in such large phenocrysts. As the porphyritic tendency, however, is only rarely observed, this fact is not likely to affect to any great extent the variations within the rock body.

Turning now to the curves given in Figs. 9, 10, and 12, we have already pointed out that the projected points show a tendency to clustering around the GAUSS curve although this tendency is not expressed altogether satisfactorily except in the pyroxene diagram. It may be fairly safely concluded, however, that a greater number of observations would afford quite close coincidence also in the other two figures, and thus a discussion of the variations of all three minerals may be based upon the fact that they follow more or less closely the curve of normal distribution. On the other side, according to physico-chemical laws, the end result of crystallization of minerals forming isomorphous mixtures should be either zoned crystals or — provided there is slow cooling and opportunity for complete diffusion — an assemblage of crystals of identical composition. In our case no zoning is observed — only the plagioclase may sometimes display an outer edging of lime-poor material (see p. 145), but this phenomenon is not directly comparable to zoning and, moreover, it does not affect the present discussion, as the measurements were always made inside this outer zone or in grains where it did not appear. Thus in the present case we should expect all individuals to show the same composition.

Now, what inference may be gained from these facts? I think that the general validity of the following statements can hardly be disputed, and, moreover, that they might be extended to most holocrystalline, reasonably coarse-grained rocks with non-zoned crystals. As will be seen later on, however, they are most probably valid only in cases when crystallization was effected under fairly quiet conditions.

1. Actually each mineral grain does not show the composition theoretically required. The mineral in question is, on the contrary, represented by an assemblage of grains of somewhat variable composition, distributed around the theoretical one. The deviation from the theoretical value is often considerable — the greater the deviation, the less the frequency.

2. The bulk composition of all individuals of the same mineral tallies fairly well with the mean of a large number of observations on separate grains — the greater the number of observations, the closer the correspondence.

Now it must be stressed that these facts cannot simply be accounted for by the assumption of chemical inhomogeneity within this rather extensive rock mass, for even in the same thin section very great variations in the optical properties of a mineral may be observed. Thus in slide 102 four measurements of the optic axial angle of pyroxene gave the results 45°, 52°, 53°, and 59°. We must, therefore, infer that the differences are not due only to chemical variations of the magma but that they would result also from a crystallization of a purely homogeneous melt.

In order to present an explanation of the peculiar facts mentioned above, I wish to call attention to some theoretical considerations, all referring to the crystallization of isomorphous mixtures. It is known that one of the factors governing crystallization is the number of crystal *nuclei* formed in a unit of volume and time. As cooling proceeds this number first increases, then passes a maximum and eventually decreases to zero. (See BOEKE-EITEL, 1923, p. 29). In their experimental studies SCHUMOFF-DELEANO and DITTLER (1911) were able to show that in a melt of diopsidic composition the number of *nuclei* under formation attained a maximum at c:a 1200°, *e.g.* about 100° below the melting point. Now let us consider the moment when one *nucleus* has already formed and a second one is on the verge of forming. It is quite evident that at this very moment solid matter will be deposited in two different ways *viz.* forming a new *nucleus* and contributing to the growth of the one already existing. In the first case the crystal resulting will be of the composition theoretically required by the composition of the melt whereas in the second case a crystal will form which — taken as a whole — is chemically a mixture of the earlier *nucleus* and the slightly different new material deposited. Whether this mixture takes the form of a zoned crystal or — as in our present case — diffusion is allowed to effect complete compensation, the net result of deposition during this infinitesimally short interval of time will be two crystals or *nuclei* of a slightly different total composition. As crystallization proceeds, the same phenomena will repeat themselves and the final result will necessarily be, not an assemblage of identical crystals but a series of grains showing more or less continuous differences in composition. The results gained by SCHUMOFF-DELEANO and DITTLER (*cf.* above) show that these processes are at work during a considerable part of the crystallization period.

If it could be assumed that the heterogeneity of the melt, caused by crystal separation, was immediately compensated by diffusion, an earlier crystal would be richer in the higher-melting component than a later one.

Such an assumption, however, is scarcely justified, as most probably in the earlier stages of crystallization an aureole will form around each *nucleus* and the growth of the *nucleus* will at this stage be governed almost entirely by the composition of this aureole. Up to the time when the isolation of these aureoles is broken by mutual diffusion, therefore, the relative content of the higher-melting component will, as a matter of fact, be less in the older crystals than in the younger ones, as this content is steadily decreasing during crystallization and the decrease itself, consequently, becomes merely a function of time. Eventually, when diffusion is strong enough to bring about compensation between the different aureoles, an increase of the higher-melting component around the older crystals will result and *vice versa.* It is my opinion that in this fact should be sought an explanation of many of the inverse zonal structures which have been frequently observed.

Whatever may be the rate of diffusion in the melt, however, it seems in view of the above considerations to be quite evident that even in a portion of magma of rather limited volume, the composition of the growing crystals will vary within limits, the width of which is a function of the rate of cooling and the rate of diffusion, firstly within the solid crystals and secondly in the generating melt. On the other hand the rate of diffusion is controlled by the temperature, viscosity and conditions of movement in the magma.

As a consequence of the above deductions it should be stressed that the mineral composition of a rock can very seldom, if ever, be sufficiently well known from one or two optical determinations of its different minerals. Even if the optical data permit of a fairly accurate chemical interpretation being made, only a large number of observations will lead to a reasonably reliable result.

It must be considered, however, that movement of the magma during the period of crystallization would tend to compensate more or less for the compositional differences. Consequently, a wide range of variation should be expected only in rocks which have crystallized when movement of magma had more or less ceased. Now, the beautiful ophitic texture of the mottled dolerite seems to indicate such conditions and in this case, indeed, the variations are fairly great. As will be seen later on, the Hällefors dolerites exhibit a far narrower range of variation, and it is interesting to find that these rocks show clear indications of having been intruded in a rather violent manner (see p. 173).

B. The central series.

a. The Hällefors dolerite.

1. Normal development.

Megascopically this rock is medium to coarse grained and is characterized by the contrast between its numerous white feldspar laths and the black or dark-green colour of the remainder of the rock. Very often by reason of this contrast the rock takes on a porphyritic appearance, which in thin sections, however, is hardly recognizable. It is true that fine-grained interstitial material is almost always present, but in the most typical specimens it is very limited in its occurrence and only forms a sparse infilling between the larger crystals. Sometimes, however, this material increases greatly in amount and in these cases a continuous transition is effected towards the truly porphyritic types, which will be treated later. As Hällefors dolerites *sensu stricto* only the types with subordinate quantities of fine-grained interstitial material are included.

Very often these rocks display a marked fluidal texture which is apparent even to the naked eye. As this tendency is especially conspicuous in certain peculiar glassy types (see p. 171 ff.) it will be discussed in more detail in connection with them.

Microscopically the rock is found to consist of *plagioclase, pyroxene, olivine pseudomorphs, iron ore,* and *apatite*, and further in the groundmass there are found *alkali-feldspar, amphibole,* a finely scaly biotite-like mineral, most probably of chloritic affinities, and, finally, small amounts of *quartz.*

The *plagioclase* is of andesine composition, Measurements on 17 different individuals in 14 specimens gave as a mean:

$$Ab_{60}An_{40}.$$

The deviations on either side of this mean in no case exceeded *5 % of anorthite*, and thus the composition must be considered remarkably constant. Quantitatively, the plagioclase is the dominant mineral, occurring in laths or plates and showing quite good idiomorphism. Twinning according to the Albite and Carlsbad laws is prominent. The laths and plates generally attain an average diameter of 2 to 3 mm., and as a rule they are but slightly decomposed, mainly with the development of *sericite,* more rarely of *zoisite*. No typical zoning is observed — sometimes a slightly undulose extinction is displayed — but the plagioclase laths are very often surrounded discontinuously by a zone of albitic composition, which may continue into the interstitial groundmass. Sometimes this outer albitic zone is crowded with zoisite grains, sometimes the latter mineral is altogether wanting. The albitic borders very often show beautiful anthiperthitic structure and, further, they are sometimes seen to enter into micrographic intergrowths with quartz, or more often with pyroxene. The slight sericitization also seems to be most pronounced in the outer parts of the crystals and to decrease continuously inwards, often leaving the central parts quite limpid and unaltered. Sometimes the surrounding albitic zone may be even larger than the andesine kernel and this gives the impression that large parts of the slide are built up of a coarse xenomorphic albite mosaic. Closer investigation, however, discloses the fact that there is in every case an andesine kernel in the centre of the supposed homogeneous albite grain.

Often the plagioclase, most probably owing to reactions with iron-rich solutions, is intensely altered to a very finely scaly aggregate, which consists of an obscure *biotite-like mineral* of green colour together with some common, light-green *chlorite*. These aggregates may sometimes replace the plagioclase completely, *viz.* in the immediate vicinity of the iron ore and the olivine pseudomorphs, and often even those andesine laths that are still preserved are seen to be strongly veined by the same scaly material. In a few cases somewhat strong chloritization of the andesine is observed, the faintly green chlorite from basal fissures spreading along the cleavage planes (010).

Clinopyroxene occurs in varying amounts, but as a rule it is fairly abundant and almost equal in quantity to the plagioclase. It always shows fairly good idiomorphism and is developed in grains that are generally 1 to 2 mm. in diameter but sometimes may become much larger. Often the pyroxene is seen to extend in crystallizing into the interstitial matter in just the same manner as in the porphyritic types to be described later on (p. 175 ff.), and further it may, as was previously mentioned, be intergrown with the albitic border of the andesine crystals. Large pyroxene fields dissected by plagioclase laths such as were described from the marginal dolerite are never encountered, and the texture, consequently, is decidedly doleritic according to the nomenclature suggested by me in a previous paper (KROKSTRÖM 1932 b). In a few slides intergrowths of pyroxene and iron ore are observed.

The composition of the pyroxene seems in general to be much the same as in the case of the marginal dolerite. A great number of measurements gave results only very slightly deviating from the mean values:

$$2\,V_{\gamma} = 50^{\circ} \qquad c/\gamma = 40^{\circ}$$

Thus the range of variation seems to be considerably narrower than in the marginal dolerite. A marked difference between the pyroxenes of the two rocks, however, lies in their colour. The pyroxene of the Hällefors dolerite always shows a distinctly reddish tint, and may sometimes exhibit weak pleochroism in varying shades of pale red. Most probably this is to be ascribed to a considerable titanium content — an assumption which is strengthened by the high titanium percentage of the chemical analysis (p. 169).

In most cases the pyroxene is well preserved, showing only a slight marginal amphibolization. In a few slides, however, [325, 326, 327] this amphibolization is rather strong, leading to the formation of numerous aggregates of *iron ore, amphibole* and *pyroxene relics*, together with *diabantite* scales and some ill-defined *chloritic material*. The secondary amphibole displays a very marked change in its optical properties from the interior outwards, as is seen from the following scheme of pleochroism:

	Interior	Margin
γ	*olive green*	*bluish green*
β	*olive brown*	*grass green*
α	*pale yellow*	*colourless.*

In the interior the amphibole shows

$$2\,V_\alpha = \text{about } 70^\circ \qquad c/\gamma = 15^\circ$$

whereas at the margin the axial angle is considerably smaller and the mineral shows a strong dispersion $\varrho > v$. Probably these changes are caused by an outwardly increasing alkali content, and the marginal parts of the mineral seem to belong to the group of hastingsitic hornblendes, whereas the interior represents common hornblende.

About 40 thin sections of this rock from different localities were examined, but nowhere was fresh olivine found. Instead we find in all slides numerous pseudomorphs which no doubt are after olivine. The pseudomorphs generally are of about the same size as the pyroxene grains, and as a rule they show rounded forms reminiscent of olivine, but sometimes they may also display very distinctly the crystal boundaries characteristic of idiomorphic olivine (Fig. 13). Very often one may observe a veined structure, similar to that commonly exhibited by olivine and, thus, no doubt seems to remain as to the origin of the pseudomorphs. The latter are almost always bordered by a seam of *iron-ore* grains, and generally the interior, too, is crowded with grains of this mineral. Often the pseudomorphs are surrounded by broad aureoles of a finely scaly green material which is very difficult to identify but which is most probably made up of the same biotite-like mineral, as was found to replace some of the andesine laths. Besides, there is some *amphibole* and *common chlorite*. These scaly aggregates are referred to by TÖRNEBOHM as *viridite,* a term that has been frequently used as a collective name for products of this type. The term was first proposed by VOGELSANG (1872, p. 529) and afterwards DATHE (1874, p. 10) pointed out that the aggregates most probably corresponded to the green material which had been named diabantachronnyn by LIEBE (1870, p. 2), a name which is synonymous with the »diabantite» of to-day.

On the whole it appears as if the agencies causing the alteration of the olivine had strongly affected the environment of the pseudomorphs, and the distinct connection between the latter and the scaly aggregates seems to prove that there has been an exchange of material between the olivine and its surroundings, most probably effected by the pseudomorphosing solutions. In part these aggregates, as previously mentioned, seem to have formed out of plagioclase by reaction with iron-rich solutions, in part they appear to represent a late phase of primary crystallization.

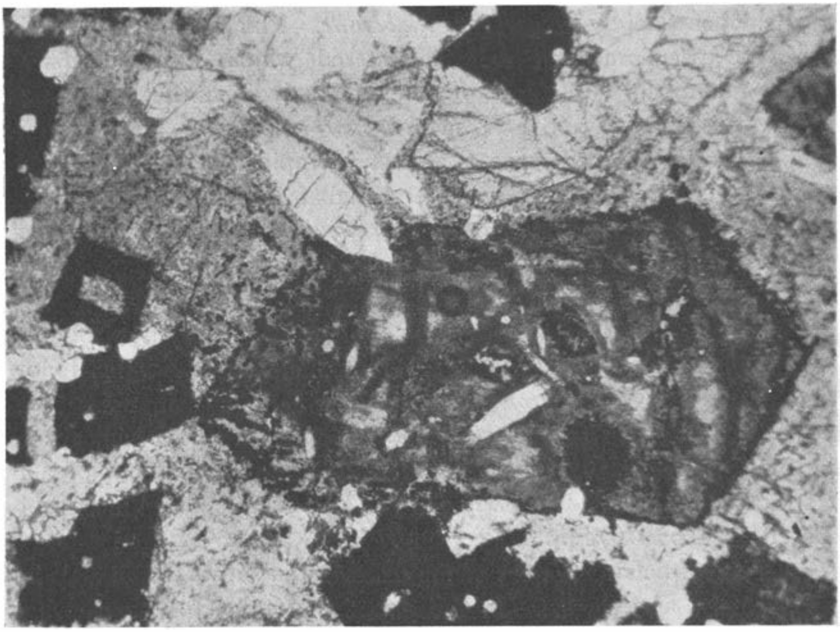


Fig. 13. Idiomorphic olivine pseudomorph in Hällefors dolerite. White inclusion=apatite. Specimen 137, one nicol. Magnification 40 diameters.

It is true that the olivine pseudomorphs are rather easily identified, but nevertheless tney may vary very much in appearance. In order to picture these variations as clearly as possible, the most important observations made in all slides examined, are put together below.

In most cases the pseudomorphs are composed of *iron ore* and a felted aggregate of *actinolite* lying in a matrix of colourless, very slightly birefringent *chloritic material* and, consequently, they remind one very much of the pseudomorphs described from the marginal dolerite. Sometimes, however, the actinolite needles are very scarce and the chloritic material becomes altogether dominant. It is then found to be of at least three different types. Most common is a variety very much similar to diabantite but colourless and only slightly birefringent. It should, no doubt, be classed as *delessite*. Sometimes, however, it may become rather strongly coloured and shows a distinct or even strong pleochroism:

γ *green*
α *colourless*.

This type, consequently, represents *diabantite*. Finally, in a few specimens [184] olivine pseudomorphs are encountered which, with regard to their habit, are identical with those of delessite and diabantite, but which are made up of *iron ore* and *a reddish-brown translucent mineral* which is faintly pleochroic, but otherwise of almost isotropic appearance. Marginally this mineral is often replaced by green diabantite. This almost isotropic variety may probably correspond to *chlorophaeite,* which has recently been observed to occur very often in doleritic rocks (CAMPBELL and LUNN 1927).

In the delessite fields large amounts of iron ore are invariably present and often this iron ore arranges itself in parallel lamellae which follow the cleavage planes. Also *a brown biotite-like mineral* is sometimes found to form intergrowths with the delessite and the diabantite, following the planes of the micaceous cleavage, or to occur as bands or patches of a finely scaly structure within the pseudomorphs. The mineral should most probably be classed as *ferrite* (*cf.* pp. 183—184).

A very conspicuous feature of the delessite-diabantite individuals is their irregular patchy appearance. In the direction parallel to the cleavage the greater part of the mineral may be deep green in colour whereas a few patches are very faintly green or colourless. In directions perpendicular to the cleavage, on the other hand, the mineral is for the most part colourless and the patches just mentioned are coloured an intense bluish-green. A study with very high magnification reveals that the patches are made up of aggregates of extremely small *amphibole* prisms. These, because of their small size, could not be optically determined, but to judge from their bluish-green colour they are most probably to be classed with the hastingsitic hornblendes. It was not possible to ascertain any regular mutual orientation between the amphibole and the diabantite except that the amphibole prisms are never seen to be arranged parallel to the cleavage planes of the host mineral. As a consequence, the bluish-green colour, which represents the γ-direction of the amphibole, is more prominent in the colourless position of the diabantite than in the green one. As a matter of fact the contrasted pleochroism of the two minerals is more pronounced than one would expect from a purely random arrangement, and thus it seems quite probable that a homoaxial position was strived after, with the γ-direction of the amphibole parallel to the α-direction of the diabantite.

As to the mutual genetic relations of the minerals they seem to be quite obvious. The ferrite-lined cleavage planes of the diabantite are seen to continue unbroken through the amphibole aggregates and, consequently, the latter must have been formed at the expence of the diabantite. Sometimes this mineral is completely replaced and the final result is a monomineralic amphibole aggregate in which the cleavage planes of the original mineral are often still preserved.

There appears to be little doubt that a close relationship exists between the different mineral varieties found in the olivine pseudomorps *viz.* delessite, diabantite, chlorophaeite(?), and ferrite. As concerns the two first-mentioned ones there are some indications as to the cause of the variation. We always find delessite in those pseudomorphs that are crowded with grains of iron ore, whereas in the diabantite pseudomorphs there is considerably less iron ore or none at all. It will appear, then, that the transition from delessite to diabantite — indicated by an increase of birefringence and colour — is caused by iron entering the compound.

The secondary products of olivine, which have been described and discussed above, are in no respect new to petrologists. Firstly, much of what is often simply described as delessite should most probably be better classified as diabantite and, secondly, quite similar products have been noted on several occasions from the basalts of Skye and Mull. Thus HARKER in describing the basic effusives of Skye speaks of olivine-pseudomorphs »composed mainly of some undetermined mineral of which several varieties have been noticed, sometimes with the general appearance of a mica and recalling in some respects the iddingsite of LAWSON . . . . The substance is usually of a very pale tint or almost colourless in a thin section and gives about the same interference-colours as augite. It has a strong cleavage . . . . and extinguishes straight or very nearly straight . . . . At a late stage [of the alteration] both serpentinous pseudomorphs and those of the class which we have likened to iddingsite, sometimes absorb part of the iron-oxide again, becoming of a deep green colour with strong pleochroism. We find also pseudomorphs with a deep red-brown colour, which probably belong to what Professor HEDDLE has named ferrite.» (HARKER 1904, p. 34).

Further, THOMAS describes from the mugearites of Mull an alteration product of olivine of high birefringence and deep green colour (BAILEY 1924, p. 144). There seems to be no doubt that the pseudomorphs, described in the previous pages, are altogether identical with the Scottish ones, but even so there is no certainty as to their exact mineralogical classification. From a somewhat extensive study of papers dealing with the chloritic minerals, and from my own observations, however, I have been led to the conclusion that a lot of mineral names such as ferrite, hullite, bowlingite, iddingsite, diabantite, delessite *etc.* represent simply different members of one mineral series and, moreover, are very prone to pass one into another. Most probably antigorite forms one of the end members, and delessite, to judge from its optical properties, occupies a position rather close to antigorite. I am well aware that a similar opinion concerning the chlorites has been announced by WINCHELL (1926), but it seems appropriate to stress the point still more, as there is still great confusion in petrological literature in regard to these minerals. My observations in all respects tend to confirm the views of WINCHELL (*loc. cit.*). A final solution of the problem can, of course, be arrived at only by detailed mineralogical and chemical investigations but, according to the nature of the minerals in question, such investigations meet with great difficulties, and thus it seems justifiable to put forward the opinions gained even by a superficial microscopical study.

Iron ore is very abundant, occurring partly as dust in the olivine pseudomorphs, partly as independent grains which often show a corroded or skeleton development. In most slides a marked *leucoxene* alteration is observed, resulting in grate-like forms, where leucoxene occupies the larger part of the grain, leaving only narrow lamellae of iron ore along the planes of the rhombohedron.

In addition to the coarse mineral components hitherto described, the rock contains varying quantities of fine-grained interstitial material. In its most usual development this material is composed of a fine mixture of *alkali-feldspar* and a little *quartz.* Both *potash feldspar* and *albite* are undoubtedly represented, but it was impossible to estimate their mutual quantitative relations. The texture varies a little from one specimen to another — most common is a sort of microspherulitic development but a micropegmatitic one is also sometimes observed. Besides these main felsic components the interstitial material almost always contains fair quantities of mafic minerals, *viz. amphibole, pyroxene, iron ore,* and the scaly biotite-like mineral that was found as lamellae and patches in the delessite-diabantite individuals and which seems most properly to be referred to as *ferrite.*

Ferrite occurs as fine rosette-formed aggregates of a yellowish brown colour which are scattered all over the feldspathic groundmass, or, more rarely, it is found as larger ragged patches of a dirty colour. The *amphibole* occurs in much the same way as the ferrite and shows the following optical properties:

$2V_\alpha$ varying within rather wide limits but always $< 60^\circ$
$c/\gamma = 14 - 18^\circ$
γ *faintly bluish green*
β *olive green*
α *colourless*

These properties seem to indicate that the amphibole is closely related to the hastingsitic series, members of which were previously observed to be represented as secondary products from the coarse pyroxene. As a matter of fact, this secondary amphibole is also seen in direct connection with the amphibole of the interstitial material.

The *pyroxene* of the latter also shows an intimate connection with the main pyroxene of the rock. One may observe how the latter continues its growth in bunches of narrow crystallite-like rods, which dissect the interstitial material in parallel groups. Most probably the groundmass amphibole represents a secondary product of the groundmass pyroxene, and thus the relations within the fine-grained material should correspond to those of the larger crystals.

Finally, the interstitial material carries rather large quantities of *iron ore,* which is generally developed as long narrow needles. As this development is still more common in the typical porphyritic rocks it will be described in more detail in that connection, and at the present moment attention will only be directed to its occurrence in these rocks.

Apatite is as a rule very abundant in the feldspathic groundmass and occurs in the form of small crystals showing perfect idiomorphy.

As has been already hinted at, the interstitial material is sometimes developed in quite another manner, *viz.* as a dense scaly aggregate of mafic minerals, and frequently the two types may occur in the same slide in different interstices. Transitions between them are often observed and it appears as if the main difference were to be found in the quantity of ferrite. In the dense aggregates the latter is considerably more abundant than in the other types, and it seems as if a certain antagonism can be traced between ferrite and hastingsite, in as much as the latter decreases in amount as the former increases. It is very possible, however, that this relation is only apparent and is caused by the difficulty of observing minute hastingsite scales in rocks rich in strongly coloured ferrite.

The microscopic investigation of the Hällefors dolerites gives a strong impression that in the later stages of the evolution of these rocks two different trends were manifesting themselves. One is represented by the interstitial material of feldspathic composition, the albite bordering of the andesine laths, and the hastingsitic character of the secondary amphibole. The other is mainly depicted by the sometimes enormously abundant aggregates of finely scaly mafic minerals. These two trends to a certain extent seem to be opposed to one other, as is indicated by the continuous transition between the two types of interstitial material. As a matter of fact it will be clear that in the later stages two different residual solutions were operating — one rich in the alkali-feldspar components and the other extremely rich in iron. Now, the first type of solution is quite easily accounted for, as it represents the composition towards which the melt should normally tend as crystallization proceeds. Further it is true that crystallization will also bring about an enrichment of the melt in iron, but this enrichment is only a relative one, *viz.* leading to an increase of the ratio *Fe* : *Mg*. The ratio *femic oxides* : *alkalies* on the other hand must tend to decrease, as an early crystallization of mafic minerals is clearly indicated by the rock. Thus it is hardly possible that crystallization alone would be able to give rise to a residual melt highly enriched in iron. We have found, moreover, that the mafic aggregates are especially dominant in the vicinity of the iron ore and the olivine pseudomorphs, and it is my opinion that in this fact the clue for solving the problem is to be found. The iron-rich solutions operating alongside the alkaline ones have been simply generated by the break-down of mafic minerals of early formation, mainly olivine and iron ore. Before discussing in more detail the evolution leading to such processes, some attention should, however, be directed to the chemical aspects of the rock.

In table XII below a chemical analysis of a typical rock of the Hällefors dolerite group is given. The most conspicuous features of the analysis are the high content of iron, titanium and phosphorus and the correspondingly low content of magnesia and alumina. As these relations most probably are inherent in the magma itself, they will, however, be more closely considered in another connection (see p. 228 ff.), and at present attention should only be directed to the norm.

Considering the occurrence of fine-grained interstitial material and the abundance of secondary minerals, it is not surprising that great discrepancies between the norm and the mode are found. Thus the normative anorthite content is only *11.8 %* whereas the modal plagioclase was determined as An_{40}. This difference is, of course, very easily explained since, firstly, the andesine grains are surrounded by albite borders and, secondly, some amount of alkali-feldspar is found in the interstitial material.

If this explanation is accepted, however, another difficulty arises as the proportion of plagioclase in the rock, calculated from the normative anorthite percentage and the plagioclase composition, microscopically determined, comes out as only 13.2 %, whereas the microscopical investigation shows that there is at least 30 % andesine in the rock. This discrepancy indicates that too much lime was allotted to pyroxene, and this is caused by the low alumina value. The only possibility is to free some alumina by placing part of the alkalies in compounds claiming less alumina than the feldspars. As neither of the well-defined minerals of the rock can serve such a purpose, attention must be directed to the obscure aggregates of mafic minerals that partly fill the interstices, cluster around the olivine pseudomorphs and sometimes replace the plagioclase. In these aggregates we have observed two different scaly minerals; one referred to as ferrite, the other described as green and biotite-like. Biotite certainly contains potash, but it is very improbable that the proportion $Al_2O_3 : K_2O$ can be less than that of the feldspars. As a matter of fact only one biotite that meets this requirement is found among all biotite analyses recorded in DOELTER's manual (1917, p. 680 ff.) *viz.* a mica occurring in dikes, cutting some islands in the Oslo firth (BRÖGGER 1890, pp. 189—194). As this mica, both in regard to its occurrence and its general character, seems quite incomparable with the present one, I am not inclined to assume a similar composition for the latter.

Table XII.

Analysis 3.

Hällefors dolerite, Ölmstorp. Specimen 221.

Spec. gr. $^{17^\circ}_{4^\circ} = 3.003$. Analyst: N. SAHLBOM.

	Weight-%	Mol. Prop.
SiO_2	47.30	788
TiO_2	3.20	28
Al_2O_3	9.49	93
Fe_2O_3	5.54	34
FeO	14.96	208
MnO	0.29	4
CaO	7.60	136
MgO	3.28	82
Na_2O	2.76	45
K_2O	2.69	29
P_2O_5	1.44	10
H_2O+	1.50	
	100.05	

Norm			
	Qu	0.06	
	Or	16.12	
	Ab	23.58	
	An	5.28	Σ sal 45.04
di	$CaSiO_3$	9.74	19.84
	$MgSiO_3$	3.10	
	$FeSiO_3$	7.00	
hy	$MgSiO_3$	5.10	16.32
	$FeSiO_3$	11.22	
	Mt	7.89	
	Ilm	6.08	
	Ap	3.36	Σ fem 53.49
		H_2O+	1.50
			100.03

III : 5 : 2 : 3 *Lamarose*

Or : Ab : An = 35.8 : 52.4 : 11.8

OSANN's System

s55.1 a4.0 c1.0 f25.0 n6.1

S : Al : F = 17.5 : 2.0 : 10.5

Al : C : Alk = 9.0 : 13.5 : 7.5

k = 0.86

NIGGLI values

qz	−25.5	si	118.5
al	14.0	ti	6.0
fm	54.5	mg	0.23
c	20.5	k	0.39
alk	11.0	p	1.50

There seems to exist another possibility, however, to dispose of the alkalies without great consumption of alumina, *viz.* the formation of *celadonite* or related minerals belonging to the group of alkali-bearing iron chlorites. The green »biotite-like» mineral can hardly be identified in a reliable manner, as the fineness of the scales greatly hampers a close investigation. Nor is the green colour altogether characteristic of biotite, and thus I should not consider it impossible that the scales in question may represent an iron chlorite. A point in favour of this explanation is that the mineral in question is of a *habitus* and an occurrence very much similar to that of the ferrite. An examination of the analyses of celadonite recorded by DOELTER (1921, p. 351 ff.) reveals the fact that the proportion *alumina*: *alkalies* is in most cases less than 1.00, very often lies about 0.3—0.8, and in one case attains a value as low as 0.12. The corresponding values for orthoclase and albite are 1.09 and 1.65 respectively and, consequently, the presence of even a moderate quantity of celadonite would imply a considerable disagreement between the normative feldspar composition and the modal one.

Now, celadonite has been described on several occasions as a secondary product in basaltic and doleritic rocks and it was pointed out by HEDDLE (HEDDLE and THOMSON 1894, p. 249—250) that it is always found to represent a transported product of alteration. Thus it never remains within the boundaries of the original minerals as a pseudomorph in a strict sense. In the present case the basic interstitial fillings can hardly be characterized as a product of alteration, but we have previously reached the conclusion that there has been some exchange between the numerous olivine-pseudomorphs of the rock and the late interstitial material. Such an exchange may very well have resulted in the deposition of some of the olivine material in the form of celadonite or related minerals. The question whether celadonite or diabantite may be formed, should then be a matter of the alkali concentration only. However, it seems hardly necessary to postulate that such minerals must have resulted from alteration. If a mineral originates as a secondary product its stability during the prevailing conditions seems to be proved and, consequently, there should be nothing to prevent a simultaneous primary deposition of the same mineral, provided that the oxides required are accessible in the melt. Previously it was pointed out that diabantite, which is rather closely connected with celadonite, evidently was formed both as a secondary product from olivine, and as a primary constituent.

It should be emphasized that the assumption that celadonite occurs in the interstitial material and in the aureoles of secondary matter is made for purely theoretical reasons and has not been proved by observation. It seems, however, that this assumption is the only one that can in any way account for the peculiarities of the chemical analysis as compared with the modal mineral assemblage.

Taking into consideration both the microscopical observations and the conclusions drawn from the chemical analysis the evolution of the rock-forming magma may be pictured as follows.

At some depth a basic magma, extremely rich in iron and rather poor in alumina, was partly crystallized, yielding as main minerals some iron ore, olivine, pyroxene and andesine. (Concerning the possibility of such a crystallization see p. 185). After this crystallization the residual melt was still more impoverished in alumina and enriched in iron relatively to magnesia. Moreover, it was strongly enriched in alkalies. The magma was then intruded to higher levels as a crystal porridge, the liquid portion being of about trachytic composition. Owing to the new physico-chemical conditions introduced by intrusion some of the minerals previously deposited were no longer stable and so reacted with the residual liquid. Thus albite partly replaced the andesine and partly was simultaneously deposited around the old andesine laths. (These processes will be more fully dealt with in a later chapter, p. 202 ff). As the lime, liberated by albitization, was generally disposed of by the formation of zoisite, no great change in the composition of the residual melt was effected by this process. In the case of the mafic minerals, however, the result was quite different. We have found that olivine, being very susceptible to alteration, was completely replaced by a great many different types of secondary products and I have been able to show, moreover, that the formation of one type or another was to a great extent controlled by the more or less marked inclination of iron to enter into the compound. It is evident, then, that in places vast amounts of iron must also have migrated into the residual melt, which was effecting the alterations. As there would hardly have been time to effect a compensation of the chemical differences thus brought about in the melt, the result must have been that the liquid portions of the last stages were highly heterogeneous in composition, as is witnessed by the different development of the interstitial mass in different parts of the rock or even of the same thin section.

The break-down of olivine, however, did not result only in a further enrichment of the melt in iron, but as the pseudomorphs are mainly of chloritic composition, considerable amounts of alumina must have been taken away from it, thus leading to a still more accentuated deficit in this oxide. Therefore, when the final crystallization set in, the alkalies were left after combining with the alumina present to form feldspar. Consequently, residual alkalies combined with the abundant iron to form celadonite, a mineral which might be expected to be stable at the temperature prevailing during the later stages of crystallization.

2. Glassy development.

It has been already mentioned that the Hällefors dolerite very often displays a fluidal texture, which is due to the parallel or sub-parallel arrangement of its feldspar laths. This texture is almost everywhere recognizable, at least in the most central part of the dike. It is more or less pronounced at different localities, but especially within a small area south of Lake Skogssjön it is extremely well developed. As the rocks of this district differ slightly from the prevalent types in other respects, too, it seems convenient to treat them separately.

A section from the south shore of Lake Skogssjön, proceeding southwards, first shows the usual mottled dolerite and a very narrow zone of the coarse-grained dolerite of marginal type. Very abruptly the latter is succeeded by a Hällefors dolerite, which is black in colour and medium in grain [203]. Even to the naked eye the parallel arrangement of its feldspar laths is very conspicuous but this texture is better seen under the microscope. Plagioclase and pyroxene laths about 1 mm. in width and attaining a length of 5—10 mm. are arranged in a strictly parallel fashion, being separated from each other by an almost isotropic mesostasis, in which, moreover, are embedded numerous isometric and idiomorphic pyroxene grains, 1—3 mm. in diameter. The rather peculiar texture is illustrated in fig. 14 above.

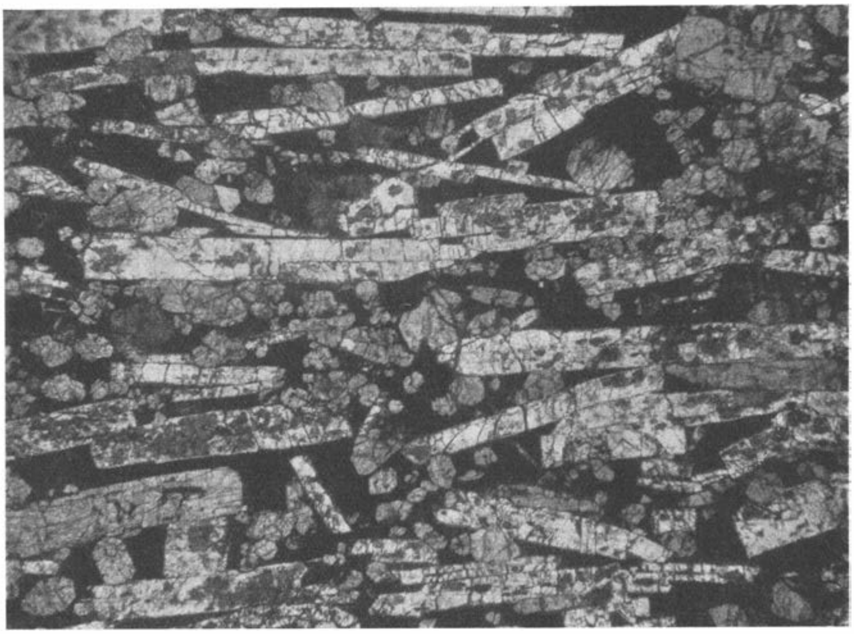


Fig. 14. Fluidal texture of the glassy Hällefors dolerite. White plagioclase, grayish pyroxene and black glass. Specimen 203, one nicol. Magnification 7 diameters.

The plagioclase crystals are the dominant component of the parallel texture. The pyroxene, on the other hand, only to a limited extent contributes to this texture, a large part of it being represented by isometric grains. Both minerals are of exactly the same type as in the normal Hällefors dolerite, and the plagioclase was determined as $Ab_{60} An_{40}$. In addition to these main minerals there are found a few isometric pseudomorphs, consisting of diabantite and most probably representing original olivines. They occur in much the same manner as the isometric pyroxene grains.

Sometimes the pyroxene shows a slight marginal alteration to a faintly bluish-green amphibole of the hastingsitic type, and likewise, the plagioclase may sometimes exhibit a certain amount of sericitization.

The mesostasis, comprising about 25 % of the rock, is of a greenish black colour and can hardly be resolved by the microscope. By aid of a high-power objective and a condensor, however, one may observe abundant felty aggregates of a greenish mineral, apparently amphibole, scattered in a grayish matrix, which is probably of feldspathic composition. In some interstices — especially in the types immediately bordering upon the marginal mottled dolerite, where the parallel texture is not quite so pronounced as in the interior parts of the dike — the mesostasis is a little coarser and reveals much the same features as the groundmass of the porphyritic rocks (see p. 175 ff.). Thus, the characteristic pyroxene needles are represented and, further, there are indications of parallel rods of iron ore. It can hardly be doubted that the mesostasis is partly glassy and, probably, it was originally completely hyaline.

There seems to be little doubt that this parallel texture is a purely fluidal one, and that this interpretation should be generally applied to the parallel tendency of the Hällefors dolerites which is noticeable almost everywhere. It is very remarkable that the parallel arrangement becomes more pronounced in the inner parts of the dike than at the boundary against the marginal rocks, and this fact strongly supports the fluidal conception. It is also natural that the glassy development of the mesostasis should accompany the extreme type of fluidal arrangement. The contrast between the coarse pyroxene and plagioclase crystals and the somewhat abundant glassy groundmass can only be explained as the result of abrupt and very rapid intrusion, which has led to a pronounced fluidal arrangement of the phenocrysts. In places where the velocity of intrusion decreased, this arrangement becomes less well marked and, further, the mesostasis may attain a higher degree of crystallinity.

Although the Skogssjö area furnishes the most extreme example of the fluidal Hällefors dolerite, types with only slightly less pronounced development are met with in other parts of the dike, *e.g.* S.E. of the Svalbo inlet and S.E. of the eastern part of Lake Örhammaren.

It may be concluded from the textural development of the Hällefors dolerite in general that it was intruded as a crystal porridge with crystals of earlier formation suspended in a more or less abundant melt. The extreme types, just referred to, must then be interpreted as the result of especially strong intrusive forces, and thus their distribution

Table XIII.

Analysis 4.

Glassy Hällefors dolerite, S. of Lake Skogssjön. Specimen 203.

Spec. gr. $^{17^\circ}_{4^\circ} = 2.996$. Analyst: N. SAHLBOM.

	Weight-%	Mol. Prop.
SiO_2	44.41	740
TiO_2	5.30	66
Al_2O_3	10.77	106
Fe_2O_3	5.51	34
FeO	13.14	182
MnO	0.25	4
CaO	9.98	179
MgO	5.37	134
Na_2O	2.60	42
K_2O	1.08	12
P_2O_5	0.76	5
H_2O+	0.75	
	99.92	

Norm				
	Or	6.67		
	Ab	22.01		
	An	14.46		Σ sal 43.14
di	$CaSiO_3$	12.70	25.08	
	$MgSiO_3$	6.70		
	$FeSiO_3$	5.68		
hy	$MgSiO_3$	4.30	7.86	
	$FeSiO_3$	3.56		
ol	Mg_2SiO_4	1.68	3.31	
	Fe_2SiO_4	1.63		
	Mt	7.89		
	Ilm	10.03		
	Ap	1.68		Σ fem 55.91
			H_2O+	0.75
				99.80

III : 5 : 3 : 4 — *Camptonose*

Or : Ab : An = 15.5 : 51.0 : 33.5

OSANN'S System

$s_{52.4}\ a_{3.5}\ c_{1.5}\ f_{25.0}\ n_{7.8}$

S : Al : F = 16.5 : 2.0 : 11.5

Al : C : Alk = 9.5 : 16.0 : 4.5

k = 0.79

NIGGLI values

qz	—28.5	si	101.5
al	14.5	ti	9.08
fm	53.5	mg	0.35
c	24.5	k	0.22
alk	7.5	p	0.69

may give some hint as to the *focus* or *foci* of magmatic activity (see p. 227).

The fluidal dolerite from south of Lake Skogssjön was subjected to a chemical analysis, the result of which is given in table XIII. The norm, with one exception, tallies fairly well with the modal composition, an exception being the very high percentage of iron ore in the former. As a matter of fact, there is practically no iron ore whatever among the coarser constituents, and, although rather large amounts of it may be concealed in the mesostasis, the high values in the norm cannot very well be assumed to correspond to the actual composition. The explanation is, no doubt, that considerable amounts of TiO_2 enter into pyroxene, which is indicated by the reddish tint of the latter. This would imply, in its turn, an increase of the olivine percentage at the expense of hypersthene — a correction that is by no means contradicted by the microscopical observations. As to the general relations between this analysis and those of other Hällefors rocks these will be discussed in more detail on p. 228 ff. It may suffice here to point out that, although there are several differences, the general character of the analysis corresponds fairly well with that of the Hällefors dolerite of table XII. Especially the high titanium and phosphorus contents, as also the high ratio $Fe:Mg$ and the low percentage of alumina are noteworthy. In regard to the alkali percentages and the mutual proportions of Na_2O and K_2O, however, the analysis corresponds more closely with that of the rock 205, which will be treated in a later chapter. This rock, too, must be grouped with the Hällefors dolerites.

b. The Hällefors porphyrites.

As indicated by their name these rocks exhibit porphyritic texture, which is, however, more or less marked, owing to the varying frequency and dimensions of the phenocrysts. Furthermore, great variations in the texture and general *habitus* of the groundmass give rise to a large number of different types, and a detailed description of all of them is not possible. However, the variations seem to imply no important difference in the general chemical and mineralogical character of the rocks, and thus it is considered appropriate to treat them all under the same heading.

It is hardly possible to trace a distinct boundary in the field between the porphyrites and the Hällefors dolerites, as they seem to be connected by transitional types, and it may be considered that the two rock names connote the extreme members of a continuous rock-series. Megascopically the typical porphyrites show plagioclase phenocrysts in a black fine-grained or even quite aphanitic groundmass. In some types the groundmass is of a yellowish brown colour, but as these rocks seem to constitute a special variety they are treated separately on p. 191 ff.

Microscopically the phenocrysts are found to consist preponderatingly of *andesine* and to a less extent of *pyroxene, diabantite* and *iron ore*. In most cases, however, the last-mentioned minerals are restricted to the groundmass.

The andesine phenocrysts, as a rule, show good idiomorphism (Fig. 15) and are strongly twinned according to the Albite and Carlsbad laws. Except for slight sericitization, observed in most specimens, they are generally quite limpid, and because of this they contrast rather strongly with the turbid feldspar of the groundmass even when the difference of size between andesine grains and groundmass grains is so slight as to almost conceal the porphyritic texture. FEDOROFF stage measurements on a large number of andesine grains showed that their composition varies only very little around a mean value of

$$Ab_{60}\,An_{40}$$

In the majority of the specimens — especially those that possess a groundmass of some degree of coarseness — the andesine grains are seen to be surrounded by an outer zone of *albite* or *oligoclase-albite* which may sometimes attain considerable thickness.

Fig. 15. Microphotograph of a Hällefors porphyrite showing idiomorphic andesine phenocrysts in a relatively coarse-grained groundmass. Specimen 310, nicols +. Magnification 7 diameters.

The groundmass seems to be of the same mineralogical composition in all specimens but texturally its range of variation is very great (Figs. 15—17, of the same magnification). It is dominated by a feldspar that is rather turbid and shows no twinning. Because of this and owing to the generally very fine grain no exact determinations could be carried out, but it was found that both *orthoclase* and *albite (albite-oligoclase)* are present. As it is not possible to estimate their mutual proportions this mixture will be referred to below as alkali-feldspar. Sometimes, however, the alkali-feldspar is chiefly *perthite* or *antiperthite*, and in a few specimens the perthitic structure is so marked as to suggest an irregular twinning and may even lead to phenomena very similar to the »*Schachbrettalbit*» of BECKE (1913, p. 124) or to microcline structure. To judge from a chemical analysis of one of these rocks (analysis 8 of table XVIII, p. 200) they are to be considered as transitional to the albitic rocks treated on p. 191 ff. The groundmass very often exhibits a very fine-grained texture that may be termed microspherulitic or micrognanophyric (*cf.* GEIJER 1913, p. 52). In some specimens of considerably coarser grain the same texture may be preserved, in some it is replaced by an allotriomorphic or hypidiomorphic mosaic texture (Fig. 17), and in others the two types may be observed together in the same slide. In the last case one gets the impression that the microspherulitic portions represent the final congealing and in a way they form a groundmass of the second order for the larger allotriomorphic alkali-feldspars which in their turn serve as a matrix for the andesine phenocrysts. It would seem, too, as if the anorthite content of the larger »alkali-feldspars» were slightly higher than that of the fine-grained groundmass feldspars, which is probably to be connected with the fact that the fine-grained types are decidedly richer in phenocrysts than the coarser ones.

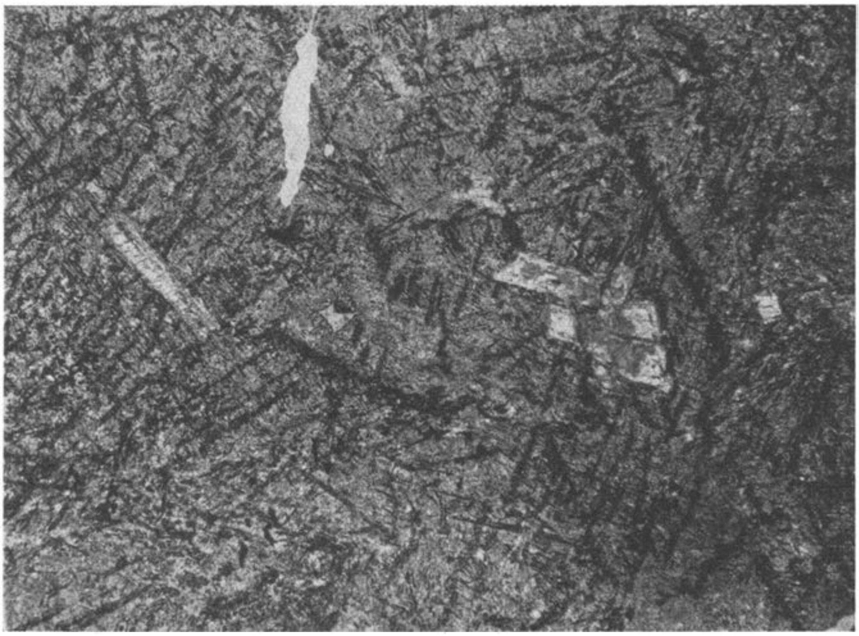


Fig. 16. Hällefors porphyrite with very fine-grained groundmass. Specimen 302, one nicol. Magnification 7 diameters.

The textural variations are still more manifold owing to different types of intergrowths between the alkali-feldspar and the other components of the groundmass, which will, however, be treated more fully below.

Quartz is almost invariably observed, but always in very small quantities. Sometimes it forms beautiful small micropegmatites with the alkali-felspars, but as a rule it occurs as a component of the microspherulitic texture and in this case it sometimes shows a development reminding one of the reticulating quartz of porphyries.

Next to feldspar, *pyroxene* is the most abundant mineral. As was previously hinted at, it may sometimes form grains of the dimensions of phenocrysts — giving rise to types transitional to the Hällefors dolerites — but as a rule its occurrence is confined to the groundmass. Its textural development is mainly of two types. It may occur in very long (up to 15 mm.) needles, generally not more than a few hundredths of a millimeter broad, or it may form intergrowths with the alkali-feldspar, reminding one of the common micrographic intergrowths between quartz and feldspar (Fig. 18). To some extent such an intergrowth is also observed between pyroxene and the andesine phenocrysts. Very often there seems to be a certain relation between the development of the pyroxenes and the coarseness of the groundmass, the intergrown types being more abundant in the specimens with relatively coarse groundmass. As a consequence of the general increase of grain-size the pyroxene needles that still occur become much broader than in the very fine-grained types. When pyroxene occurs as phenocrysts, there is almost always a direct connection between the phenocrysts and the groundmass needles and granophyric portions. Thus

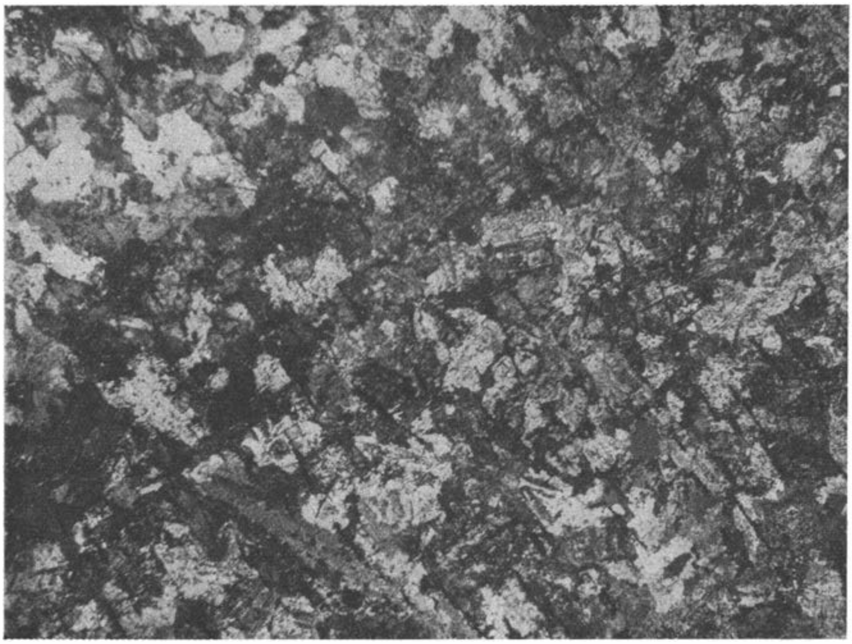


Fig. 17. Hällefors porphyrite of a relatively coarse mosaic texture. Specimen 302, one nicol. Magnification 7 diameters.

a pyroxene phenocryst may be surrounded by an aureole of granophyric pyroxene-feldspar intergrowths, and similarly a phenocryst of prismatic *habitus* may show forked ends, continuing its growth out into the groundmass as a series of needles of parallel or sub-parallel arrangement (Fig. 19). The development is quite similar to that described by LEHMANN (1930, p. 337) from the Stöffel rocks. Sometimes these needles display a fan-like arrangement and in the fine-grained types very beautiful minute intergrowths between pyroxene and alkali-feldspar may result. Sometimes the pyroxene needles are somewhat discontinuous, leading to the development of margarite-like forms. The granophyric intergrowths are found not only in the groundmass proper but also in the albitic outer zones of the andesine phenocrysts.

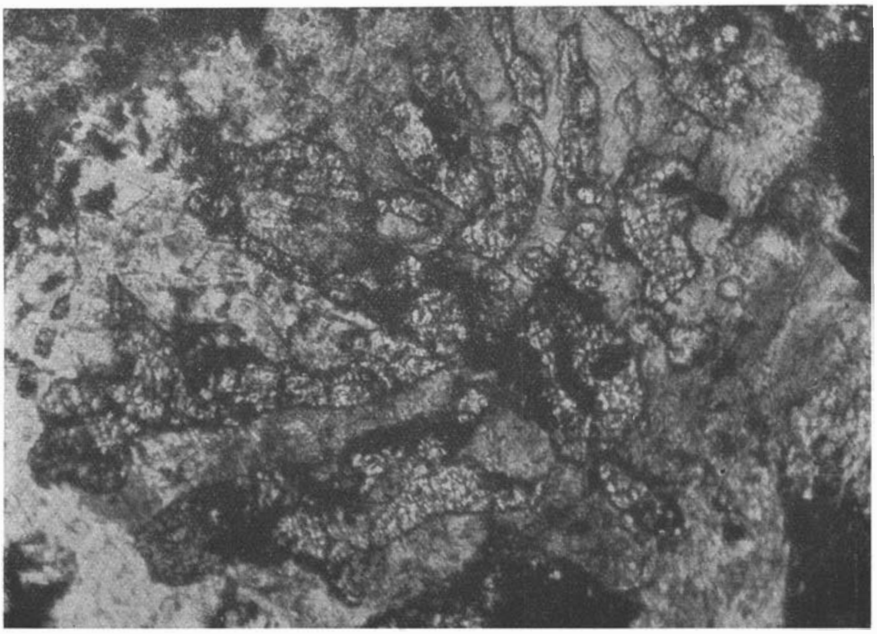


Fig. 18. Micropegmatitic intergrowth between pyroxene (high relief) and alkali-feldspar. Specimen 302, nicols +. Magnification 35 diameters.

The pyroxene has usually been altered marginally to *amphibole*, the latter being of two different kinds. The dominant variety has a small, somewhat variable axial angle: $2V_\alpha = 0—35^\circ$, $c/\gamma = 15—17^\circ$, low birefringence, strong dispersion $\varrho > v$ and marked pleochroism with γ *bluish green*, β *olive green* and α *light green*. These properties show that it belongs to the *hastingsitic group*. The other type is more restricted in occurrence, has a larger axial angle, weaker pleochroism, and no marked dispersion, and is of a pale yellowish brown colour. Most probably it belongs to the group of *common hornblendes*. The mutual relations of the two amphiboles are always the same: the yellowish type forming the centre or rather the inner parts of the amphibole border, the bluish green one constituting the outer fringe. The transition seems to be quite continuous, and the impression is gained that there has been a successive change of the material deposited or rather of the agents responsible for the alteration.

The pyroxene itself is markedly reddish in colour and shows a weak but perceptible pleochroism. From this fact as well as from the high titanium values of the chemical rock analyses (see pp. 187—188) the conclusion is arrived at that it belongs to the group of titaniferous augites. Its optical properties are found to vary rather markedly. Thus in a single slide the following values were found.

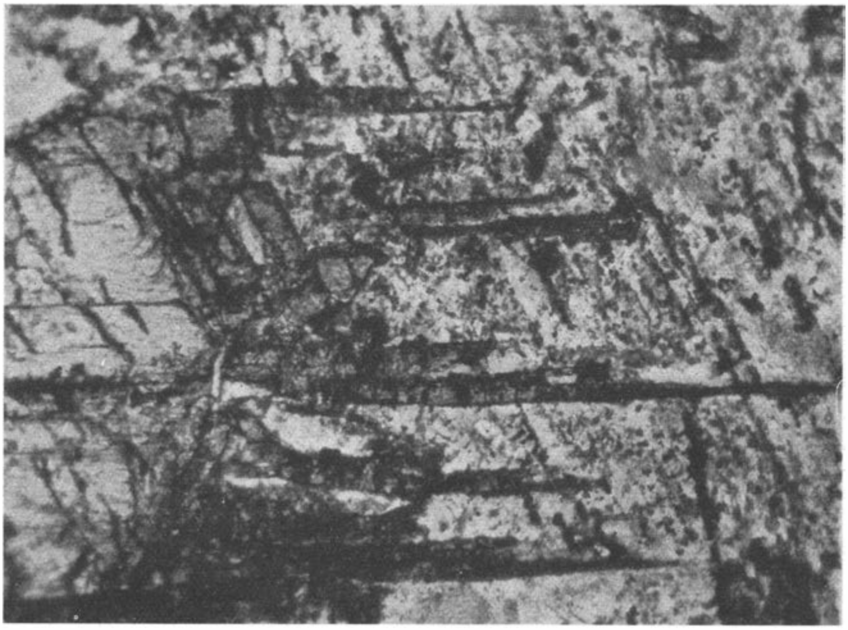


Fig. 19. A group of parallel pyroxene rods traversing the groundmass and projecting from a common large pyroxene phenocryst (left part of the figure). Specimen 313, one nicol. Magnification 100 diameters.

$$\begin{matrix} 2V_\gamma \\ c/\gamma \end{matrix} \quad \left.\begin{matrix} 48^\circ \\ 50^\circ \end{matrix}\right\} \quad \left.\begin{matrix} 42^\circ \\ 45^\circ \end{matrix}\right\} \quad \left.\begin{matrix} 54^\circ \\ 45^\circ \end{matrix}\right\} \quad \left.\begin{matrix} 56^\circ \\ 39^\circ \end{matrix}\right\} \quad \left.\begin{matrix} 44^\circ \\ ? \end{matrix}\right\}$$

Now, according to several authors, the different zones of growth of the titaniferous augites show considerable differences in their optical properties. The following data may be quoted.

	Core	Pyramide	Prism
1.	$2V_\gamma = 61^\circ$	$2V_\gamma = 55^\circ$	$2V_\gamma = 44^\circ$
	$c/\gamma = 42^\circ$	$c/\gamma = 51^\circ$	$c/\gamma = 59^\circ$

2.	$c/\gamma = 42^\circ$	$c/\gamma = 45^\circ$	$c/\gamma = 52^\circ$
3.	$2V_\gamma = 70^\circ$ $c/\gamma = 49^\circ.5$	$2V_\gamma = 50^\circ$ $c/\gamma = 45^\circ$	$2V_\gamma = 46^\circ$ $c/\gamma = 52^\circ$

1. SIGMUND 1896, pp. 372--374.
2. SIGMUND 1897, p. 342.
3. MICHEL 1914, p. 354.

Fig. 20. Groups of fine iron-ore rods perpendicular to long bars of diabantite. Specimen 303, one nicol. Magnification 40 diameters.

It is evident that the optical values, determined by the author, fall very well within the area found for titaniferous augites. Moreover, DRESCHER and KRUEGER (1928, p. 587) have described a titaniferous augite from Kaersute, Greenland, which showed $2V_\gamma = 58^\circ$, $c/\gamma = 48^\circ$ and, notwithstanding a titanium content of 2.98 %, was only slightly pleochroic and did not display hour-glass structure. In view of these facts the augite under discussion may, no doubt, be considered to belong to the titaniferous series. The great variation in optical properties found even in the same thin section is hardly surprising, since variations as great as those quoted above may be observed in the same crystal.

Titaniferous iron ore occurs rather abundantly in these rocks and, as in the case of the pyroxene, it may sometimes form grains of the dimensions of phenocrysts. In its most typical development, however, it belongs to the groundmass, and its mode of occurrence is rather remarkable. It forms long and narrow rods, intersecting the feldspathic material as groups with a mutually parallel arrangement, passing without a break from one feldspar grain to another. An idea of the peculiar texture resulting from this arrangement may be gained from Fig. 20. It is quite evident that there is a connection between the coarseness of the groundmass and the dimensions and the frequency of the iron-ore rods. In the coarser types the latter are rather broad and of considerable length, each group of rods becoming simultaneously less dense. Sometimes the rods may even become so sparse that the parallel arrangement is hardly discernible, a group of rods being replaced by one or two rather coarse laths. The relations just described may be better understood by a comparison of Figs. 20 and 21 which represent the same magnification, the former showing a very fine-grained groundmass, the latter a coarse one with mosaic texture.

Similar iron-ore rods have been described by PEHRMAN (1935) from a glassy dolerite from Kirjala, Finland, and this author was able to show that they are composed of a number of separate individuals, bounded by basal plane and rhombohedron (*loc. cit.* p. 7 and Pl. Fig. 1—3). Such a structure has not been proved with certainty in the present case, but there are certainly indications of it. There seems to be no doubt that the rod-form is real. If they represented merely cross-sections of parallel ilmenite plates, it seems very improbable that in more than twenty thin sections the plates should nowhere have happened to be cut in such a way as to show a two-dimensional extension.

In the groundmass yet another very conspicuous mineral component is observed, forming numerous long rectilinear bars that remind one of the pyroxene needles previously described (*cf.* Fig. 20). Like the latter their dimensions are evidently related to the degree of coarseness of the groundmass. In some specimens they are made up of *diabantite*, in others of another chloritic mineral, the exact identification of which is rather difficult. Both types are fairly well developed with a marked cleavage perpendicular to the long axis of the bars. The diabantite is strongly pleochroic with γ *green* and α *colourless.* In one specimen [313] the following optical properties were determined.

$$N_\alpha = 1.564 \pm 0.003 \qquad N_\gamma = 1.598 \pm 0.003$$

$$N_\gamma - N_\alpha \text{ (calculated)} = 0.034 \pm 0.006 \quad N_\gamma - N_\alpha \text{ (determined)} = 0.035 \quad 2\,V_\alpha = 10^\circ$$

The α-direction is perpendicular to the cleavage. For comparison it may be noted that ROSS and SHANNON (1924, pp. 15—17) have described a chlorite from Challis, Idaho, that shows $2\,V_\alpha = 15^\circ$ $N_\gamma - N_\alpha = 0.023$ with pleochroism in olive green and brownish yellow. A chemical analysis showed that the mineral is closely related to diabantite or delessite and that the iron content is very high $(FeO + Fe_2O_3 = 31.88)$.

WALKER (WALKER and PARSONS 1922, pp. 45—46) describes a diabantite with $FeO + Fe_2O_3 = 16.78$ which was found by LARSEN to be almost uniaxial negative with $\gamma = \beta$ *olive green*, α *pale yellow*, and

$$N_\gamma = 1.595 \qquad N_\alpha = 1.555 \qquad N_\gamma - N_\alpha = 0.040.$$

Fig. 21. A coarser development of the same texture as illustrated by Fig. 20. Specimen 304, one nicol. Magnification 40 diameters.

The other type of chlorite mentioned above occurs in exactly the same way as the diabantite, the only difference being the colour. It is strongly pleochroic with γ *dark brown or almost black*, α *golden yellow*. Possibly its birefringence is somewhat lower than that of the diabantite, but owing to its strong colouring exact comparison is difficult.

Sometimes, instead of forming single crystals, the chlorite bars consist of intricate aggregates of small scales or rosettes of diabantite, or else brown chlorite. Further, there is almost invariably some *hastingsitic amphibole* scattered all over the bars in the form of slender prisms. It should also be noted that the chloritic material is not generally restricted to the long bars, but that in most cases the whole groundmass is abundantly crowded with scales or rosettes of the same type as those observed in the bars.

It is not easy to classify the brown chlorite. In some respects it reminds one very much of biotite, but its general character and its marked aptitude for replacing diabantite seems to contradict such an interpretation. As a matter of fact, it must be rather closely related to diabantite, and most probably it belongs to the group of iron chlorites. EMERSON (1882, p. 201) has found that, by oxidation, diabantite alters readily to a brown almost isotropic substance that he named *diabantite-vermiculite*, and there are certainly marked resemblances between our brown chlorite and the vermiculite or jefferisite determined by LARSEN (1921, p. 93). On the other hand it may be questioned if the mineral is not also related to the ferrite of HEDDLE (1882, p. 28 and 1887, p. 134). Owing to the great confusion in the terminology of the chlorite group and the large number of synonymous mineral names applied to its members, it is rather dificult to apply any of them to the species under discussion, but it seems appropriate to point out its probable relationships. In the following descriptions the mineral is referred to as *ferrite*, which is considered justifiable because of its very intimate connection with diabantite. It should be stressed, however, that this name must be considered as provisional.

Diabantite and ferrite, just as in the case of pyroxene, sometimes form fairly large, irregularly isometric individuals which must be regarded as phenocrysts. The distinct antagonism between the two mineral varieties should be specially noted. They almost never occur together in a specimen. The transition, therefore, from diabantite to ferrite seems to be caused by some process affecting the rock as a whole and inverting not only the material of the bars and phenocrystal patches but also the fine scales and rosettes of the groundmass. Owing to the strong colour of the ferrite the difference is readily appreciated by the naked eye. In the field one is tempted to interpret it as a result of weathering, as there seems to be a laminar alternation between fresh, black types and brownish ones, of an altered appearance. Microscopically, however, it is at once apparent that the only difference lies in the colour of the chloritic material. (See, however, the chapter on the albitic rocks, p. 191 ff.). In the black portions diabantite is megascopically discernible as thin scales with a resinuous lustre.

Now, a very peculiar relation may be observed between the abovementioned iron-ore rods and the diabantite bars, the former almost without exception arranging themselves at right angles to the latter. From almost every diabantite bar on each side a series of parallel iron-ore rods is seen to diverge, the resulting structure being similar to that of a double-sided comb. As a matter of fact, the peculiar groupwise parallelism of the iron-ore rods is brought about simply by this mutual arrangement between them and the diabantite bars. These relations are most conspicuous in the very fine-grained types, where the rods are numerous, but even in the coarser specimens one may observe the occurrence of one or two rather broad iron-ore laths arranged at right angles to a diabantite bar.

The first question for consideration concerns the genesis of the diabantite-ferrite minerals. A primary origin cannot, of course, be entirely excluded, but their arrangement in the long bars with the cleavage at right angles to the long axis, seems to make such a possibility less probable. It seems easier, then, to interpret them as secondary products of some other mineral, which was originally developed in long, narrow forms. Now the diabantite of the rocks previously described was most certainly secondary after olivine, and it seems reasonable to claim the same origin for it even in the porphyritic rocks. It is of great interest to find that quite similar phenomena were observed by SCHWANTKE (1904) in a rock from Ofleiden which he describes as »dendritic dolerite» and which seems to be almost identical with those now under discussion. In the Ofleiden rock all the pyroxene and feldspar structures described above are encountered and also the groups of parallel iron-ore rods. Similarly, the latter are perpendicular to long bars, now consisting of iron oxides but representing original olivines. SCHWANTKE states that this arrangement is so typical that he ventures to claim an original olivine content in a rock from the observation of such groups of iron-ore rods only (1910, p. 678).

Further exactly similar phenomena are described by CAMPBELL and LUNN from the Dalmahoy dolerites (1927, pp. 497—498 and 1925, pp. 435—440) the bars being in this case formed by chlorophaeite which is proved to have originated from the alteration of fayalite. (It has already been suggested (p. 164) that there is a close relation between the chlorophaeite and diabantite types of alteration).

One may fairly confidently conclude, then, that the diabantite of the porphyritic rocks represents olivine pseudomorphs. The very interesting question of the order of crystallization next arises. It has been stressed that andesine phenocrysts always occur, whereas pyroxene and diabantite attain phenocrystal dimensions only in a very limited degree. Furthermore the occasional graphic intergrowths between pyroxene and the phenocrysts of andesine show that the two minerals were to some extent crystallizing simultaneously. No indications of the simultaneous crystallization of olivine and andesine are found and, moreover, diabantite is considerably rarer as phenocrysts than pyroxene. The obvious conclusion would be that crystallization started with andesine, followed by pyroxene and that, eventually, as the third mineral, olivine began to form. At first such a succession seems rather surprising, but as a matter of fact it should not be altogether impossible. We must bear in mind that the rocks in question are extremely rich in iron (see the analyses of table XIV—XV) and most probably the olivine that formed was very rich in the fayalite molecule. Even in the marginal dolerites with their considerable higher ratio $MgO : FeO$ the olivine was found to be as rich in fayalite as about *40 %* (p. 129) and in the porphyrites a variety still richer in iron must be expected. The fact that no olivine is anywhere preserved seems to strengthen this opinion, as the iron-rich members of the series are far more susceptible to alteration than the Mg-rich ones. Now, fayalite is decidedly a low-temperature mineral which is met with even as a pneumatolytic product, and thus it seems by no means improbable that its crystallization should have been postponed until the greater part of the plagioclase and pyroxene had formed (see also p. 242). SCHWANTKE has also stressed the fact that the groundmass olivine of the dendritic dolerites belongs to a second, younger generation. The author takes the liberty of quoting SCHWANTKE (1910, pp. 680—681):

»Der einzige Fall, der dem Verfasser bekannt ist, in dem wir von dem Olivin einer zweiten, jüngeren Generation sprechen können, ist das Auftreten von jüngeren Olivin in der intersertalen Grundmasse der Dolerite. Hier tritt durch die frühe Ausscheidung des Feldspats die Möglichkeit ein, dass sich wieder Olivin bildet, und erst damit beginnt die für die porphyrischen Ergussgesteine charakteristische Rekurrenz der Gemengteile. Auch das Erz folgt hier auf den Olivin. Besonders die genannten Fälle sind es, die namentlich in der hier häufig zu beobachtenden dendritischen Ausbildung der Grundmasse, das orientierte Anwachsen der Ilmenittafeln an die Olivinsäulchen erkennen lassen.»

From this quotation it is evident that SCHWANTKE recognized the olivine as of late formation in these rocks. His explanation may, however, be questioned. If olivine was precipitated at an early stage and this crystallization was brought to an end, it seems rather improbable that the precipitation of plagioclase should be able to effect such a change in the composition of the melt that the conditions for the crystallization of olivine should once more be fulfilled. More likely, owing to the high iron-content of the melt, the deposition of olivine would be almost completely deferred till the stage of groundmass formation. By this interpretation one may also avoid the difficulty implied in the assumption of a *hiatus* in the course of crystallization of a mineral belonging to an isomorphous series that has been shown to belong to ROOZEBOOM's *Typus I* (BOWEN and SCHAIRER 1935, p. 206). It is to be regretted that no chemical analysis of the Ofleiden rock is given, which would allow us to discuss the possibility of a similar interpretation in that case.

Finally, there are found in the groundmass of the porphyrites very numerous crystals of *apatite*, generally showing excellent idiomorphism.

In order to illustrate the chemical characters of the Hällefors porphyrites two analyses were made, which are given in tables XIV and XV below. No 5 is of a slightly porphyritic type with a relatively coarse groundmass with mosaic texture, no. 6 is a markedly porphyritic variety with a very fine-grained groundmass. Both types carry the normal green diabantite, but types with ferrite will be considered later on in connection with the albitic rocks.

The two analyses are seen to agree very well. The total amount of iron oxides is almost exactly the same, but there is a slight difference in the degree of oxidation. Otherwise only the values of Al_2O_3 and of CaO differ slightly. It must, however, be borne in mind that the rocks are porphyritic, and consequently the analytical values may show some variations caused by an irregular distribution of the phenocrysts. Now the rock 123 (analysis 5) is very poor in phenocrysts, and has a fairly coarse groundmass. It is very probable that in this case more lime has entered the groundmass feldspars — as was, indeed, microscopically stated (see

Table XIV.

Analysis 5.

Hällefors porphyrite, E. of Lake Holmsjön. Specimen 123.

Spec. gr. $\frac{17^\circ}{4^\circ} = 2.818$. Analyst: N. SAHLBOM.

	Weight-%	Mol. Prop.
SiO_2	52.23	871
TiO_2	2.60	33
Al_2O_3	10.56	104
Fe_2O_3	5.91	37
FeO	10.79	150
MnO	0.30	4
CaO	7.57	135
MgO	1.73	43
Na_2O	2.84	46
K_2O	3.48	37
P_2O_5	0.66	5
H_2O+	1.20	
	99.87	

Norm			
Qu		6.42	
Or		20.57	
Ab		24.10	
An		5.84	Σ sal 56.93
di	$CaSiO_3$	11.25	23.00
	$MgSiO_3$	3.30	
	$FeSiO_3$	8.45	
hy	$MgSiO_3$	1.00	3.64
	$FeSiO_3$	2.64	
Mt		8.58	
Ilm		5.02	
Ap		1.68	Σ fem 41.92
		H_2O+	1.20
			100.05

III : 5 : 2 : 3 — *Lamarose*

Or : Ab : An = 40.7 : 47.7 : 11.6

OSANN's System

$s_{60.2}$ $a_{5.0}$ $c_{1.5}$ $f_{23.5}$ $n_{5.5}$

S : Al : F = 19.5 : 2.0 : 8.5

Al : C : Alk = 9.5 : 12.5 : 8.0

k = 0.98

NIGGLI values

qz	−9	si	147
al	17.5	ti	5.6
fm	46.0	mg	0.16
c	22.5	k	0.45
alk	14.0	p	0.84

Table XV.

Analysis 6.

Hällefors porphyrite, S. of Hälleforsnäs. Specimen 316.

Spec. gr. $\frac{17^\circ}{4^\circ} = 2.885$. Analyst: N. SAHLBOM.

	Weight-%	Mol. Prop.
SiO_2	50.41	840
TiO_2	2.50	31
Al_2O_3	11.97	118
Fe_2O_3	5.36	34
FeO	11.81	164
MnO	0.20	3
CaO	6.70	120
MgO	2.04	51
Na_2O	2.87	47
K_2O	3.51	37
P_2O_5	1.08	8
H_2O+	1.44	
	99.89	

Norm				
	Qu	3.48		
	Or	20.57		
	Ab	24.63		
	An	8.90		Σ sal 57.58
di	$CaSiO_3$	7.08	14.49	
	$MgSiO_3$	2.00		
	$FeSiO_3$	5.41		
hy	$MgSiO_3$	3.10	11.15	
	$FeSiO_3$	8.05		
	Mt	7.89		
	Ilm	4.71		
	Ap	2.69		Σ fem 40.93
				H_2O+ 1.44
				99.95

III : 5 : 2 : 3 — *Lamarose*

Or : Ab : An = 38.0 : 45.5 : 16.5

OSANN'S System

$s_{58.6}$ $a_{5.0}$ $c_{2.5}$ $f_{22.5}$ $n_{5.6}$

S : Al : F = 18.5 : 2.5 : 9.0

Al : C : Alk = 11.0 : 11.0 : 8.0

k = 0.94

NIGGLI values

qz	—18	si	138
al	19.5	ti	5.1
fm	47.0	mg	0.18
c	19.5	k	0.44
alk	14.0	p	1.32

p. 177) — and thus the total lime content of the rock would be less affected by an irregular distribution of the phenocrysts.

The chemical investigation seems to bring out, then, the fact that these rocks, although very different in texture, are still closely related, and thus we get a strong confirmation of the opinion gained from their microscopical investigation, *viz.* that they are all to be placed in the same magmatic group. Their marked mutual affinities become still more readily realized when we consider the NIGGLI and OSANN numbers, which are very much the same for both rocks.

Because of the general texture, which is either very fine-grained or very intricate, it is difficult to ascertain exactly the modal mineral composition, but — as is evident from the petrological description given above — it ought not to differ materially from the normative one.

When attempting to classify these rocks certain difficulties are encountered. They cannot well be classed with any of the magma-types of NIGGLI's (1923) and although, according to the CIPW-system, they fall in the same sub-rang, *Lamarose,* no analysis could be found in WASHINGTON's tables (WASHINGTON 1917) that can be said to show satisfactory agreement. The best agreement is shown by a dike rock from N. Ulfö in the Nordingrå area of Northern Sweden, which has been classed as kentallenite (SOBRAL 1913, p. 116). In table XVI below, for the sake of comparison, the two Hällefors analyses are repeated together with that of the Ulfö rock, and that of the original kentallenite (HILL and KYNASTON 1900, p. 357). It comes out that the Nordingrå rock, in regard to CaO, MgO and alkalies, differs but slightly from the Hällefors types. Silica is somewhat lower, alumina a little higher. Further it does not attain the high iron values of the Hällefors porphyrites, but the general tendency is the same, *viz.* low alumina, high TiO_2 and $FeO + Fe_2O_3$ with a correspondingly low magnesia value.

To judge from the microscopical description, the Ulfö rock is very similar to some of the Hällefors porphyrites and, moreover, they show a similar geological occurrence, both being associated with olivine dolerites of

Table XVI.

	1.	2.	3.	4.	5.	6.	7.
SiO_2	50.41	52.23	48.84	52.09	50.19	49.92	49.24
TiO_2	2.50	2.60	4.39	0.73	2.72	2.04	1.84
Al_2O_3	11.97	10.56	13.83	11.93	14.57	12.83	15.84
Fe_2O_3	5.36	5.91	2.92	1.84	4.39	6.96	6.09
FeO	11.81	10.79	12.24	7.11	8.96	6.21	7.18
MnO	0.20	0.30	0.22	0.15	0.32	0.52	0.17
MgO	2.04	1.73	2.18	12.48	2.79	3.78	3.02
CaO	6.70	7.57	6.05	7.84	7.60	7.35	5.26
Na_2O	2.87	2.84	3.20	2.04	4.24	3.72	5.21
K_2O	3.51	3.48	3.59	3.01	1.53	1.73	2.10
P_2O_5	1.08	0.66	0.73	0.34	1.12	0.45	1.47
H_2O+	1.44	1.20	1.01	0.35	1.54	1.05	1.61

1. Hällefors porphyrite, S. of Hälleforsnäs.
2. Hällefors porphyrite, E. of Lake Holmsjön.
3. Kentallenite, N. Ulfö, Nordingrå (SOBRAL 1913 p. 116).
4. Kentallenite, Argyllshire (HILL and KYNASTON 1900 p. 537).
5. Mugearite, Pembrokeshire, Wales (THOMAS 1911 p. 202).
6. » , Canna Island, Scotland (HARKER 1908 p. 130).
7. » , Skye (HARKER 1904 p. 263).

the Åsby type. Thus a close relationship between the two rocks can hardly be doubted. Whether the name kentallenite should be accepted or not is, however, another question. From the table on p. 189 it will be seen that the correspondence between the three Swedish types is far closer than between any of them and the original kentallenite. Above all, there are three characteristics of the Hällefors porphyrites that are very conspicuous and of especial importance for arriving at their genetical interpretation, *viz.* the high content of iron oxides (implying a correspondingly low magnesia content), and of TiO_2 and P_2O_5. All these characteristics are found also in the Ulfö rock, whereas they are missing from the Argyllshire kentallenite. I cannot find it appropriate to give the same name to two rocks that show as great differences of composition as $FeO + Fe_2O_3 = 16.94$ (Hällefors mean) resp. 8.95 (Argyllshire kentallenite) and $MgO = 1.88$ resp. 12.48. Now it may be objected that iron and magnesia mutually replace each other and that the differences are caused by a continuous change of composition of the femic minerals. As a matter of fact, the quotient $FeO : MgO$ must be considered as a very important quantity, as it may generally be expected to indicate the position of the rock on the liquid line of descent. Consequently, I will give it as my opinion that the chemical differences are sufficiently great to justify keeping the Hällefors rock apart from the kentallenite.

In view of the above considerations I have found it convenient to designate the present rocks only by a local attribute and so I have named them Hällefors porphyrites. I wish to point out that in my opinion they are to be grouped with the Ulfö rock, and my objections against applying the kentallenite name are equally valid for this rock.

Before closing the discussion of the chemical analyses it seems appropriate to point out that the Hällefors porphyrites, chemically and mineralogically, show certain resemblances to another group of rocks also, *viz.* the mugearites. In the three last columns of table XVI on p. 189 a few mugearite analyses are given, and a comparison between them and the Hällefors rocks shows that they agree quite well in that both show a high content of iron, titanium, and alkalies and a low percentage of lime and magnesia. The alumina content of the mugearites is generally decidedly higher, but may sometimes sink to almost the same values as in the Hällefors porphyrites. The most conspicuous difference is found in the distribution of the alkalies, the mugearites always showing $Na_2O > K_2O$ whereas in the Hällefors rocks this relation is reversed. The name mugearite was first proposed by HARKER (1904, pp. 257, 263—265) and I take the liberty of quoting a few lines from his description: »The chief mineralogical peculiarities of mugearite, which result from its unusual chemical composition and go to characterize it as a special rock-type, are two. Firstly the feldspar is not labradorite but oligoclase with subordinate orthoclase, and secondly the ordinary bisilicate minerals are very poorly represented, augite being typically quite subordinate to olivine and iron ore. Among minor points of interest may be noted the unusual richness in apatite . . . Feldspars of species rich in alkalies . . . appear in thin slices as a crowd of little elongated sections . . . with parallel or subparallel arrangement at any given point, the microstructure being consequently of the trachytic type.»

Although there are some points of difference between the two rock-types, certain important similarities cannot be denied, and I therefore consider it worth while to stress the possibility of the Hällefors porphyrites being related to the mugearitic suite.

c. The albitic rocks.

In the central parts of the dike, which are entirely occupied by the Hällefors dolerites, the Hällefors porphyrites, and transitional types there are found a few rock-types of restricted distribution which show very close relations to the dominant rocks, but which carry phenocrysts of *albite* instead of andesine. It has not been possible to give a general description including all these somewhat markedly varying types, and in the following pages a number of localities are treated separately, the rocks being in each case described both in regard to their geological relations and their petrological character. It would appear as if almost every type of rock within the central area has developed an albitic equivalent.

1. The area S. of Ölmstorp.

Traversing the dike from south to north, we first encounter the mottled marginal dolerite, and next to it a rock is exposed that shows phenocrysts of red feldspar in a fine-grained to aphanitic groundmass [217]. Microscopically the rock is found to represent an intermediate type between Hällefors dolerite and porphyrite, the groundmass being more abundant than in the former rock but without reaching the amount present in the latter. The groundmass is of the type common to the porphyrites with a fairly coarse microspherulitic texture and is crowded with spherulitic aggregates of ferrite. The larger mineral grains consist of dominant *plagioclase* and subordinate *pyroxene* and *chloritic pseudomorphs* after olivine. The latter are not of the usual diabantite type but consist of a finely aggregated green mass probably of *delessitic* composition, generally dissected by streaks of *ferrite*. The plagioclase grains show a core of the composition $Ab_{60}An_{40}$ and obviously they were originally composed of this material throughout. In their present state, however, they are intensely clouded by finely disseminated secondary products, mainly *zoisite* and *sericite,* and in consequence of this alteration the lime content of the plagioclase has decreased to such a degree that the outer parts show lower refraction than canada balsam and, consequently, approach the composition of *albite*. The very edge of the crystal, anyhow, is pure albite, but it is always quite limpid and shows an irregular outward boundary, indicating that it is more likely a primary deposit than a result of alteration. Often the plagioclase is dissected by veinlets of ferrite of the same type as that observed in the groundmass. The pyroxene is to some extent altered to *hastingsitic amphibole* and sometimes it also is veined by ferrite.

At some distance from the boundary against the mottled dolerite the rock just described is seen to be associated with a type of slightly different appearance [218]. In the field it conveys the impression of having an almost effusive structure; and its relations to the main rock are very difficult to unravel. Sometimes it is found as irregular portions within the latter, sometimes it forms long streaks in it, and everywhere it shows a very marked parallelepipedical jointing and an almost scoriaceous surface. Microscopically it is markedly porphyritic in texture with abundant phenocrysts, among which *albite* is dominant. The albite is crowded with *zoisite* aggregates, but is otherwise limpid. It exhibits well-developed twinning and an excellent idiomorphism. Further there are subordinate phenocrysts of *pyroxene* and *diabantite pseudomorphs* after olivine, but both these minerals have been subjected to intense alteration to *ferrite,* and in this way the pyroxene has been almost completely incorporated in the ground-mass. The latter is of the same type as in the main rock, but it is so intensely soaked with ferrite that its texture may only occasionally be observed. The same ferrite also fills some veinlets dissecting the slide and all cavities in their neighbourhood. A few irregular fissures, about 1 mm. broad, traverse the section and are filled with *epidote*. They are younger than the ferrite veins. *Apatite* is extremely abundant, as are also small prisms of *hastingsite*.

A little farther to the north a fine laminated cleavage is observed, striking S.E.—N.W. Under the microscope this laminated rock [219] shows exactly the same mineral composition as the one just described, but its albites and pyroxenes are intensely crushed and strongly veined by ferrite and a light green chlorite. Furthermore the slide is traversed by several zones of a few millimeters width, along which all the silicate components are chloritized and drawn out into long narrow seams in the chloritic material. In these zones a good deal of *epidote* is found in the form of small sharp-ended prisms.

This alternation of different rock-types is continued for some distance towards the north, but gradually a somewhat normal Hällefors dolerite becomes dominant and is eventually seen to replace all the other varieties. In the northernmost part of the section mottled dolerite is again observed.

A few hundred metres E. of the last locality somewhat similar relations may be studied in the outcrops immediately E. of the main road. The rock [212] is doleritic in character, no porphyritic types being encountered, but even megascopically it displays strong chloritization, intense jointing, and a laminar cleavage. It is dirty green in colour and carries abundant quantities of *apatite* and *pyrite*. It is dissected by numerous *epidote* veins. Microscopically, apart from the presence of *albite* instead of andesine, the general doleritic character is confirmed. The *pyroxene* has to a great extent been subjected to alteration with the formation of light-green spherulitic *chlorite,* and *ferrite* is also rather abundant. The albite crystals are only slightly charged with *zoisite,* but they generally show turbid surfaces owing to a rich development of *sericite*. They are strongly twinned.

2. The Svalbo area.

Immediately W. of the little tarn S.E. of the Svalbo inlet a single isolated outcrop is found, which is composed of a rock [205], strongly reminiscent of the one just described. Owing to its isolated position, its relations to the surrounding rocks could not be established. It is brownish in colour and conveys the impression of not being quite fresh. *Apatite* is seen even in the hand specimen to be extremely abundant. Microscopically the rock is found to be chiefly composed of long (5 mm. and more) laths of *albite*, $Ab_{95}An_5$, which show a markedly sub-parallel arrangement. They are partly altered to light-green *chlorite* which appears in patches within the feldspar. Outside these patches the albite is quite fresh and limpid.

Originally the rock also carried fairly large quantities of *pyroxene,* in grains showing good idiomorphism. Just as in the case of the albite, but to a far greater extent, the pyroxene is altered to light-green chlorite, which dissects the mineral in a rather coarse net-work of veins, leaving only small relics of pyroxene in the meshes. Sometimes the pyroxene has continued its growth into the mesostasis (see below) in the form of slender needles or prisms. One may also observe the partial conversion of the pyroxene into *hastingsitic amphibole,* this type of alteration being earlier in date than the chloritization.

Finally, there are very numerous rounded patches, which may sometimes show indications of crystallographical boundaries and in all probability represent *olivine pseudomorphs*. These now consist mainly of a dominant *light-green chlorite,* with abundant intercalated streaks of *ferrite*.

As a mesostasis for these coarser components we find a fine-grained groundmass of the same type as that found in the porphyrites, except that feldspar is practically wanting, and the dominant minerals are *pyroxene,* *hastingsite*, *iron ore*, and *ferrite*. *Apatite* is also extremely abundant in the mesostasis, but it always shows good idiomorphism and, besides, it is found as an inclusion in the coarse mineral components. Thus it seems likely that it should properly be grouped with the »phenocrysts» although its crystals are of smaller size. The iron ore is partly arranged in the parallel groups previously described. Finally, there is also some *epidote* and *titanite* in small sharp-pointed crystals.

A chemical analysis of this rock was carried out and the result is given in table XVII. It will be immediately realized that there is very little agreement between the normative and the modal composition. The most conspicuous discrepancy is found in the composition of the plagioclase, the norm indicating a considerable anorthite content. However, if we try to picture the type of rock which would answer to the normative

Table XVII.

Analysis 7.

Albitized Hällefors dolerite, S. of Svalbo. Specimen 205.

Spec. gr. $\frac{17^\circ}{4^\circ} = 3.077$. Analyst: N. SAHLBOM.

	Weight-%	Mol. Prop.
SiO_2	39.54	659
TiO_2	5.26	66
Al_2O_3	12.30	121
Fe_2O_3	6.97	44
FeO	15.52	215
MnO	0.29	4
CaO	8.75	156
MgO	5.27	132
Na_2O	2.31	37
K_2O	0.81	9
P_2O_5	1.02	7
H_2O+	1.78	
	99.82	

Norm				
Or		5.00		
Ab		19.39		
An		20.85		Σ sal 45.24
di	$CaSiO_3$	6.73	13.36	
	$MgSiO_3$	3.20		
	$FeSiO_3$	3.43		
hy	$MgSiO_3$	2.80	5.84	
	$FeSiO_3$	3.04		
ol	Mg_2SiO_4	5.04	11.16	
	Fe_2SiO_4	6.12		
Mt		10.21		
Ilm		10.03		
Ap		2.35		Σ fem 52.95
				H_2O+ 1.78
				99.97

III : 5 : 3 (4) : 4 (4—5) { *Camptonose* / *Auvergnose*

Or : Ab : An = 11.0 : 43.0 : 46.0

OSANN's System

$s_{48.5}\ a_{2.0}\ c_{3.5}\ f_{24.5}\ n_{8.0}$

S : Al : F = 15.0 : 2.5 : 12.5

Al : C : Alk = 11.0 : 14.5 ; 4.5

k = 0.77

NIGGLI values

qz	−38	si	86
al	16.0	ti	8.7
fm	57.5	mg	0.35
c	20.5	k	0.20
alk	6.0	p	0.92

composition, we find that it should be composed of roughly 50 % of andesine, probably about $Ab_{60}An_{40}$ — as some of the alumina must be assumed to enter into the pyroxene — and 50 % of dark minerals, *viz.* abundant *iron ore*, much *pyroxene* and somewhat less *olivine*. Moreover, the *apatite* content must be rather high. As a matter of fact such a rock would be fairly representative of the Hällefors dolerites at a stage when their olivine was still preserved.

Now, in what respects does the present rock differ from the rock pictured above? Instead of andesine it carries almost pure albite; no fresh olivine is encountered but instead there are numerous pseudomorphs probably after olivine; and, finally, the pyroxene is to a great extent chloritized. Thus we find that the actual rock could have originated from the »normative» one through the albitization of the plagioclase and the marked alteration of the dark minerals. Yet another fact seems to indicate that the difference between norm and mode is due to secondary processes only. From the texture of the rock it is evident that plagioclase and pyroxene, at least for a certain time, crystallized together, and it seems rather improbable that such a relatively low-temperature mineral as albite should have been formed at a stage when the pyroxene phenocrysts were being deposited, the more so as the formation of pyroxene proves that lime must have been available. Thus it is more likely that originally andesine was formed, which was later on converted into albite. The question then arises, as to what might be considered the cause of this conversion. In a later chapter the problem will be more fully dealt with, and it may suffice to point out here that albitization was most probably controlled by temperature relations only. As the analysis shows an Na_2O-content of only 2.30 %, it is hardly probable that there has been any considerable enrichment in this oxide. It is my opinion that the magma, after having deposited olivine, pyroxene and andesine, was brought into a position of lower temperature relations, where the andesine became unstable. The residual melt at this stage must have been rather rich in alkalies, and most probably also in volatiles, and it was able to exert an autolysing influence on the andesine grains, converting them into albite without disturbing the crystal structure. The ultimate fate of the lime, liberated in this process, is a little more difficult to discover. It is not, of course, altogether impossible that it might have been carried away, but the rather high CaO-value of the analysis makes this possibility unlikely. It is, therefore, more probable that it was taken up by the residual melt, and was later on deposited as pyroxene. It may appear unlikely that pyroxene would have been precipitated at a stage when andesine was already unstable, but it must be borne in mind that the melt was extremely rich in iron. For that reason the pyroxene crystallization must have continued until a very late stage. Such a late precipitation of pyroxene in these rocks is, indeed, proved by the glassy type described on p. 150 where pyroxene crystallized from a glassy mesostasis. During the later stages of solidification the alkali content of the residual melt has, moreover, manifested itself in the formation of hastingsite, which is found in some quantity as a marginal alteration-product of the pyroxene phenocrysts and is rather abundant in the mesostasis. At lower temperature it was succeeded by the chloritization which also attacked the feldspar.

There are certain indications that the processes of alteration were accompanied by mechanical deformation, most probably previous to the chloritization. Thus the chlorite occupies fissures along which transitional movements of the albite laths have taken place. In these cases chlorite is found to fill the fissure at both sides of the albite crystal, but it does not penetrate into it (Fig. 22).

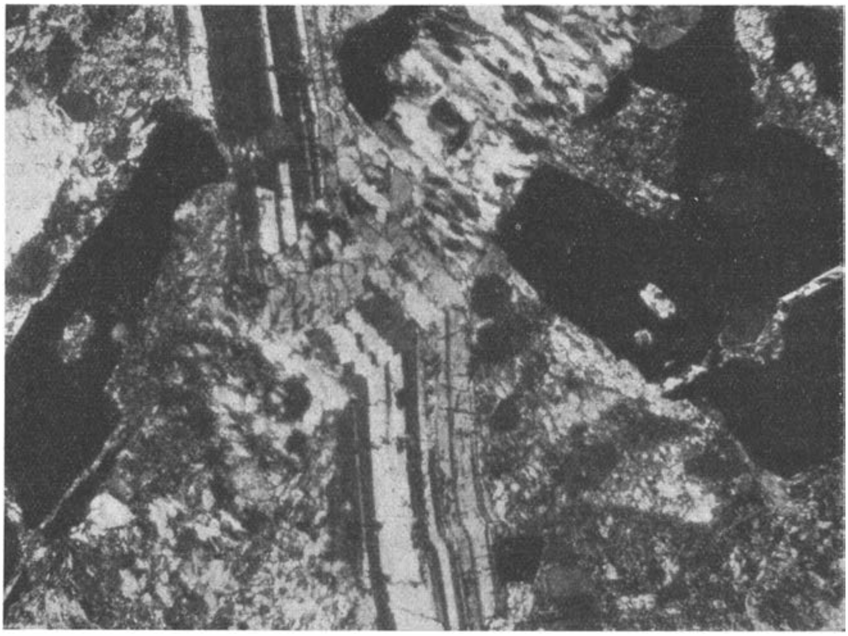


Fig. 22. Translation phenomena displayed by an andesine lath at a fissure intersecting the rock. Note the chlorite filling in the fissure at both sides of the feldspar. Specimen 205, nicols +. Magnification 40 diameters.

3. The Fredriksberg area.

At the farmhouse of Fredriksberg a fairly coarse dolerite of the marginal type is exposed. Towards the north its place is taken, in the usual way, by Hällefors dolerites. Some hundred metres north of the farm there are observed in the outcrops numerous irregular portions of very fine grain and with exceptionally abundant *apatite*. Sometimes they are quite even-grained, sometimes they exhibit a good porphyritic texture with feldspar phenocrysts up to a few centimetres of length. They are always intensely jointed. Microscopically [70] the porphyritic types show *plagioclase phenocrysts* with good idiomorphism set in a groundmass of the usual microspherulitic type, mainly consisting of *alkali-feldspar* and with great quantities of *ferrite* in fine scales, some *hastingsitic amphibole*, and a little *quartz*. The phenocrysts in their central parts are quite limpid, and show no sign of alteration. These portions are of the composition $Ab_{60} An_{40}$. In a marginal zone of varying width, however, marked alteration has occurred. The outer boundary of this zone coincides with the crystal contours, but the inner one is rather irregular (Fig. 23). The alteration has led to the development of some *sericite*, but large quantities of *zoisite* are especially conspicuous, occurring as small rounded »drops» that are preferably arranged along the traces of the (010) cleavage. In this zoisite-bearing zone the composition of the plagioclase has changed considerably. The refraction on γ is lower than that of canada balsam and, consequently, the anorthite content cannot surpass *8 %*. The albitization, however, has not disturbed the original crystal structure, for the cleavage traces continue without a break from the andesine core to the albite border. A little *pyroxene* is sometimes

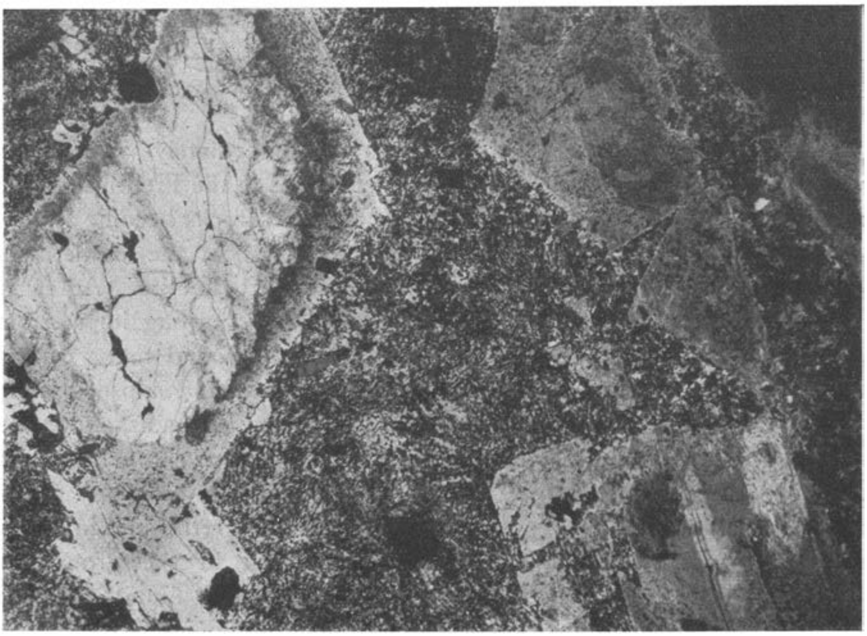


Fig. 23. Idiomorphic andesine phenocryst with an outer albitized border which is irregularly bounded inwards. Specimen 70 a, nicols +. Magnification 7 diameters.

observed in micrographic intergrowth with the outer zone of the plagioclase phenocrysts.

There are also some fairly large phenocrysts of *ilmenite*, which are generally strongly altered to *leucoxene*, intercalated along the rhombohedral planes. Finally, large amounts of *apatite* are found.

This rock appears to be continuously connected with the surrounding, extremely coarse Hällefors dolerite. Microscopically the transition is easily followed. The interstitial material of the dolerite increases in quantity until it becomes predominant, and when this occurs the andesine phenocrysts undergo albitization.

4. The Norrkärr area.

A section through the dike from S. to N. immediately W. of the farm Norrkärr exhibits practically the same relations as in the Fredriksberg area. The only difference is that the jointed fine-grained rocks become still more abundant and, indeed, dominate the whole section. At the southern shore of Lake Örhammaren they are replaced by mottled dolerite. A few specimens taken along this section [226, 227] convey a strong impression of crushing (see also p. 251). Microscopically they are found to be markedly porphyritic with phenocrysts of *albite*, *iron ore*, and *diabantite* pseudomorphs after olivine. The albite carries a little *zoisite* in small grains, and is sometimes to a great extent replaced by a light-green *chlorite*, which is apt to arrange itself along the (010) cleavage planes. A few *pyroxene* phenocrysts are also observed, but they are intensely veined by ferrite and in this way they come to be almost completely incorporated in the ground-mass. It is noteworthy that, contrary to what is generally found, the olivine pseudomorphs are composed of green diabantite, although ferrite is otherwise very abundant in the rock.

The groundmass consists of an extremely dense, felted fabric of *alkali-feldspar* and *ferrite* with some scattered prisms of *epidote* and *hastingsitic amphibole*. In places where the ferrite is a little less abundant, the texture is seen to be the usual microspherulitic one. A few crystallites of *iron ore* are also observed. One thin section is traversed by a narrow, epidote-filled vein.

5. The Hälleforsnäs area.

Along the main road S. of Hälleforsnäs a great many outcrops are encountered, and the variations of the central rocks may be well studied. At some localities albitic rocks are observed.

Only a few metres N. of the marginal dolerite, exposed in the southern part of the section, an almost black, slightly porphyritic rock is found [302].

It does not differ materially from the normal porphyrites as seen with the unaided eye. Microscopically it is found to possess a rather coarse, mosaic texture and to consist largely of *feldspar,* of which there are two kinds. Some large grains which are strongly altered, and in consequence cannot be optically determined, contribute to the slight porphyritic appearance of the rock and, in addition, there are a lot of smaller strongly twinned grains of fairly good idiomorphism which have an *albitic* composition. In contrast to this kind of feldspar, the whole remaining mass consists of rather large allotriomorphic grains, intensely perthitic and partly with a good chess-board structure. The rock may be said to correspond to the coarse types of the normal porphyrite except that the andesine grains of the latter are replaced by albite. The whole aggregate of feldspar is dissected by some rather coarse rods of *iron ore* with the arrangement usual in the porphyrites, and on the whole all the details of these rocks (pyroxene crystallites etc.) are repeated. *Ferrite* is abundant.

A chemical analysis of the rock was carried out and is given in table XVIII. The normative composition appears to agree fairly well with the modal one, especially as the somewhat high values of iron ore and anorthite in the norm may be lowered, if some of the alumina is allotted to pyroxene. The analysis will be further discussed later on (p. 205).

A few hundred metres farther towards the north a small outcrop is observed, which includes in its northern part a gray porphyrite without jointing [314] in its southern part a greenish black, strongly jointed type [313] with red feldspar phenocrysts. In the field the transition appears to be quite continuous.

Microscopically the gray rock is seen to represent a porphyrite very rich in phenocrysts. Large idiomorphic phenocrysts of *andesine,* $Ab_{60}An_{40}$, are accompanied by smaller ones of *pyroxene* and *diabantite.* The andesine is often surrounded by an albitic border, which may partly be due to alteration, as it is sometimes crowded with *zoisite.* The groundmass is of medium grain and shows the usual microgranophyric or microspherulitic texture. In addition to *alkali-feldspar* it is mainly made up of skeletal *pyroxene* crystals, some *hastingsitic amphibole, iron ore, titanite* and a little *quartz.*

The jointed rock is strongly porphyritic with numerous large phenocrysts of *albite,* $Ab_{90-95}An_{10-5}$, with perfect crystal outlines, together with less numerous and smaller ones of *pyroxene, iron ore*, and *diabantite.* The groundmass is extremely fine-grained and of the usual porphyrite type with *alkali-feldspar,* skeletal *pyroxene* and *iron-ore* rods. No ferrite is observed.

In the nearest exposure to the south of the albitic rock a normal porphyrite without jointing is again found [312]. It carries phenocrysts of *andesine.*

In another outcrop in the same district there is also an apparently

Table XVIII.

Analysis 8.

Albitic Hällefors porphyrite, S. of Hälleforsnäs. Specimen 302.

Spec. gr. $\frac{17°}{4°}$ = 2.862. Analyst: N. SAHLBOM.

	Weight-%	Mol. Prop.
SiO_2	51.55	859
TiO_2	2.54	32
Al_2O_3	11.10	109
Fe_2O_3	8.31	52
FeO	8.39	117
MnO	0.22	3
CaO	5.94	106
MgO	2.06	52
Na_2O	3.12	51
K_2O	3.43	36
P_2O_5	1.18	8
H_2O+	1.96	
	99.80	

Norm				
	Qu	8.88		
	Or	20.02		
	Ab	26.72		
	An	6.12		Σ sal 61.74
di	$CaSiO_3$	6.61	13.05	
	$MgSiO_3$	3.40		
	$FeSiO_3$	3.04		
hy	$MgSiO_3$	1.80	3.52	
	$FeSiO_3$	1.72		
	Mt	12.06		
	Ilm	4.86		
	Ap	2.69		Σ fem 36.18
			H_2O+	1.96
				99.88

II : 4 : 2 : 3 — *Adamellose*

Or : Ab : An = 37.9 : 50.5 : 11.6

OSANN'S System

$s_{60.3}\ a_{5.5}\ c_{1.5}\ f_{23.0}\ n_{5.9}$

S : Al : F = 19.5 : 2.5 : 8.0

Al : C : Alk = 11.0 : 10.5 : 8.5

k = 0.96

NIGGLI values

qz	−11.5	si	148.5
al	19.0	ti	5.5
fm	47.5	mg	0.19
c	18.5	k	0.41
alk	15.0	p	1.38

irregular alternation between different rock types. Megascopically the differences are not very marked and so the field relations could not be made out in detail. The chief rock is of the same type as the non-jointed porphyrite just described, but it is associated with a rock of quite another character [315]. The latter shows microscopically a markedly porphyritic texture with numerous idiomorphic phenocrysts of *albite* $Ab_{90}An_{10}$ — 2—3 mm. in length — and a few *pyroxene* phenocrysts of the same dimensions but without good crystal boundaries. Further there are numerous phenocrysts of smaller size (less than 0.5 mm.) including albite as well as pyroxene, both showing excellent idiomorphism. There seems to be a clear *hiatus* between the large phenocrysts and the small ones. Both types of albite grains are rather markedly intergrown with light-green *chlorite* in small irregular patches, and the larger ones especially are often crowded with *zoisite* and are sometimes slightly *sericitized.* A few small grains of *epidote* seem to be comparable to the small phenocrysts, and so do the rather abundant *apatite* crystals that are scattered through the groundmass. The latter is veiled by an intense impregnation of finely scaly *ferrite,* but it seems to consist mainly of *alkali-feldspar* with abundant *pyroxene* crystallites and, possibly, a little *quartz.*

Table XIX.

Analysis 9.

Albitic Hällefors porphyrite, S. of Hälleforsnäs. Specimen 315.

Spec. gr. $\frac{17^{\circ}}{4^{\circ}} = 2.775$. Analyst: N. SAHLBOM.

	Weight-%	Mol. Prop.
SiO_2	50.52	842
TiO_2	2.40	30
Al_2O_3	12.51	123
Fe_2O_3	10.09	63
FeO	6.61	92
MnO	0.36	5
CaO	6.05	108
MgO	1.82	46
Na_2O	3.82	61
K_2O	2.39	26
P_2O_5	0.99	7
H_2O+	2.32	
	99.88	

Norm			
	Qu	8.88	
	Or	14.46	
	Ab	31.96	
	An	10.01	Σ sal 65.31
di	$CaSiO_3$	5.80	10.93
	$MgSiO_3$	4.60	
	$FeSiO_3$	0.53	
	Mt	14.62	
	Ilm	4.56	
	Ap	2.35	Σ fem 32.46
			H_2O+ 2.32
			100.09

II : 4 : 2 : 4 — *Dacose*

Or : Ab : An = 25.6 : 56.6 : 17.8

OSANN's System

$s_{59.5}\ a_{5.5}\ c_{2.5}\ f_{22.0}\ n_{7.0}$

S : Al : F = 19.0 : 3.0 : 8.0

Al : C : Alk = 11.5 : 10.5 : 8.0

k = 0.97

NIGGLI values

qz	—17	si	143
al	21.0	ti	5.1
fm	46.0	mg	0.17
c	18.0	k	0.30
alk	15.0	p	1.19

A chemical analysis of this rock was carried out and is given in table XIX. The norm shows a somewhat higher anorthite content than has been microscopically stated, but that is most probably due to the fact that part of the alumina enters into the pyroxene. Similarly some Fe_2O_3 is most probably bound in pyroxene and ferrite, which would lead to a decrease in the quantity of the iron ore and the free quartz of the norm and an increase of the pyroxene — all in good agreement with the microscopical observations. The analysis will be further discussed later on (p. 205).

Finally, in a fourth outcrop the prevalent rock is a porphyrite of the usual type with feldspar phenocrysts of the composition $Ab_{65}An_{35}$. The chlorite of the pseudomorphs and the groundmass aggregates is both of the diabantite and the ferrite types, and it seems as if the rock represented an intermediate stage in which the conversion had begun, but was not completed.

In this rock there are irregular portions or streaks with a fine parallelepipedical jointing, with the same porphyritic texture as the main rock, but with red feldspar phenocrysts and a very fine-grained groundmass which is yellowish brown in colour. In these portions *epidote*-filled veins are rather frequent.

A microscopical investigation brings out numerous fairly idiomorphic phenocrysts of *albite* and a few larger grains of *iron ore* set in an extremely fine-grained groundmass, which is composed mainly of *alkali-feldspar* and *ferrite*. The feldspars form a base which is so intensely impregnated with ferrite, that one cannot get any impression of its texture, nor is it possible to decide whether some quartz is present or not. The whole mass is, as it were, ruled over in all directions by long narrow rods which are now composed of ferrite but originally must have represented crystallites of one or more of the minerals pyroxene, olivine, and iron ore. Sometimes the ferrite forms slightly larger portions in which it develops a good cleavage. Finally, the groundmass is very rich in *epidote* in small grains, and it has previously been mentioned that epidote-filled veins dissect the rock.

6. Origin of the albitic rocks.

When we attempt to view the relations between the normal porphyritic and doleritic rocks on the one hand and the albitic ones on the other, the first point to be decided is, whether the latter are to be considered as primary or secondary. Here we touch upon a problem that has been intensively discussed in recent years *viz.* the problem of spilitic rocks and their origin. It is hardly necessary to give a review of the different opinions offered by different authors on this question, as they are probably by now well known to the majority of petrologists. It may suffice to refer to the comprehensive paper by J. GILLULY (1935) in which a very complete bibliography is found.

In the present case there are a great many facts in favour of a secondary origin. Some of them were discussed in connection with the rock of the Svalbo area, but there are yet others to which attention may be drawn. Firstly, the intimate field-relations make it rather probable that the albitic types are due to the same intrusion as the normal andesine-bearing types, and if this be so it is very difficult indeed to explain why the same magma, generally forming andesine phenocrysts, should have locally developed albitic ones. Further, in some rocks albitization is actually observed to have taken place in such a manner as to suggest that, when completed, it would have led to albitic rocks of the type described above (p. 197 and Fig. 23). Another point of importance is the occurrence of fairly large amounts of epidote in most of the albitic rocks. This may account for the absence of zoisite in some of the albite phenocrysts. It is probable that the original lime-content was partly carried away from the feldspar crystal, partly retained within its boundaries. In the former case it was deposited, later on, as epidote, owing to the abundance of iron in the surrounding *milieu* — in the latter it was precipitated as zoisite. Whether the one course or the other was followed must have depended upon the general physico-chemical conditions prevailing at the time of alteration, and, moreover, may have been controlled by the relative accessibility of soda. If soda was supplied *ad libitum* to the altering andesine, the lime might be completely driven off; otherwise it might have been partly held back within the crystal. As a matter of fact, the wholly fresh and limpid albite crystals of some of the rocks in question seem to prove that there was actually an addition of soda, for otherwise it is difficult to picture how the crystal structure and even the well-developed twinning could have been preserved. A second question, then, is whether this soda addition represented only an interchange between phenocrysts and ground-mass (melt) or if the rock as a whole was enriched in soda. This question will presently be discussed in connection with the chemical analyses.

Before doing so, however, it seems convenient to consider whether there are other characteristics, belonging to the albitic rocks only, which might give some indications as to how the presumed albitization was effected.

Indeed, there are several such characteristics. From a mineralogical point of view attention has been called above to the fact that the albitic rocks practically always carry epidote in veins or as fine grains in the groundmass. Another mineralogical feature of great interest is the content of ferrite. Whereas in the normal porphyritic rocks diabantite must be said to represent the normal chlorite type, in the albitic varieties it is with one exception replaced by ferrite. This rule is so marked that, in examining a great number of thin sections, one cannot possibly avoid the impression that the albitization and the formation of ferrite instead of diabantite are two different results of the same process or processes, operating within the magma. As a third mineralogical characteristic the frequent occurrence of pyrite may be considered.

Turning now to the structural relations, it was mentioned in the above description that the albitic rocks without exception are characterized by a peculiar megascopic structure, reminiscent of that of certain lavas, and by a fine parallelepipedical jointing, which also recalls that exhibited by surface flows. Moreover, there are sometimes indications of mechanical forces having been active, which resulted in a laminar cleavage, translation phenomena in plagioclase crystals, *etc.* To judge from the intensely streaky structure of the laminar rocks at Ölmstorp, it seems rather probable that these mechanical forces were operating at a time previous to the final solidification of the rock, or in other words, that they affected the viscous crystal porridge.

In the description of the porphyrites (p. 184) attention was called to a peculiar laminar alternation of fresh black types and brown ones in appearance suggesting that they are not quite fresh. The difference was found microscopically to lie in the character of the chlorite — the black types being characterized by diabantite, the brownish ones by ferrite. Now, we have found that the albitic rocks are also, as a rule, characterized by ferrite, and further, that they appear as narrow streaks or irregular portions within the normal rocks. As a matter of fact, their occurrence reminds one very much of the brownish bands or lamellae described on p. 184, and I am of the opinion that there is no outstanding difference between the two phenomena from a genetical point of view. It is true that the ferrite-bearing laminae of the porphyrites do not carry albite phenocrysts, but, as there are always albitic borders around the andesine phenocrysts, this difference is only a partial one, as indeed are the other differences between the albitic rocks and the normal ones. It is my opinion that in the laminar structure of the porphyrites is to be seen the result of the same processes as those that, on a larger scale, have led to the formation of the albitic rocks. It should, therefore, be of some interest to discuss in a little more detail this peculiar lamination. The structure may be described as an irregular schistosity, marked by numerous cleavage planes of sharply curved shape, which lead to the development of a subconchoidal fracture in the rock. From any hand-specimen one gets a strong impression of a banded or lamellar lava. Microscopically, however, no schistosity as a rule is observed, and no doubt the structure is a purely magmatic one, due to mineralogical heterogeneity. Such a magmatic »schistosity» has been already described by KLAUTSZCH (1893) and BERGT (1914), who agree that it is to be attributed to fluxional movements in the magma during the later stages of solidification. In all probability similar processes have operated also in the present case, and it may be assumed that these movements caused an irregularly streaky distribution of the volatiles, which in its turn led to a heterogeneous mineral-development in the rock. According to this interpretation the differences between the albitic rocks and the normal ones, as well as the locally developed lamination schould be referred to internal processes in the magma at a late stage in its history.

The chemical aspects still remain to be considered. For this purpose, in table XX, the two analyses of normal Hällefors porphyrites are repeated together with the two analyses of albitic porphyrites. For a description of the specimens in question the reader is referred to the text above.

Table XX.

	1	2	3	4
SiO_2	50.41	52.23	50.52	51.55
TiO_2	2.50	2.60	2.40	2.54
Al_2O_3	11.97	10.56	12.51	11.10
Fe_2O_3	5.36	5.91	10.09	8.31
FeO	11.81	10.79	6.61	8.39
MnO	0.20	0.30	0.36	0.22
CaO	6.70	7.57	6.05	6.70
MgO	2.04	1.73	1.82	2.06
Na_2O	2.87	2.84	3.82	3.12
K_2O	3.51	3.48	2.39	3.43
P_2O_5	1.08	0.99	1.18	0.66
H_2O	1.44	1.20	2.32	1.96
	99.89	99.88	99.80	99.87

1. Hällefors porphyrite S. of Hälleforsnäs. Specimen 316 (see p. 188).
2. » » E. of Lake Holmsjön. Specimen 123 (see p. 187).
3. Albitic porphyrite S. of Hälleforsnäs. Specimen 315 (see p. 201).
4. » » S. of Hälleforsnäs. Specimen 302 (see p. 200).

It is evident that the four analyses are in most respects very similar, but there are two or three conspicuous differences, *viz.* the state of oxidation of the iron and the proportions between Na_2O, K_2O, and CaO. From the table XXI below we may gather that in these respects the two normal porphyrites are almost identical and differ markedly from the strongly porphyritic albitic rock no. 3, whereas the coarser albitic rock no. 4 occupies an intermediate position.

We find that the albitization seems to be accompanied by rather strong oxidation of the iron and by an increase of Na_2O relatively to both K_2O and CaO. Especially the ratio $Na_2O : K_2O$ is very strongly affected, and whereas the normal porphyritic rocks show a decided dominance of K_2O over Na_2O, the albitic types may show the reverse relation. Finally, a glance at the table of analyses reveals a much higher proportion of H_2O in the albitic rocks than in the normal ones.

Table XXI.

	1	2	3	4
$FeO : Fe_2O_3$	2.20	1.83	0.66	1.01
$K_2O : Na_2O$	1.22	1.23	0.63	1.10
$CaO : Na_2O$	2.33	2.63	1.59	2.13

Now, how do the chemical differences, pictured above, conform to the hypothesis advanced in the previous pages? I think that the chemical data most decidedly speak in favour of it. Let us assume that in a magma under consolidation the volatiles come to be concentrated in certain portions or streaks. The probable result would be that these portions of the magma would remain for a longer time in the fluid or semi-fluid state than the surrounding ones, and the minerals already deposited would have a much better opportunity to react with the residual liquid. This condition must be highly favourable to albitization. Already in 1909 BAILEY and GRABHAM presented a theory, according to which calcic plagioclase might be metasomatically albitized by residual liquors, in which the concentration of soda was retained at an unusual high value *e.g.* by the presence of large amounts of carbon dioxide. Recent experiments by ESKOLA, VUORISTO and RANKAMA (1935) seem to prove the possibility of such a reaction. The process is most drastically pictured in the repeatedly quoted statement, that the plagioclase crystals have been »stewing in a concentrated solution of sodium carbonate» (BAILEY and GRABHAM 1909 p. 253). It is also natural, that from such a solution primary albite should have been deposited, and thus the albite formation need not necessarily have been restricted to a mere replacement.

Further, in a *milieu* enriched in volatiles — among others water vapor, as evidenced by the analyses, and oxides of sulphur, as indicated by the frequent occurrence of pyrite — we should expect marked hydrolysis and oxidation to take place. That this was indeed the case in our albitic rocks, is proved by the formation of abundant ferrite and by the marked increase in the ratio $Fe_2O_3 : FeO$.

There is another feature, however, of table XXI that deserves special attention, *viz.* the mutual proportions of Na_2O and K_2O. From table XX we may gather that the total of alkalies is almost exactly the same in all four rocks, but table XXI reveals a strong increase in the ratio $Na_2O : K_2O$ in the albitic type nr. 3. As this increase is due to a change of the values of both oxides, it cannot simply be explained as the result of an enrichment in soda, and here a great difficulty arises. Of course, it might be contended that K_2O was in some mysterious manner carried away, but such an assumption seems rather adventurous, as it has nothing to support it but the figures of the chemical analyses. There seems to be, however, another way out.

As in the porphyritic rocks a great part of the soda is contained in the phenocrysts, the groundmass of the non-albitic rocks must be still more dominated by K_2O than the rock as a whole, and also in the albitic types the potash must be confined mainly to the groundmass. Thus it seems very likely that, at a stage when the present groundmass was still a melt, a differentiation of the alkalies within the rock-body has taken place. In this connection the above-mentioned high ratio $Fe_2O_3 : FeO$ of the albitic types is of great interest. BOWEN, SCHAIRER and WILLEMS (1930) in investigating the system Na_2SiO_3-Fe_2O_3-SiO_2, were able to show that the system tends to several binary and ternary eutectics at rather low temperatures of about 800°. In our present case the residual melt (the groundmass of the present rocks) was fairly rich in iron and alkalies, and as Fe_2O_3 increased at the expence of FeO, there must have arisen the possibility for Na_2O and Fe_2O_3 to remain in the liquid fraction until a very late stage of the evolution. The presence of hastingsitic amphibole in the groundmass seems to support the assumption that the residual melt was at least approaching the system investigated by the above authors. It is true that this hastingsite is encountered also in the non-albitic rocks, but, as has just been stressed, the oxidation of iron must have still more augmented the possibilities of the melt reaching low temperatures. However, this possibility, as far as the alkalies are concerned, applies only to Na_2O, and so we must expect K_2O to enter into the solid phase at a considerably earlier stage. The result of this discussion is that by an heterogeneously streaky distribution of the volatiles an oxidation of the iron was brought about, which in its turn entailed a concentration of Na_2O in the liquid portions. The latter, consequently, may be considered as residual liquids of a second order, which are enriched in soda but impoverished in potash. Before their consolidation they effected an albitization of their own andesine phenocrysts and to some extent they have exercised a metasomatic effect upon the parts of the rock-body, that, owing to their greater »dryness» had begun to consolidate at an earlier stage. These albitic streaks must by no means be considered as distinctly later intrusions — they may be said to represent late phases of the magmatic stage, which forced their way through the surrounding semi-solid earlier phases. The difference between the two phases was not even as great as between, for instance, a granite and its pegmatites, which is evident from the fact that there is always quite a continuous transition between them.

The conception of the albitic portions being squeezed or forced up through their highly viscous surroundings, moreover, tallies very well with the indications of schistosity and fluidal structures previously described.

In connection with the tables XX and XXI a few words more should be added. We find from the analyses that the absolute amount of CaO is almost the same in the albitic rocks as in the normal ones. This, no doubt, is due to the fact, that the lime of the andesine phenocrysts, when replaced by soda, was not carried very far, but was soon re-deposited in the form of epidote in the very surroundings from which it was once liberated.

Further, there are two statements in the above discussion that might appear to be mutually inconsistent. Firstly, it is stated that ferrite is formed by replacement of diabantite in consequence of oxidizing processes. Secondly, the oxidation of ferrous iron to ferric is assumed to have exercised a very strong influence upon the evolution of the residual liquid. It is evident that the oxidation is registered mainly by the chlorites, but if all diabantite was previously formed, a subsequent oxidation of that mineral to ferrite could have no influence whatever upon the liquid portion. Thus it must be assumed, not only that diabantite was to a great extent primarily formed in the late stages — as is also indicated by its abundance in the groundmass — but also that ferrite must have formed in the same way. As it is difficult to ascertain at what period the olivine alteration took place, it cannot be safely decided whether in the albitic rocks this alteration proceeded through diabantite to ferrite, or if ferrite was directly formed. We may stress, however, the fact that under normal conditions diabantite was developed both as pseudomorphs and as a primary constituent, whereas under oxidizing conditions its place was taken by ferrite.

C. Minor intrusions.

a. Adamellitic dikes.

In the mottled dolerite immediately south of Lake Tallsjön, some 20 m. east of the main road, a narrow dike is observed. It may be followed for about 2 m. with a width of 5 cm. and is fairly rectilinear, striking N. 45° E. with a vertical dip. The boundary against the adjacent dolerite is clean-cut. Megascopically the rock is grayish brown with very fine grain and reminds one in some respects of a leptite. At one place it is seen to send a well-defined apophysis out into the dolerite.

Microscopically the rock [91] shows a very fine grain, and is composed

Table XXII.

Analysis 10.

Adamellitic dike, S. of Lake Tallsjön. Specimen 91.

Spec. gr. $^{17^\circ}_{4^\circ} = 2.613$. Analyst: N. SAHLBOM.

	Weight-%	Mol. Prop.
SiO_2	67.63	1127
TiO_2	0.60	8
Al_2O_3	13.34	131
Fe_2O_3	1.91	12
FeO	3.11	43
MnO	0.05	1
CaO	1.93	35
MgO	1.71	43
Na_2O	3.97	64
K_2O	4.04	43
P_2O_5	0.29	2
H_2O+	1.43	
	100.01	

Norm				
Qu		21.96		
Or		23.91		
Ab		33.54		
An		6.67		Σ sal 86.08
di	$CaSiO_3$	0.58	1.13	
	$MgSiO_3$	0.33		
	$FeSiO_3$	0.22		
hy	$MgSiO_3$	3.97	6.77	
	$FeSiO_3$	2.80		
Mt		2.78		
Ilm		1.22		
Ap		0.67		Σ fem 12.57
				H_2O+ 1.43
				100.08

II : 4 : 2 : 3 — *Adamellose*

Or : Ab : An = 37.3 : 52.3 : 10.4

OSANN's System

$s_{74.6}\,a_{12.5}\,c_{3.0}\,f_{14.5}\,n_{6.0}$

S : Al : F = 24.0 : 3.0 : 3.0

Al : C : Alk = 14.5 : 4.0 : 11.5

k = 1.40

NIGGLI values

qz	+81.5	si	293.5
al	34.0	ti	2.0
fm	29.0	mg	0.39
c	9.0	k	0.40
alk	28.0	p	0.52

mainly of *alkali-feldspar* and *quartz* in microgranophyric intergrowth. Both *albite* and *orthoclase* are present, but, owing to the fine grain, their mutual proportions could not be ascertained. It would appear as if the albite were of a slightly better idiomorphic development, forming small laths surrounded by fine micropegmatites of orthoclase and quartz. The quartz content is considerable.

All over this quartz-feldspar mass there are scattered minute prisms and scales of *amphibole* in a more or less advanced stage of decomposition. The amphibole is of the *hastingsitic* type, showing low birefringence and faint pleochroism with γ *faintly bluish green* and α *colourless.* The mineral is to a great extent replaced by a biotite-like product, which shows strong pleochroism in *golden yellow* and *blackish brown.* Most probably this material is identical with the *ferrite* of the central rocks.

Finally, the rock carries *calcite* in amounts that are not to be neglected. The calcite occurs as fine scales or as rather large ragged patches, and often seems to form the centre of radiating aggregates of *amphibole* or *ferrite* needles. Some minute needles of *apatite* may also be observed.

A chemical analysis of this rock was carried out and the result is given in table XXII. The norm conforms fairly well with the modal composition except that the place of pyroxene is, modally, taken over by amphibole and chlorite. Further the largest part of CaO is probably present as calcite, which leaves some alumina for the femic minerals and liberates still more silica. The iron-ore percentage seems to be a little too high, as very little if any iron ore is observed in the rock, but probably both Fe_2O_3 and FeO, now allotted to magnetite, enter to a great extent into amphibole and chlorite.

Table XXIII.

	1	2		1	3
SiO_2	67.63	69.19	si	293.5	290.0
TiO_2	0.60	0.54	al	34.0	35.0
Al_2O_3	13.34	11.86	fm	29.0	28.5
Fe_2O_3	1.91	1.22	c	9.0	8.0
FeO	3.11	4.72	alk	28.0	28.5
MnO	0.05	0.08	k	0.40	0.45
CaO	1.93	2.45	mg	0.39	0.35
MgO	1.71	2.02			
Na_2O	3.97	3.80			
K_2O	4.04	3.57			
P_2O_5	0.29	0.10			
H_2O+	1.43	0.60			

1. Dike-rock cutting the mottled dolerite, S. of Hälleforsnäs.
4. Adamellite, Svartbergsviken, N. Ulfön, Nordingrå.
3. Tasna-granitic magma-type of NIGGLI.

The chemical composition of the rock is of little use when attempting to establish its petrological character, as it conforms fairly well with several analyses of syenites, granites, monzonites, *etc.* The mineralogical composition, however, seems to bring out clearly that the dike is consanguineous with the central dike-rocks, and as a matter of fact the whole rock reminds one very much of the groundmass of some of the porphyrites. It is interesting to find, then, that from a chemical point of view there is a fairly good correspondence between the rock in question and a rock from Nordingrå that was named adamellite by SOBRAL (1913, pp. 124—126). This fact is illustrated by table XXIII above, where the two analyses are put side by side. The Nordingrå rock is interpreted by SOBRAL as a hybrid, formed by the remelting of granite by a dolerite magma. Although this explanation can hardly hold good in the present case, the strong affinities between the two rocks cannot be denied, and I am inclined to group them together. It is very interesting to find (table XXIII) that the NIGGLI values of the Hällefors rock are almost identical with those of the tasna-granitic magma-type of NIGGLI, which magma is put together with the adamellitic one as one group of the quartz-syenitic magmas. (NIGGLI 1923, p. 172). Thus it seems convenient to give the name *adamellite* also to the present rock. It should be stressed, however, that the name is used in its first conception, given by CATHREIN (1890, p. 73—74). TRÖGER (1935, p. 311) points out that the new definition, given by BRÖGGER (1895, p. 61) should be avoided, as in Adamello there have been found no rocks answering to BRÖGGER's definition.

At some distance W. of the locality with the dike just described, another dike or vein is encountered, cutting the mottled dolerite. Like the previous one it is rectilinear and sharply defined. It has a width of only 2 cm., strikes N.-S., and dips 60° to the east. Megascopically the rock is very similar to the one just described, and a microscopical investigation shows that they are essentially almost identical. Thus one finds a very fine-grained, microgranophyric base of *alkali-feldspar* and *quartz,* but the latter mineral is far less abundant than in the previous rock. Further there is not so much *ferrite* and this mineral shows a patchy distribution in the slide. Finally, the rock is slightly porphyritic, showing phenocrysts of *albite* and *amphibole.* It seems, however, as if this porphyritic texture should represent only a gradual change from the rock 91, due to the larger size attained by some of the amphibole prisms and albite grains of the fine-grained base. The amphibole sometimes shows central *pyroxene* relics. In the parts immediately bordering upon the pyroxene core it is almost colourless and shows an axial angle approaching 90°. In the marginal parts, however, it assumes a faintly bluish green colour, the axial angle decreases considerably, and the dispersion becomes rather strong $\varrho > v$. No doubt this indicates the same transition from a central common hornblende to a marginal hastingsitic amphibole, as was encountered in the central dolerites and porphyrites.

Chemically this rock is most probably a little less acid than the rock 91, but it seems quite proper to group them together, and thus the present rock, too, should be described as an *adamellite.*

A little S. of Israelstorp a third dike of about the same type as the two just described, is encountered. The dike cuts the mottled dolerite, strikes N. 10° W., and has a width of only 3 cm. It may be followed for about 3 m. Megascopically the rock shows slightly coarser grain than the previous ones and seems to be more basic. Microscopically this surmise is confirmed, the main minerals being *pyroxene* and *oligoclase-andesine* $Ab_{70} An_{30}$. Both minerals show fairly good idiomorphic forms and, in a measure, they may be considered as phenocrysts, embedded in a completely xenomorphic base of *alkali-feldspars.* This base — which contains both *albite* and *orthoclase* — is, however, very scant and so the porphyritic texture is not very conspicuous. The plagioclase, as a rule, does not form long laths but more equidimensional plates with fairly good twin structure. Generally it is strongly altered to *zoisite*, and often shows a lime-poor outer zone, which passes directly into the interstitial material.

The pyroxene shows good prismatic form, but seldom develops terminal faces. It is found both as short prisms and as long needles, which cannot, however, be characterized as crystallites. The mineral has nowhere been subjected to alteration. Sometimes the crystals may be zoned and in such an individual the core showed $2\,V_\gamma = 47^\circ$, $c/\gamma = 43^\circ$, whereas in the outer zone the axial angle was about 8° larger.

In the feldspathic »groundmass» *diabantite-ferrite* aggregates occur abundantly. Further there are found some quantities of *hastingsitic amphibole* in close connection with the chlorites. *Iron ore* occurs in small grains and curved rods and, finally, some *apatite* and small quantities of *quartz* are found.

It can hardly be doubted that the last dike is closely related to the two previously described. The main difference lies in its greater basicity and the preservation of pyroxene, and in this respect it shows a great resemblance to the porphyrites. It seems as if the rock occupied an intermediate position between the porphyrites and the adamellitic types and perhaps its affinities to the former are greater than to the latter. This intermediate position, however, furnishes another support for the opinion that these dike-rocks are closely related to the central Hällefors rocks.

b. Quartz-albite rock at Lake Örhammaren.

Just south of the western part of Lake Örhammaren a peculiar rock [52] is found. It occurs at the top of a high-level outcrop as a »layer» of about 10 cm. thickness, resting almost horizontally upon the mottled dolerite and covered by a continuous thin skin of the same rock. The »layer» is roughly circular with a diameter of about one metre. The boundaries against the dolerite are knife-edged and the only explanation I can offer is that the rock in question represents the remnants of a horizontally injected small dike.

The rock is fine-grained, almost flinty in appearance and grayish in colour. It differs markedly from the adjacent dolerite in displaying a close-set jointing, along the planes of which it is easily split into angular pieces. The joint planes are coated with chloritic films and, moreover, the rock is intersected by abundant sharply bounded veins that may attain a width of about 5 mm., and are filled by a greenish mineral with fibrous structure. The fibres are arranged perpendicularly to the sides of the veins.

Microscopically the rock is found to consist of a very fine-grained mass of dominant *albite* and *quartz* together with some *amphibole*. A few albite and amphibole individuals may attain somewhat larger dimensions and give rise to a slightly porphyritic texture. All minerals are completely allotriomorphic and the texture reveals that rather strong recrystallization of the components has taken place. Sometimes one may perhaps detect a relict micrographophyric texture. No orthoclase is observed. The amphibole shows the following optical properties:

$$c/\gamma = 24^\circ \quad 2\,V_\alpha \text{ large} \quad \gamma \text{ moss green} \quad \alpha \text{ colourless.}$$

Consequently, it appears to represent *common hornblende*.

In the slide examined two of the above-mentioned veins are observed. They are filled by a coarse mass of hypidiomorphic *plagioclase*, the composition of which was found to be $Ab_{70}An_{30}$. This oligoclase is intergrown with numerous fine *amphibole* threads which are invariably perpendicular to the boundary against the main rock, and are responsible for the fibrous appearance of the infilling, which is conspicuous even megascopically. In the broader veins the oligoclase crystals may attain a diameter of 4—5 mm., thereby strongly contrasting with the fine-grained mass of the rock. Microscopically the boundary between veins and rock is also found to be quite sharp.

As already mentioned, the rock can hardly be interpreted in any other way than as a small dike, and its sharp boundaries against the dolerite prove that it was intruded subsequently to the solidification of the latter. Most probably it represents an original soda-granophyre and in this case it might perhaps be considered as an indication of the existence of a granitic magma in the depth. We will shortly find that there are some other indications pointing in the same direction (see p. 221).

The numerous oligoclase veins in their turn are quite as sharply bounded against the presumed granophyre and, consequently, they must have been formed after its solidification. It seems rather reasonable to connect their period of formation with the intrusion of the central Hällefors rocks, especially as their composition does not differ markedly from the plagioclase composition of the latter. We would suppose, then, that, during intrusion, the central magma was responsible for a certain amount of pneumatolytic action outwards and that the agencies concerned preferred to follow the dike-horizon which was presumably more permeable than the main dolerite.

Thus this rock, too, seems to indicate an *hiatus* between the intrusions of the marginal and the central rocks, just as was concluded from other observations.

c. Granophyric veins.

At several localities near the outer dike-boundary in the district south of Lake Holmsjön the mottled dolerite is intersected by numerous veins of granitic composition. The rock of these veins is fine-grained and, megascopically, of a whitish gray colour. Microscopically it is found to consist mainly of *microperthite* and *quartz* together with some independent *orthoclase* and *albite.* The texture is granophyric and numerous very beautiful micropegmatitic patches are found. Further, there is some *epidote* and a little ragged *biotite.*

The boundary against the dolerite is knife-edged even in thin section, but the adjacent dolerite shows some of the usual contact phenomena previously described (p. 138 ff.).

It cannot be denied that this rock shows certain similarities to the Breven granophyre, but in spite of that I am not inclined to interpret it as belonging to the main series of dike intrusions. Its rather restricted occurrence and its localisation in the vicinity of the outer contact seem to speak in favour of another explanation, *viz.* that the veins are emanations from the wall rock activated by the dolerite intrusion. It is not possible, however, to form a definite opinion on this question.

D. Local rock modifications.

a. The helsinkitic rocks at Äs.

In three small outcrops immediately N. W. of the manor of Äs, N. E. of Lake Öljaren, a peculiar rock association is met with. The main rock megascopically reminds one very much of a rather basic syenite with numerous small rounded patches of amphibole set in a medium-grained mass of red feldspar [238 a, 240 a]. Microscopically, however, the rock is found to be considerably more acid and should more properly be classed as a granophyre. As a matter of fact it is almost identical with some of the more basic granophyres of the Breven dike (KROKSTRÖM 1932 a).

The rock is dominated by an evengrained, hypidiomorphic mass of *albitic feldspar,* more or less perthitic *orthoclase* and *quartz.* Further, there are found fair quantities of *common green hornblende,* forming ragged patches and being evidently secondary after pyroxene. Rather large amounts of *iron ore* are observed, often associated with irregular patches of deep-green *chlorite* and sometimes with *leucoxene*. The *apatite* content is considerable, and, finally, all over the rock are scattered numerous aggregates of small *epidote* grains.

Whereas the orthoclase is always completely allotriomorphic, the albite shows a tendency to develop lath-shaped crystals, and sometimes it exhibits rather well-developed twin structure. Quartz and orthoclase form numerous very beautiful micropegmatitic intergrowths.

Locally the rock becomes a little finer grained, the hornblende increases in amount and the micropegmatite becomes very scant. In these types the place of albite is taken by *andesine* with about *40 % of anorthite,* and it is very interesting to find that the epidote aggregates have almost completely disappeared. Even in the predominantly albite-bearing types some of the feldspar laths may be close to andesine in composition, as inferred from their refraction relatively to quartz. An exact determination is not possible, however, owing to the very strong clouding of the crystals by secondary products, mainly *zoisite*. Nevertheless, it would appear as if there were a continuous transition from more basic plagioclase varieties to pure or almost pure albite. From this fact, as well as from the reciprocal relations between albite and epidote, it seems very probable that the albite is of secondary origin, and was formed at the expense of andesine.

By an increase of the epidote content this rock grades continuously into a variety of helsinkitic affinities [239]. This type of rock carries practically only *albite* and *epidote* together with a little *quartz*. The albite is developed in small laths with a tendency to a divergent radiating arrangement. The epidote is mostly found in poecilitic intergrowth with the albite, but sometimes it is more individualised in its development, forming large sectors of a beautiful fan-structure (Fig. 24). Besides there are found small quantities of allotriomorphic *orthoclase,* as a rule rather strongly perthitic, some *amphibole* prisms with *pyroxene* relics and a few patches of green *chlorite*.

The enrichment of epidote may, however, also lead to quite another type of rock, *viz.* an *epidosite* [240 c]. This variety is composed to about 90 % of *epidote* and *quartz,* partly occurring as an allotriomorphic medium-grained aggregate, partly forming micropegmatitic intergrowths (Fig. 25). Very small quantities of a *feldspar* that cannot be determined occur as a sort of mesostasis and further there are found some amounts of *iron ore* and *green hornblende*, the latter in prisms that are to a great extent chloritized. In the larger quartz grains one may observe numerous hair-fine needles of a colourless mineral with high refraction, straight extinction and negative elongation. Probably it represents *sillimanite*.

The epidote is optically negative with an axial angle of about *70°*.

The birefringence $N_\gamma - N_\alpha$ was found to be 0.050. According to MALMQVIST (1929, p. 257) these data place it among the extremely iron-rich members of the series.

The rocks just described are found in two of the three outcrops mentioned, both lying on the same E.-W. line. The third outcrop is situated some 100 m. farther northwards and represents the northernmost exposure of the dike in this neighbourhood. Here the relations are somewhat different.

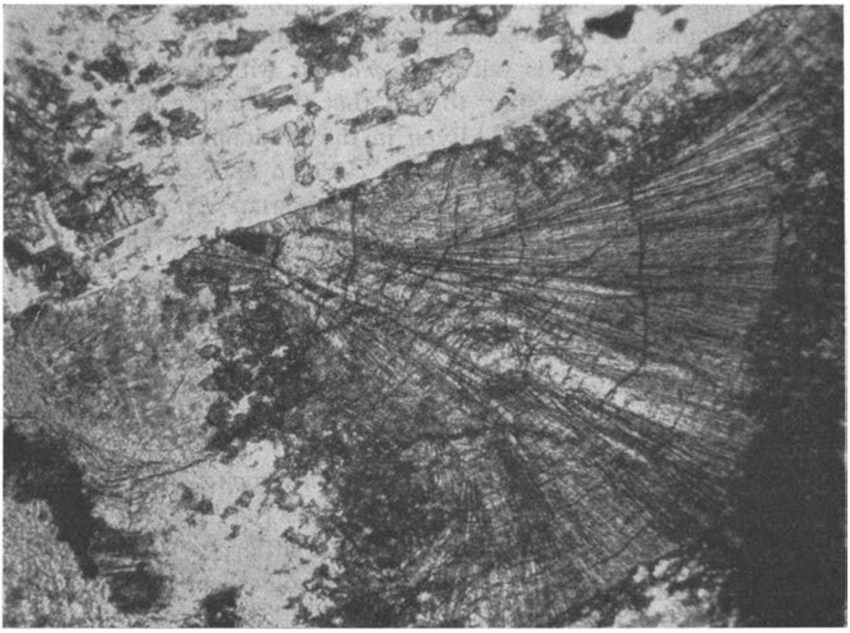


Fig. 24. Fan-shaped epidote in the helsinkitic rock at Äs. Specimen 239, one nicol. Magnification 40 diameters.

The main rock of this outcrop [241 a] is a rather coarse, black-and-red-mottled type (Fig. 26) which is seen megascopically to consist almost solely of *pyroxene* and a *reddish feldspar*. Microscopically the rock is found to be dominated by a very coarse lath-shaped feldspar that is so strongly zoisitized as to make any attempt at determination impossible. Further there is some pyroxene in rather large grains, the form of which is entirely determined by the feldspar laths. Finally, one finds some *iron ore* with *leucoxene,* a little *epidote,* some *quartz,* and *perthitic orthoclase.* By its general texture this rock differs markedly from those of the two other outcrops, and it is almost certain that it represents an original dolerite of the marginal type, which has been subjected to alteration.

Even in this outcrop, however, the variation is rather great. The rock just described is seen to grade into abundantly epidote-bearing types which are often of still coarser grain. Microscopically their texture may be traced into that of the main rock, and they are distinguished only because their state of alteration is far more advanced. Their coarse plagioclase laths, however, are not so abundant; they were determined as almost pure *albite*. Moreover, there have come in great quantities of *perthitic orthoclase* in large allotriomorphic grains. *Pyroxene* has evidently been an important constituent, but is now almost completely replaced by *green hornblende*. A little *apatite* and very little *quartz* is observed. *Epidote* occurs abundantly and generally forms large sectors with a beautiful fan-structure.

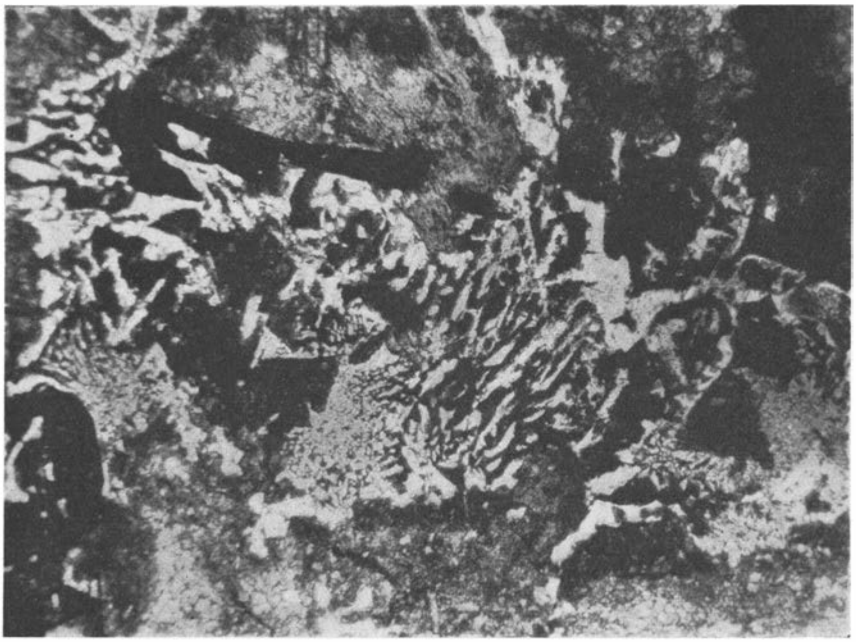


Fig. 25. Micropegmatitic intergrowth of epidote (black) and quartz (white). Specimen 240 c, one nicol. Magnification 40 diameters.

Between the two varieties just described there seem to be all kinds of transitional types. A common feature in them all is a rather strong deformation of the feldspar laths, resulting in a wavy extinction and a distortion of the twin lamellae or even in transverse fractures or flexures. (Fig. 27).

In the last outcrop a band or dike is seen to traverse the main rocks and is found to consist of a rock type that differs but slightly from the latter. Megascopically it is rather fine-grained and pale reddish in colour, sprinkled with green epidote patches. Microscopically it is seen to consist of a hypidiomorphic aggregate dominated by *albite* together with small quantities of *perthite,* fairly large amounts of *pyroxene,* more or less amphibolized, and a good deal of *epidote*. The pyroxene forms independent rounded grains, and in this respect reminds one of the doleritic texture found in the contact modifications of the marginal rocks. The epidote is to some extent poecilitically intergrown with the albite, but mostly it is concentrated in fairly large, irregular areas consisting entirely of this mineral. Quartz is practically wanting.

Locally this type is seen to grade into an almost monomineralic *epidote rock*. Except for a number of elongated darker patches that represent relics of *amphibole* or *pyroxene* prisms the rock is composed exclusively of a rather fine-grained mass of hypidiomorphic *epidote*.

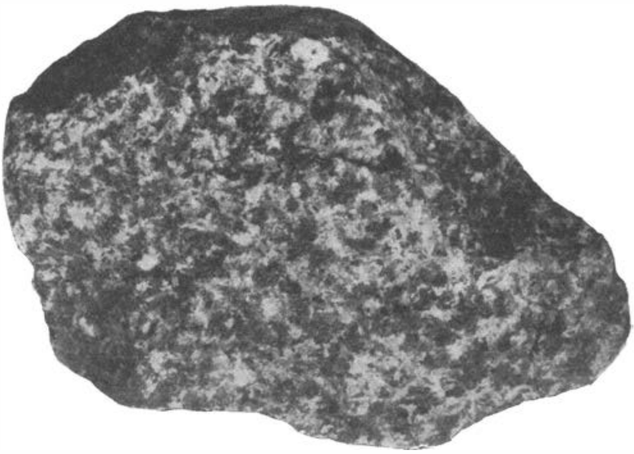


Fig. 26. Hand specimen of altered marginal dolerite at Äs. See text p. 216.

When encountering the above-described rocks in the field one is not at all certain whether they really belong to the Hällefors dike or to the surrounding country rocks. The microscopical investigation, however, brings out clearly their intimate relations to the dolerites, and the question next arises as to what was their origin. As they are found only in three small outcrops which are entirely isolated from the nearest dolerite exposures, no indication can be gained as to their field relations to the other rocks of the dike. The difference between the development in the northernmost outcrop on the one hand and the two southern ones on the other is however of great interest. It has already been pointed out that at the former locality the rocks must evidently be considered as derivatives of the marginal series, an opinion that is further supported by their topographical position. At the two southern localities, on the contrary, no such textural evidence is found. As a matter of fact these rocks are more similar to the Hällefors dolerites, especially when attention is directed towards the andesine-bearing types. Moreover, the rich development of apatite and the prismatic form of the hornblende, suggesting an original idiomorphic pyroxene, seem to indicate that these rocks have in some way or other originated from a rock or a magma of the central series. The outcome of these considerations would be to conclude that the three outcrops are situated on either side of the boundary between the marginal and the central rocks, and that they owe their peculiar development to some process operating or some condition prevailing within a restricted area of the dike only. It is quite evident from the above description that the rocks in question are closely related to the so-called helsinkites (LAITAKARI 1918) concerning the genesis of which there has been much discussion in more recent years. According to a great many petrologists (LAITAKARI 1918, ESKOLA 1921 a and b, ASKLUND 1925, v. ECKERMANN 1925, BESKOW 1929, and others) these rocks should have originated by primary crystallization from water-rich low-temperature magmas. Against this opinion SEDERHOLM, HOLMQUIST and SUNDIUS (G. F. F. 47, 1925, p. 546) have argued that the helsinkites were to be interpreted as metasomatically altered rocks, and BACKLUND *(ibidem)* for at least some of the occurrences claims a pneumatolytic-hydrothermal origin. Recently, MELLIS (1932) has carried out a rather extensive investigation of mainly Lettic helsinkite boulders and, declining to accept the theory of a primary origin, he concludes that the rocks in question are due to (auto-) metasomatic alterations effected in connection with mechanical deformations.

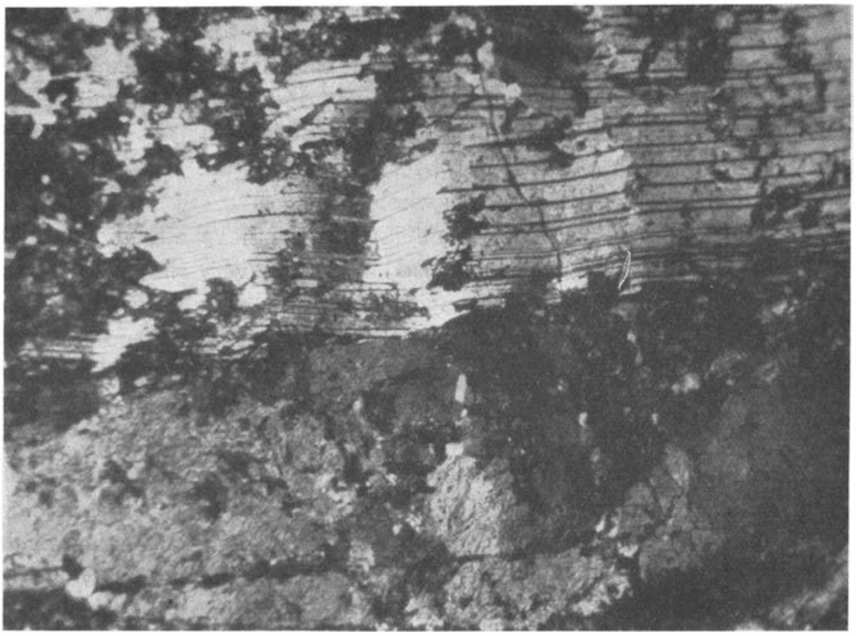


Fig. 27. Distorted feldspar lath. Specimen 241 c, nicols +. Magnification 40 diameters.

In the present case there seems to be little doubt that the interpretation maintained by BACKLUND and MELLIS is the only one applicable. The texture of the rocks can easily be traced back to an original ophitic or doleritic one, and the continuous transition from andesine to albite as well as the poecilitic intergrowths between epidote and albite seem to prove that the albite is not of primary origin. Further, the phenomena of flexure and fracture observed in the feldspar laths are entirely restricted to the epidote-bearing rocks, and are thus most probably connected with their formation. Consequently, they prove that the feldspar had already crystallized when the epidote-forming processes began to operate. Certainly, it might be said in objection to this argument that the indications of deformation may belong to a distinctly later period, the deformation having affected the helsinkite after its formation. If this be so it is odd, however, that such phenomena should be observed only in the restricted areas of helsinkites and nowhere else in the whole dike.

There is another aspect of some interest. I have already mentioned that the slightly epidotized and albitized rocks are very similar to the basic granophyres or the acid epidolerites of the Breven dike. Even in a microscopical examination one is struck by their very good agreement. Now, I have been able to show that in the case of the Breven dike the epidolerites have been formed by an intense pneumatolytic action effected by the acid granophyric magma upon the olivine-free dolerite subsequent to its solidification. It would be rather difficult, indeed, to maintain any other hypothesis for an almost identical rock found within a dike which is closely related to the Breven dike. It should be stressed, moreover, that even in the Breven dike concentrations of epidote are found at a few localities within the epidolerite area close to the boundary against the granophyre. I quote the interpretation offered by me for these peculiar rocks:

»It is the author's opinion that the volatile constituents migrating from the granophyre magma into its wall rock, *viz.* the dolerite, effected not only an alteration of the latter into »normal» epidolerite but also, the conditions being opportune, might have converted part of the femic constituents into compounds easy to remove, which then at some places might be deposited in the way already described.» (KROKSTRÖM 1932 a, p. 310. The word »femic» is of course a mis-statement. It should be »iron- and lime-bearing»).

Now, as the evidence obtained from the Hällefors helsinkites and epidote rocks in general seems to force us to assume a subsequent alteration of rocks previously solidified, the explanation closely follows that the agencies operating were the same as in the Breven dike, *viz.* emanations from a granitic magma belonging to the intrusion-series of the dike rocks. It is true that no representative of such a magma is to be found within the Hällefors dike, but this absence of positive evidence is not a conclusive objection. As will be stressed later on, the present section through the Hällefors dike is likely a higher-level one than that through the Breven dike and it is quite possible that further denudation would expose granitic members also in the former. As a matter of fact, I am inclined to regard the peculiar characters of the rocks just described (and those treated in the next chapter) as the only manifestations of such a magma in the Hällefors dike.

The objection may be raised that if the effects of such emanations were to result in the formation of helsinkitic rocks, one would expect to find such types still more abundantly represented in the Breven dike, where the granophyre is exposed over large areas. On the contrary no such rocks are found with the exception of the epidote concentrations just referred to. This apparent inconsistency, however, may also be explained by the different depths of the present sections. The Breven section is more deeply situated, and represents a level of higher temperature and pressure, and so it is only natural that the effects of pneumatolytic action should, as a rule, have been different from those recorded in the probably rather shallow Hällefors section.

As indicated by the microscopical observations this pneumatolytic action was probably connected with mechanical deformation. In the present outcrops, however, the deformation seems to have been rather slight, which does not of course exclude strong dynamic effects having been displayed in adjacent parts of the rock under-ground. Indeed, such an assumption seems rather probable, and it is of great interest to find at another locality a proof of its validity. We will now proceed to give a description of this locality, which presents rocks of only slightly different character, and afterwards an attempt will be made to follow in more detail the processes that have been operating at both places.

b. The epidote breccia at Källarboda.

In a small outcrop S.W. of Källarboda some effects are observed that must necessarily be ascribed to mechanical forces acting upon the rock. The outcrop is situated within the zone of mottled marginal dolerite and its main rock undoubtedly belongs to that type. It is, however, markedly altered in appearance and even megascopically conveys the impression of being slightly crushed. Microscopically this surmise is confirmed. The rock represents an ophitic dolerite with *labradorite,* $Ab_{35}An_{65}$ (*extinction* $\perp$ *M and* $P = 36°$) and *pyroxene* as its main constituents. The plagioclase is rather strongly *sericitized* and to some extent dotted with *zoisite.* It is intersected by numerous narrow, *chlorite*-filled veins, and sometimes it shows indications of crushing, such as distorted twin lamellae, transverse fractures, *etc.* The pyroxene is generally fresh but sometimes slight *amphibolization* may be observed. Further there is some *iron ore* — generally with ophitic relations to the plagioclase — a fair quantity of *orthoclase* and rather abundant secondary products of chloritic character. The rock is dissected by numerous narrow veins, filled by *chlorite, epidote* and *quartz.*

In the easternmost part of the exposure a zone of about two metres width runs in an N.N.E. direction. This zone consists of strongly crushed rocks and in the field one is inclined to characterize it as a breccia formed *in situ.* In the immediate vicinity of this zone of crushing the main rock becomes still more pronouncedly altered and vague in appearance, and even megascopically some *epidote* is seen to enter into it. Under the microscope it is found to exhibit fairly marked indications of crushing and, moreover, its mineralogical composition has undergone remarkable changes. Almost all the pyroxene is replaced by light-green *chlorite,* forming rather large aggregates of small spherulites. The plagioclase displays still stronger phenomena of distortion and fracture, shows a markedly wavy extinction, *etc.* Further, it has changed its composition very materially, being now almost pure *albite (extinction* $\perp \alpha = 16^\circ$, $N_\gamma =$ *Canada*, $N_\alpha <$ *Canada*). As a matter of fact the albite laths and the spherulitic chlorite aggregates are the only fairly well developed constituents of the rock. The remaining portions are made up of a very intricate mixture of *plagioclase* and *pyroxene* relics together with some *orthoclase,* a few ragged patches of *amphibole* and a little *chloritic* material. *Epidote* is found rather abundantly in the rock, partly as an infilling of very numerous narrow veins, partly distributed in small rounded grains all over the slide, but especially concentrated in the aggregates of spherulitic chlorite.

The rock of the main zone of crushing displays a kind of banding, caused by an alternation of almost aphanitic types and varieties of a distinct although still extremely fine grain. The former are light-green in colour with occasional red dots, the latter are generally a darker shade of green. Under the microscope the difference is seen to be caused by the more or less intense crushing, which is however very strong in both types.

In the coarser variety there may still be found portions where a few feldspar fragments of some size are so well preserved as to be readily recognized. In the aphanitic types, on the other hand, the dominant part of the rock is represented by an extremely fine-grained, almost opaque mass which cannot, as a rule, be resolved by the microscope. Only occasionally a few patches may be observed, in which a strongly granulated fine-grained mixture of *feldspar* and *quartz* is detected. Otherwise the whole mass seems to consist mainly of *epidote,* very finely distributed. Besides, epidote in somewhat larger grains is abundantly scattered all over the mass. Finally, in both types of rock there are extremely abundant narrow veins intersecting the slide in all directions and filled by *epidote* and *quartz*.

Further, there are observed within the zone of crushing a number of dike-like bands, sometimes attaining a width of 10 cm. They run conformably to the above-mentioned banding, which is in its turn approximately parallel to the strike of the whole zone. The rock composing them is megascopically rather similar to the aphanitic one just described, and microscopically the only difference to be found is a higher content of *quartz*. Thus the rock is composed of the usual almost opaque and non-resolvable material, which probably consists mainly of *epidote* and sometimes grades into areas of lighter colour, which are found to represent a finely granulated mixture of *feldspar* and *quartz*. The whole mass is intensely dissected by an irregular network of veins, containing rather large crystals of *quartz*. In these quartz grains there are rather abundant inclusions of *chlorite*, forming curved, worm-like aggregates exactly similar to those described by v. ECKERMANN (1925, p. 506 and Fig. 6, Pl. XX) from the Alfta helsinkite boulders under the term »*coin-rouleaux*». The general impression gained from the present rock is that of a brecciated mass — corresponding to the epidote-feldspar mass — which has been cemented by quartz, and this description may to some extent be applied also to the other rocks of the zone of crushing.

Although there are some differences between the development of the rocks at this locality and at the Äs outcrops, it seems rather probable that the explanation of both occurrences must be essentially the same. The consolidated dolerite has been affected by dynamic stresses that might have been of a tectonic character, but which might also have been caused by the contraction that accompanied the cooling of the rock. MELLIS (1932, p. 432, foot-note) has pointed out that very probably such contractional stresses may lead to a brecciation:

»Es ist ja denkbar, dass lokale Breccienbildungen in der Weise entstehen konnten, dass bei der Kontraktion des sich abkühlenden Gesteins Spannungen auftraten und Spalten aufrissen, längs denen die einzelnen Gesteinsschollen sich infolge einer mit ihrer Volumenverminderung verbundenen unbedeutenden Platzänderung verschieben und so die zur Breccienbildung nötige Reibung hervorrufen konnten.»

It is true that the zone of crushing just described is perhaps a little too strongly developed to be explained as a result of contraction only, but as there is no direct evidence on that point the question must be left open. (See, however, p. 255—256.) A third possibility is that the brecciation was effected by the very emanations that are held responsible for the epidotization *etc.*, or in other words that the zone of crushing should be interpreted as an intrusion- or explosion-breccia. This explanation, however, seems to me less probable.

Anyhow, at the Källarboda locality the emanations from the supposed underlying granitic magma must have been rising mainly through the present breccia zone and there they have effected rather strong pneumatolytic alteration of its rocks. The plagioclase was almost completely broken down, its lime entered into epidote, combining with iron from the mafic minerals. The emanations must have been of an acid and alkaline character and by the break-down of the plagioclase still more alkalies were set in circulation. Thus from the zone most immediately affected there must have been a migration of alkalies and silica into the adjacent parts of the rock body. This migration has led to the albitization of the andesine, the amphibolization and chloritization of the pyroxene and the formation of some epidote from the lime liberated by albitization. In other words, the same processes as were operating in the zone of crushing may be traced also in the adjacent rock although they were there less accentuated. It is evident, moreover, that the epidote formed by the break-down of the plagioclase need not necessarily have been deposited at once but to some extent must have remained together with quartz in a rather mobile state capable of later »auto-intrusions», as witnessed both at Källarboda and at Äs.

As to the differences between the two localities they are probably to be referred to a different intensity of the mechanical deformation. At Källarboda the deformational forces were rather violently released within a restricted zone, in which the alteration attained its greatest intensity, whereas the adjacent rocks were comparatively little affected. At Äs there seems to have been a less intense but more wide-spread action, the rock has been more uniformely permeated by the emanations, and the results were correspondingly more uniform. As to the occurrence of pure quartz-epidote rocks at Äs, the above considerations about the late mobility of the epidote material ought again to be valid.

V. Mutual field relations of the main rocks. Mode of intrusion.

In the previous pages all the principal rock varieties of the large dike have been described. Although, occasionally, in this connection some remarks were made concerning their field relations, it is improbable that the reader has been able to form any clear conception in this respect. The relations are, indeed, extremely complicated. As a matter of fact there is only one tolerably well defined rock-boundary within the whole area, *viz.* between the mottled dolerite and the coarse-grained dolerite of the marginal series, as described on p. 144. When the mottled dolerite borders immediately upon the central rocks without any interposed zone of the coarse-grained type — as for instance at same places in the area of glassy Hällefors dolerites S. of Lake Skogssjön — the change also seems to be quite abrupt, although the actual boundary line was nowhere encountered. The same relation seems to hold when the coarse-grained dolerite borders upon the fine-grained porphyritic varieties of the central rocks as is the case S. of Hälleforsnäs (*cf.* p. 198).

In most cases, however, at the junction the marginal and central rocks are represented by the coarse-grained marginal dolerite and the typical Hällefors dolerite respectively, and in all these cases there seems to be a sort of continuous transition. This statement must not be interpreted in a petrological sense, as there are scarcely any rocks intermediate between the two types in question. The junction may better be described as a zone of mixing. These relations may be very well studied in the neighbourhood E. of Lake Norrtorpsjön. The central parts of the dike are occupied by a rather homogeneous Hällefors dolerite with occasional streaks of porphyritic character. On approaching the dike boundaries, however, one observes in this dolerite irregular portions of very coarse grain which are of exactly the same character as the coarse dolerite of marginal type. These portions become more numerous as one proceeds outwards and, finally, they become entirely dominant, forming a continuous zone of the usual type, which is soon replaced by the mottled dolerite. The relations between the Hällefors dolerite and the coarse marginal type are, consequently, in some respects those of a breccia, but there are no sharp boundaries. The field examination has led me to the opinion that the central rock has intruded itself slightly later than the marginal one and has brecciated it at a stage when it had not yet completely solidified. Instead of a real breccia the result was a zone of imperfect mixing, where, because of high viscosity and low temperature, assimilation and chemical contamination have played but a very small role.

Turning now to the relations between the Hällefors dolerite and the porphyrites, it has been pointed out previously that even petrologically all transitions between these rock-types are found. In the field their mutual distribution is quite an irregular one. It is true that, generally speaking, the typical dolerite occupies a position bordering upon the marginal rocks, whereas the porphyrites are most abundant in the very centre of the dike, but not even this rule always holds good. At many localities the two types alternate in a very intricate fashion, as for instance S. of Hälleforsnäs and at Ölmstorp. At the last-mentioned place, as also in the Fredriksberg area, the porphyrites form long streaks in the dolerite, giving rise to a more or less pronounced banded structure. Now, the most prominent difference between the two rock types lies in the relative abundance of the groundmass, and in a later chapter (p. 228 ff.) it will be shown that, from a chemical point of view, they are very closely related. It appears, then, that their intricate field relations may probably be explained in the following way.

A magma, at some depth, deposited a rather large amount of crystals and the resulting crystal porridge was afterwards forced upwards. During this movement there was effected not only a fluidal arrangement of the separate crystals but also a streaky distribution of the residual melt, leading to alternating bands of phenocryst-rich and phenocryst-poor portions. Such an arrangement might in all probability be attained even if the intrusion is assumed to be the result of one single paroxysm. In the present case, however, considering the great width of the fissure to be filled, such an assumption is hardly possible. On the contrary, we must suppose that the filling of the fissure, *i.e.* the formation of the dike, was effected successively in several »pulsations», and it is quite evident that in this case the possibilities of a streaky distribution are still more enhanced.

There is yet another feature in favour of the conception just outlined. It is evident that a fissure of the width occupied even by the central rocks could not very well have been formed suddenly but must have developed gradually in response to tensional forces. Most probably this gradual widening of the fissure was effected simultaneously with the process of intrusion, and so it is quite natural that the porphyritic rocks should be more abundantly represented in the central (*i. e.* the late-formed) parts of the fissure, as these rocks must have retained their fluidity until the very last stages of intrusion.

From the above considerations the main features of the intrusion of the dike may be pictured as follows. First of all the opening fissure was filled by a magma, consolidating rather quietly (see p. 159) as the mottled dolerite. Some time afterwards, but most probably before this rock had completely cooled down (see p. 144), the fissure was again torn open and was now intruded by another portion of the same magma, which had, however, crystallized to a great extent before intrusion. In this case the intrusion was rather rapid, as is evident from the occurrence of the glassy rocks with coarse phenocrysts, described on p. 145 ff. and the fluidal texture observed at several localities (see p. 144). This intrusion, too, was followed by a period of quiescence but one of no long duration, for in the next stage of evolution, when the Hällefors magma was rather violently intruded, the coarse-grained dolerite in most places could still react in a plastic manner with the new-comer. From this stage on, the intrusive forces seem to have gained their greatest strength, and moreover, there are no indications of intervening periods of repose. During this period it seems very likely that the magma actually reached the surface, and as the fissure was widened it was successively filled by new supplies of the underlying crystal porridge. The dying out of magmatic activity was most probably accompanied by the albitization processes, which must be referred to the late-magmatic stage.

It should be stressed, moreover, that the mutual age-relations of the dike rocks, thus deduced, tally well with the conclusions made from the minor intrusions of adamellitic character (see p. 208 ff.), which show a close relation to the central rocks and intersect the mottled dolerite.

On p. 174 attention was directed to the possibility of locating the *focus* or *foci* of intrusion from the position of the coarse glassy rocks. It is very interesting in this connection to find that the glassy marginal dolerite and the glassy Hällefors dolerite are situated in close vicinity of each other. This would imply that the site of the strongest intrusive forces was about the same throughout the period of successive intrusions.

VI. Chemical variation and differentiation of the rocks.

In order to get a clear view of the chemical variations within the area and to form a conception of the nature of the differentiation, a number of diagrams (Figs. 28—31) have been constructed. As the similarity of geological position and the marked petrological analogies seem to place beyond doubt the close relationship between the Breven and the Hällefors dikes, it was thought appropriate to plot in these diagrams some of the Breven analyses also. For this purpose three analyses were selected which, according to my earlier paper on the Breven dike (KROKSTRÖM 1932 a), are of undoubtedly primary magmatic origin. These rocks are the olivine dolerites, and the olivine-free dolerite. The granophyre was omitted for reasons that will be clear later on and likewise the »intermediate rock» of WINGE because there is some doubt as to its petrological character (*cf. loc. cit.* p. 317). For convenience all analyses are repeated in table XXIV.

In the diagrams one Hällefors analysis is omitted, *viz.* the rock 315 (analysis 9 on p. 201), which conforms in most respects with specimen 316 (analysis 6 on p. 188) and was found to be the result of albitization processes of a late date. For the present purpose — the investigation of the primary magmatic evolution — it may, consequently, be represented by its non-albitized equivalent, no. 316.

In Fig. 28 all other available analyses are plotted in a variation diagram, the abscissa representing the silica content in weight-% and the ordinate the weight-percentages of the other oxides. A great number of such variation diagrams from different petrographical provinces has shown that the projected points for the constituents of rocks belonging to the same differentiation-series fall along rather smooth curves, and general variation diagrams for the rock-forming oxides have been constructed by HARKER, BOWEN and others. BOWEN especially has emphasized the fact that the exact coincidence of the projected points with such curves is to be expected only in the case of rocks, the composition of which corresponds closely to that of a melt belonging to the differentiation-series. In nature this condition is only rarely realized, as a difference between melt and rock is often brought about, *e.g.* by the loss of material of early crystallization. Consequently, the projected points in most cases show a certain amount of scattering around the theoretical curves, and it must be considered quite justifiable to apply some smoothing to the curves actually formed by the

Table XXIV.

	7[205]	4[203]	1[113]	B 1	3[221]	2[236]	B 2	6[316]	9[315]	8[302]	5[123]	B 3	10[91]
SiO_2	39.54	44.41	45.80	46.54	47.30	47.69	48.20	50.41	50.52	51.55	52.23	52.89	67.63
TiO_2	5.76	5.30	1.99	0.96	3.20	2.20	1.54	2.50	2.40	2.54	2.60	2.20	0.60
Al_2O_3	12.30	10.77	15.62	16.88	9.49	17.04	18.07	11.97	12.51	11.10	10.56	14.07	13.34
Fe_2O_3	6.97	5.51	3.34	3.20	5.54	3.77	1.76	5.36	10.09	8.31	5.91	2.83	1.91
FeO	15.52	13.14	11.35	7.41	14.96	9.39	9.16	11.81	6.61	8.39	10.79	9.37	3.11
MnO	0.29	0.25	0.16	—	0.29	0.20	0.15	0.20	0.36	0.22	0.30	0.15	0.05
CaO	8.75	9.98	9.99	9.54	7.60	9.17	9.93	6.70	6.05	5.94	7.57	8.18	1.93
MgO	5.27	5.37	7.42	9.77	3.28	4.56	5.94	2.04	1.82	2.06	1.73	3.59	1.71
Na_2O	2.31	2.60	2.43	3.14	2.76	2.89	2.25	2.87	3.82	3.12	2.84	2.63	3.97
K_2O	0.81	1.08	0.96	0.63	2.69	1.50	1.46	3.51	2.39	3.43	3.48	1.67	4.04
P_2O_5	1.02	0.76	0.11	tr.	1.44	0.20	0.38	1.08	0.99	1.18	0.66	0.76	0.29
H_2O+	1.78	0.75	0.75	0.69	1.50	1.20	0.94	1.44	2.32	1.96	1.20	1.44	1.43
	99.82	99.92	100.01	98.76	100.05	99.81	99.78	99.89	99.88	99.80	99.87	99.78	100.08
si	86.0	101.5	99.0	99.0	118.5	115.0	113.0	138.0	143.0	148.5	147.0	146.0	293.5
al	16.0	14.5	20.0	21.0	14.0	24.0	25.0	19.5	21.0	19.0	17.5	23.0	34.0
fm	57.5	53.5	50.0	50.0	54.5	43.0	42.5	47.0	46.0	47.5	46.0	43.0	29.0
c	20.5	24.5	23.0	22.0	20.5	24.0	25.0	19.5	18.0	18.5	22.5	24.0	9.0
alk	6.0	7.5	7.0	7.0	11.0	9.0	7.5	14.0	15.0	15.0	14.0	10.0	28.0
ti	8.7	9.1	3.3	1.7	6.0	4.0	2.7	5.1	5.1	5.5	5.6	4.6	2.0
p	0.9	0.7	0.1	—	1.5	0.2	0.4	1.3	1.2	1.4	0.8	0.9	0.5
mg	0.35	0.35	0.48	0.63	0.23	0.39	0.49	0.18	0.17	0.19	0.16	0.35	0.39
k	0.20	0.22	0.22	0.11	0.39	0.25	0.30	0.44	0.30	0.41	0.45	0.29	0.40

1. Marginal dolerite, S. of Lake Tallsjön. (p. 135).
2. Glassy, coarse-grained marginal dolerite, S.E. of Jacobsberg. (p. 147).
3. Hällefors dolerite, Ölmstorp. (p. 169).
4. Glassy Hällefors dolerite, S. of Lake Skogssjön. (p. 174).
5. Hällefors porphyrite, E. of Lake Holmsjön. (p. 187).
6. Hällefors porphyrite, S. of Hälleforsnäs. (p. 188).
7. Albitized Hällefors dolerite, S. of Svalbo. (p. 194).
8. Albitic Hällefors porphyrite, S. of Hälleforsnäs. (p. 200).
9. Albitic Hällefors porphyrite, S. of Hälleforsnäs. (p. 201).
10. Adamellitic dike, S. of Lake Tallsjön. (p. 209).

B 1. Olivine dolerite, Krustorp, Breven dike.
B 2. Olivine dolerite, Johannisberg, Breven dike.
B 3. Olivine-free dolerite, Högsäter, Breven dike.

points. As long as this scattering remains within reasonable limits, the variation curve may be considered to depict fairly well the evolution of the residual melt during the course of crystallization. A very great deviation, on the other hand, must indicate that the rock in question could not have formed from a melt belonging to the curve by normal crystallization only. It may belong to another magmatic series or be the result of assimilation, or crystal fractionation, *etc.*

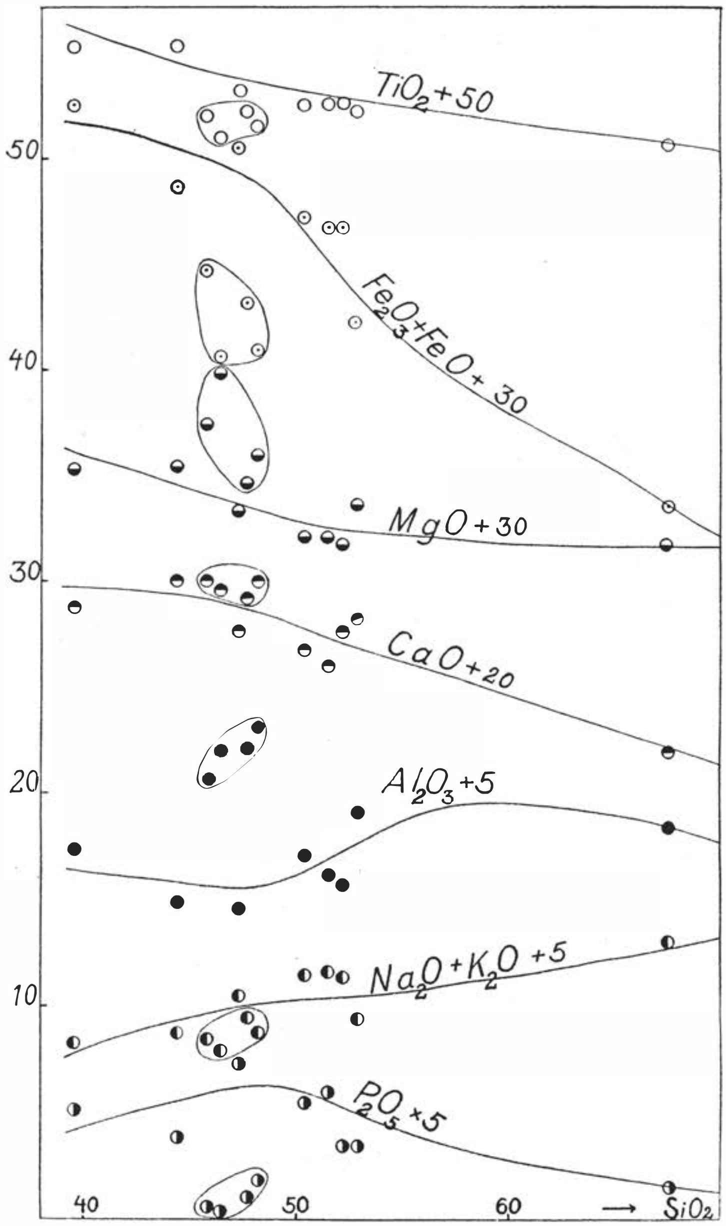


Fig. 28. Variation diagram of the Hällefors rocks and some of the Breven rocks. The points within the encircled areas represent the Breven olivine dolerites and the Hällefors marginal dolerites. (See p. 232.)

○ = TiO_2
⊙ = Fe_2O_3 + FeO
◒ = MgO
◓ = CaO
● = Al_2O_3
◐ = Na_2O + K_2O
◑ = P_2O_5.

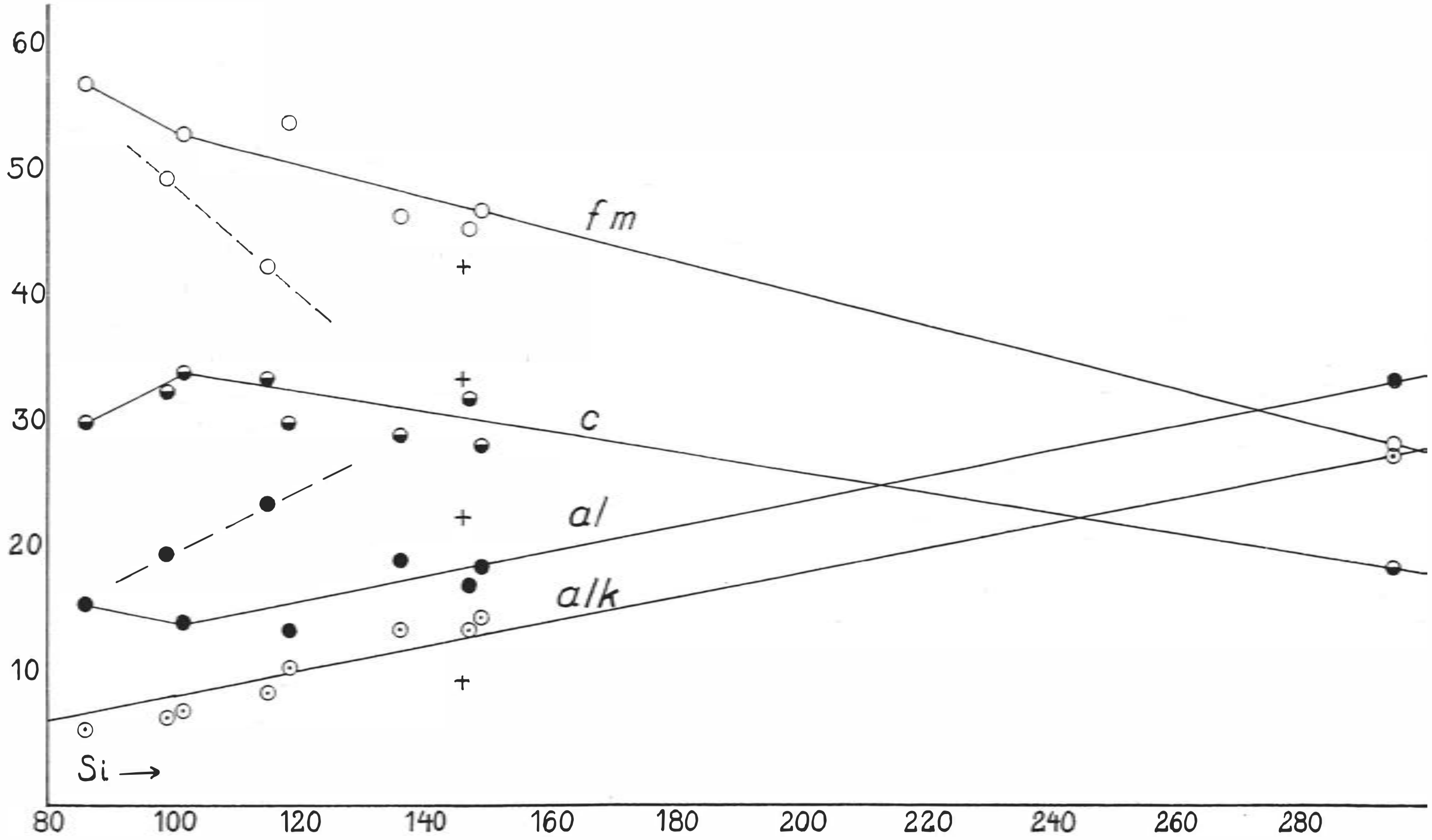


Fig. 29. NIGGLI diagram of the same rocks as in Fig. 28. Open circles=*fm*, half-filled circles=*c*, filled circles=*al*, circles with a dot=*alk*. The olivine-free dolerite of the Breven dike is represented by a cross, which should in each case be related to the nearest line of variation. The points on the broken lines represent the four rocks within the encircled areas af Fig. 28 which in the above diagram coincide two by two.

A glance at the diagram of Fig. 28 is sufficient to show that, with the possible exception of alkalies and lime — none of the oxides permits the tracing of a smooth curve which, even remotely, satisfies all the projected points. Consequently, we must assume that some of the rocks analysed do not belong to the same liquid line of descent as the remaining ones. Now, a study of the diagram reveals that smooth curves may be traced which satisfy fairly well all the analyses except four, and those four analyses (encircled in the diagram) represent the following rocks:

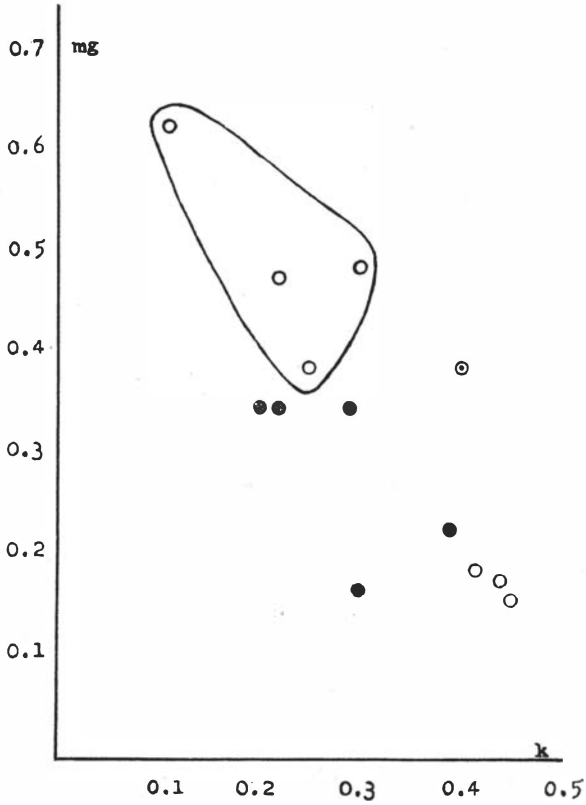


Fig. 30. *k-mg*-relations of the rocks. Open circles within the encircled area represent the marginal Hällefors rocks and the olivine-dolerites of the Breven dike. Open circles outside the area = Hällefors porphyrites. Filled circles = Hällefors dolerites. Circle with a dot = adamellitic dike-rock.

1. The mottled dolerite of the Hällefors dike.
2. The ophitic olivine-dolerite of the Breven dike (The main type).
3. The coarse-grained, partly glassy marginal dolerite of the Hällefors dike.
4. The marginal olivine dolerite of the Breven dike (KROKSTRÖM 1932 a, p. 289).

Consequently, the points that show tolerably good coincidence with the curves in the more basic part of the diagram all represent rocks of typical doleritic texture and without any olivine preserved. Moreover, as concerns the Hällefors dike, all the central rocks, which have been treated as a special group, conform with the curves, whereas the marginal types show a distinct deviation from them. It is also worth noting that the deviating analyses all tend in the same directions and that those from Breven fall rather close to those from Hällefors.

In order to elucidate still further the rock variations the analyses are also plotted on a NIGGLI diagram (Fig. 29) and from this projection also it is quite evident that the rocks of the marginal type fall distinctly outside the lines of evolution connecting the other rocks. Only the *c*- and *alk*-lines are to some extent common to the two groups, but as regards the other oxides the marginal rocks seem to differentiate along quite another direction, as indicated by the broken lines in the diagram.

Generally the *k*-*mg*-relation is very useful for deciding the mutual relations of different rocks and in fig. 30 such a diagram is given. It brings out at once that the marginal rocks fall well together also in this respect and differ markedly from the other types. In this case the central dolerites seem to occupy an intermediate position between the marginal rocks and the Hällefors porphyrites. It is surprising to find that the adamellitic dike-rock falls almost closer to the marginal rocks than to the central types, although the microscopical examination undoubtedly shows its very close relation to the latter. It is, however, the value *mg* which is the deciding factor in this case and it must be considered that this value, as the absolute amounts of mafic oxides decreases, is likely to become a more or less unreliable indicator.

Finally, the analyses were plotted in the OSANN triangle *A*-*C*-*F* (Fig. 31) in which the relations are again very distinctly depicted. In this diagram the marginal rocks are clearly distinguished from the Hällefors dolerites and the main line of evolution, tending from them through the porphyrites towards the alkali corner of the triangle. Here the olivine-free Breven dolerite seems to occupy an intermediate position, a feature that may be traced also in some of the previous diagrams. As a matter of fact it coincides fairly well with the marginal rocks, but in view of the diagrams of Figs. 28 and 29 there seems to be no doubt as to its closer relationship to the central series.

All the diagrams just discussed seem to lead us to the following conclusions:

1. The Breven rocks and the Hällefors rocks show such a high degree of correspondence and in all diagrams fall so closely together that there seems to be no doubt — as far as chemical and petrological experience goes — of their actual consanguinity.

2. Within the petrographical province formed by the Breven and Hällefors rocks, two principal rock series are represented, which differ chemically as well as petrologically. It does not seem improbable that these two series represent different lines of evolution, proceeding from a common parental magma.

The authors of the Mull Memoir (BAILEY 1924, p. 13) have introduced a very useful term in speaking of *magma-types*. This term is best defined by a quotation from the paper in question:

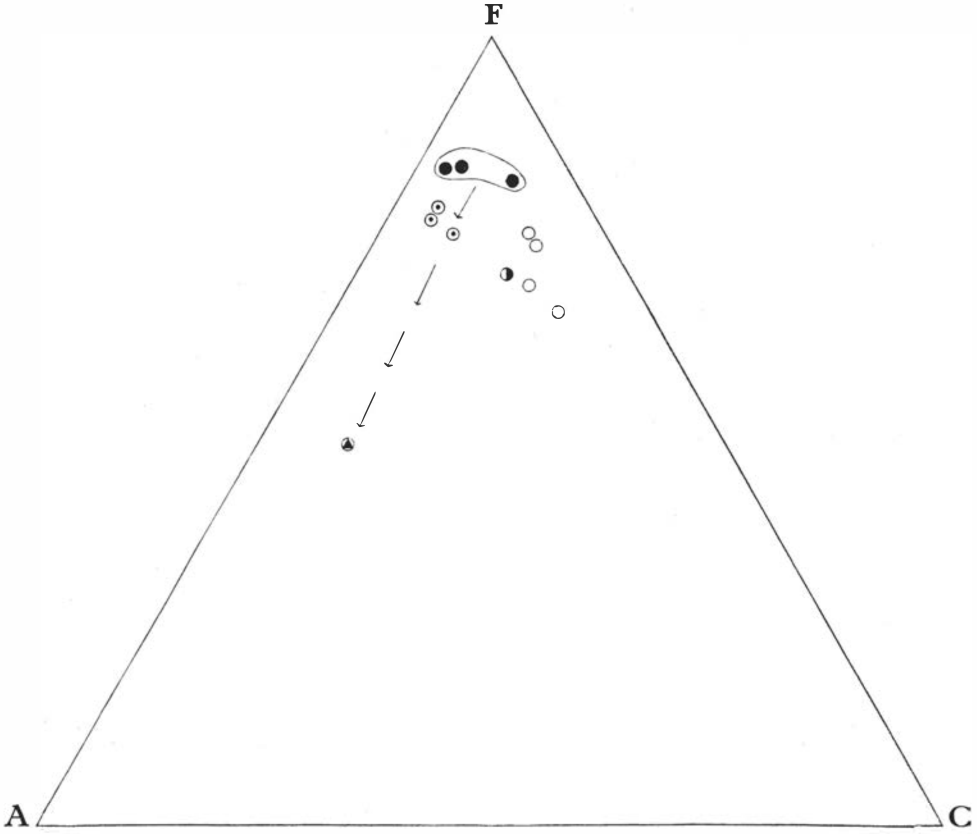


Fig. 31. The analyses plotted in the OSANN triangle *A-C-F.*

● = Hällefors dolerites. ◉ = Adamellitic dike. ⊙ = Hällefors porphyrites.
○ = Marginal Hällefors rocks and olivine-dolerites of the Breven dike.
◑ = Olivine-free dolerite of the Breven dike.

»The conception of magma-type is based upon composition alone. In this it differs from the conception of rock-type, which takes into account texture as well as composition. Thus a basalt and a gabbro may belong to the same magma-type though admittedly representatives of different rock-types.»

In our present case it can hardly be doubted that the two lines of differentiation, referred to above, represent two different *magma-types,* and as a matter of fact I have already been using this conception in speaking of the marginal series and the central series. It is true that the differences between these groups lie both in composition and in mineralogical development, but the chemical analyses show clearly that in their evolution they follow two distinctly different lines, and their contrasted characters must be due to differences inherent in the magmas themselves. In this connection attention should be called to a proposal of BOWEN's (1928, p. 139) that under the term *magma-type* should be understood not only completely molten rock material but also liquid with some crystals.

The question that next arises concerns the mutual relations of the two initial magmas, and in order to answer it we shall have to consider comprehensively the characteristic differences between the representatives of the two *magma-types:*

The marginal type	*The central type*
Typically ophitic texture with pyroxene of late crystallization.	Doleritic or porphyritic texture with pyroxene of fairly good idiomorphism.
Plagioclase with *60—65 % anorthite.*	Plagioclase with about *40 % anorthite.*
Hardly any early, idiomorphic iron ore, but practically all of it developed in large individuals of late crystallization, ophitically enclosing the plagioclase laths.	Iron ore of fairly good idiomorphism but generally rather strongly corroded.
Olivine abundant.	Fresh olivine completely wanting, but numerous olivine pseudomorphs.
Interstitially a scant development of orthoclase and quartz.	A more or less abundant interstitial material, consisting mainly of alkali-feldspar and chloritic matter and with little or no quartz.
Apatite very sparse.	Apatite abundant.
Al_2O_3 *15—20 %*	Al_2O_3 *9—13 %*
$FeO+Fe_2O_3$ *10—15 %*	$FeO+Fe_2O_3$ *17—21 %*
TiO_2 *about 2 % or less*	TiO_2 *2.5—5 % or more*
MgO *5—10 %*	MgO *2—5 %*
P_2O_5 *0.4 % or less.*	P_2O_5 *0.6—1.5 %.*

Considering the data given above, one is immediately struck by the fact that a magma of the central type would, no doubt, result if the marginal magma were to be enriched in the molecules of apatite and titaniferous iron ore, *i. e.* the mineral components that would be expected to form in the first stages of crystallization of a basaltic magma. In order to show that this relation really exists table XXV below has been computed.

Table XXV.

	1	2	3	4
SiO_2	46.19	38.81	40.33	—
TiO_2	2.01	5.47	5.37	4.5
Al_2O_3	15.76	13.24	12.55	—
Fe_2O_3	3.37	7.03	7.11	5.0
$FeO + MnO$	11.61	16.06	16.13	7.5
CaO	10.07	9.30	8.92	1.0
MgO	7.48	6.28	5.38	—
Na_2O	2.45	2.06	2.36	—
K_2O	0.97	0.82	0.83	—
P_2O_5	0.11	0.93	1.04	1.0
	100.02	100.00	100.02	19.0

In the first column the analysis 1 (Marginal dolerite, specimen 113) is recalculated as water-free and in column 3 the same calculation is made for the Hällefors dolerite specimen 205 (analysis 7 on p. 194). In column 2 the composition is given which results when the material of column 4 is added to analysis 1. It is immediately seen that there is very close correspondence between the numbers of the columns 2 and 3. Indeed, it is hardly to be expected that a better agreement can be obtained, in view of the many and complex processes which may influence the result. The normative composition of the material added comes out as follows:

37.4 % magnetite + 44.2 % ilmenite + 12.2 % apatite + 6.2 % FeO.

The slight excess of FeO hardly implies any difficulty, as the stage of oxidation of the iron may very well have undergone some change during later periods.

The objection may be raised that the rock 205 is not quite a typical Hällefors dolerite as it belongs to the albitic types. It has been pointed out, however, that it does not quite agree with the prevalent albitic rocks, and from the chemical analysis the conclusion was arrived at that it owed its special character to internal processes caused by decreasing temperature only (see p. 195). Consequently, its present compositon is not likely to differ very much from the primary one, and as it happens to be the most basic rock of those analysed it is most likely to give the best approximation to the original central magma.

Now, the two magma-types, because of their closely related geological positon, must necessarily be considered as genetically connected, either as different off-shoots from a single parental magma or as successive representatives of a differentiation-series. As the differences can hardly be explained by any hypothesis of assimilation of extraneous material, there seem to be only two alternatives — liquid immiscibility or differentiation by crystallization. It must be considered highly improbable, however, that immiscibility relations would exist between two magmas both of which, notwithstanding certain differences, belong to the basaltic group. Consequently, the only hypothesis left seems to be that of crystallization differentiation. From the diagrams of Figs. 28—29 it is quite evident that the two magmas do not belong to the same liquid line of descent, and thus we are almost forced to conclude that the compositional differences are due to the concentration of some of the early-formed crystals in one part of the magma chamber. We have also seen that such an enrichment in the minerals apatite and titaniferous iron ore would, as a matter of fact, transform a magma of the marginal type into one of the central type. As the rocks of the marginal series are rather well defined and, moreover, representatives of this petrological type are found to occupy vast and homogeneous areas not only in the Breven and Hällefors dikes but also in several other districts in Fennoscandia, it is very tempting to assume that the marginal magma represents the parental one, from which the central magma was derived by crystal accumulation. Such an assumption, however, is contradicted by the textural relations of the marginal dolerites of the Hällefors dike. I have previously emphasized that in these rocks the iron ore is of very late crystallization, and, consequently, a subtraction of this mineral in the early stages would not be possible, if the original magma was of the composition indicated by the present rock. Thus there must have been a third magma, which has been the common parent of the marginal and the central magmas. This magma must have occupied a position intermediate between the two and must have precipitated apatite and titaniferous iron ore among its earliest products of crystallization. Most probably its composition was more closely related to that of the marginal type than to that of the central type, and it is by no means improbable that some of the Swedish rocks classed as Åsby dolerites may represent a magma of this type.

As to the way in which the crystals were removed from this parental magma there are no indications. It seems reasonable, however, to assume that gravity has been the main factor in this process. The sinking down of the heavy crystals proceeded until hampered by the growing plagioclase laths and then the remaining part of the potential iron ore would fill the interstices between them as previously described. Some olivine must also have sunk, as its specific gravity is slightly higher than that of apatite, but this fact is not at all inconsistent with my hypothesis, for most of the apatite must have crystallized and been abstracted before olivine precipitation had begun, and thereafter the iron ore with its higher specific gravity was far more apt to overcome the obstruction of the plagioclase laths. Thus the amount of olivine, transported downwards, must have been rather insignificant.

It is true that the compositional differences between the two *magma-types* are rather satisfactorily accounted for by this hypothesis, but, as we know, the central and the marginal rocks do not differ in chemical composition only. There are also great mineralogical and, above all, textural differences, and these cannot be explained simply by assuming a mechanical enrichment in certain crystals. They are rather easily accounted for, however, if we assume that assimilation of the sunken material has been effected at deeper levels, and this assumption is indeed very strongly supported by the markedly corroded contours of the iron-ore grains of the Hällefors dolerite.

The pros and cons of such a remelting have received much discussion of late years. BOWEN, in his detailed work on the theory of crystallization differentiation, is decidedly unfavourable to the conception of the resorption of the accumulated crystals. He bases his views in this respect mainly on the non-existence of glassy rocks of a composition corresponding to rocks formed by crystal accumulation. In the Mull memoir (BAILEY 1924, p. 33) BAILEY accepts the theory of crystallization differentiation, but maintains that, at least in some instances, a remelting must have occurred. Further, in his extensive treatise of the differentiation of igneous rocks, J. H. L. VOGT (1924, p. 6) stresses emphatically the possibility and the necessity of such a resorption. One of his conclusions is of special interest in the present case, *viz.* his views concerning the origin of some peculiar apatite-magnetite, apatite-ilmenite, and apatite-perowskite rocks. He has been able to show »that all these segregations may have been formed by a subsidence of the first crystallizing minerals, which have been entirely resorbed in the deeper and hotter zones of the magma.» (*Loc. cit.* p. 52).

I take the liberty of continuing the quotation from this passage of VOGT'S:

»The subsiding minerals, principally apatite, magnetite-ilmenite and Fe-Mg-silicates, depending on the different density and the different size of the individuals, probably in connection with other factors, may have been resorbed in different stages or etappes . . . And the new magmas, resulting from the resorption of the downwards sinking minerals, owing to the change of equilibrium, may give rise to the formation of new minerals completely missing in the mother rock.» (*Loc. cit.* p. 52).

Since the appearance of VOGT's paper above-mentioned BOWEN has stated his reasons for denying the effects of resorption (BOWEN 1928, pp. 132—174) and has brought forward a great many important arguments. Still, I must confess that I am unable to find that the hypothesis of refusion is disproved. The non-existence of glassy or very fine-grained rocks of an extreme composition is evidence only of a negative kind, and, moreover, it may be doubted, whether such rocks have not really been observed (*Cf.* VOGT *loc. cit.* p. 97). Another argument of BOWEN's concerns the high temperatures required for the resorption (*loc cit.* p. 166), but even this reasoning does not seem quite convincing. Taking, for instance, the case of iron ore and apatite it seems rather reasonable to assume that their relations to the melt are purely eutectic ones. As in a eutectic system melting is the reverse of solidification, even a slight rise of temperature must cause a resorption of a component just deposited from the melt. Now, it will be agreed that in a magma reservoir the temperature must increase downwards and, as in a basic melt the viscosity is not extremely high, the sinking crystal quite soon after its precipitation will reach a level where its re-solution can be effected. In the case of isomorphous compounds the relations are, of course, not quite so simple, but even in this case the possibilities of resorption ought to exist.

The above considerations are not intended to be arguments in favour of the existence of ultra-basic melts in nature, but they are made in order to stress the probability of resorption being effected at least to some extent in the deeper parts of a magma-chamber.

It is of some interest that by complete resorption two entirely liquid portions of a magma would be formed, although their formation would have been controlled by crystallization. In a way such processes may be considered to constitute a kind of »missing link» between the theory of liquation and that of differentiation by crystallization, and it may be questioned, whether there is really any necessity to build such an unsurmountable wall between these two conceptions.

As a matter of fact the two contrasted *magma-types* of the Hällefors dike, according to the deductions on p. 237, must have been generated by crystal sorting, and as their different petrological characters cannot be explained by a mechanical agglomeration of crystals only, their relations seem to speak strongly in favour of the resorption hypothesis. Thus far I have attempted to show that this hypothesis is by no means theoretically disproved. It remains now to consider what would be the probable effect of resorption in the present case and to ascertain whether the known facts are in accordance with those theoretically required or not.

Disregarding the chemical differences, which are, of course, not influenced by the question of resorption, the most conspicuous difference between the two rock suites is the textural one. In the marginal dolerite plagioclase was of very early crystallization and pyroxene was not deposited until a rather late stage, thus giving rise to the typical ophitic texture. In the Hällefors dolerite, on the contrary, pyroxene began its crystallization at least at the same time as and probably even before the plagioclase, as witnessed by the doleritic texture. This must imply that the composition of the generating magma was situated rather far within the field of mafic crystallization, so as to reach the individualization curve of the plagioclase only when considerable quantities of ferro-magnesian minerals had been precipitated. It is true that in another connection (KROKSTRÖM 1932 b, p. 209) I have entertained certain doubts as to the strict validity of the deductions that are made by BOWEN from the tetrahedron Ab-An-Di-$FeSiO_3$, as the probable appearance within the system of the olivine components is not taken into consideration. For a more general treatment, however, it might be justifiable to assume that there exists an individualization boundary between the mafic minerals and plagioclase, although in such a very complex system all theoretical deductions must necessarily become more or less a matter of conjecture. Under such circumstances, however, it seems reasonable to expect that an enrichment in iron would tend to bring about an earlier crystallization of the mafic minerals and postpone the precipitation of plagioclase until later stages, just as is seen to be the case in the Hällefors dolerites. It should be stressed that the crystallization of the mafic minerals is only relatively early compared with that of the plagioclase. Of course an enrichment in iron most tend to lower the absolute temperature of precipitation and, consequently, crystallization in general would be deferred.

It may be objected that if titaniferous iron ore and apatite had been resorbed by the magma, the same minerals would also be the first ones to crystallize in response to decreasing temperature. Such a conclusion, however, is not *à priori* necessary. I have already quoted the statement of VOGT according to which altogether new minerals should be able to form, owing to the change of equilibrium caused by resorption. In our present case there is, moreover, yet another fact that deserves attention, *viz.* the simultaneous enrichment in iron and phosphorus. In his treatise on the apatite-rich Kiruna ores GEIJER states that iron ore and apatite were among the very last components precipitated from the generating magma (GEIJER 1910, p. 267). It is true that the high titanium content of the central Hällefors rocks may to some extent change the conditions, but there seems to exist a certain tendency in magmas rich in iron and phosphorus not to deposit iron ore and apatite until the later stages of their crystallization.

Considering now the curves of Figs. 28 and 29 we may fairly safely conclude that the Hällefors dolerites and porphyrites belong to the same liquid line of descent, the latter representing melts generated by partial crystallization of the common parental central magma. It is very interesting, then, to find considerable amounts of iron ore and very large amounts of apatite in the groundmass of the porphyrites. As a matter of fact the percentages of P_2O_5 are practically as high in the porphyrites as in the dolerites and this fact seems to prove that almost no apatite was deposited in the earlier stages of crystallization. Its perfect idiomorphism in all the rocks is most probably to be ascribed to its high power of crystallization. The considerable iron-ore content of the groundmass seems to indicate similar relations for the iron ore, but in this case no absolute evidence may be gained from the chemical analyses, as the iron oxides enter into several of the minerals of these rocks. The apatite relation, however, proves that a rise of temperature, after resorption has been effected, need not necessarily lead to a reestablishment of the original composition of the melt. Certainly the textural relations of the Hällefors dolerites seem to prove that at least some of the large iron-ore grains are of early formation, but in view of their strongly corroded contours I am inclined to regard them as representing for the most part non-resorbed relics of the accumulated ore.

Yet another feature supporting the hypothesis just advanced is to be found from a comparison of the plagioclase composition of the two rock groups. Whereas the marginal dolerite carries a labradorite with about 60 % An the most basic plagioclase of the central rocks is an andesine with only 40 % An. This fact agrees quite well with the relations pictured above. By a relatively early crystallization of pyroxene the melt must evidently become impoverished not only in iron and magnesia but also in lime. Consequently, when at a later stage the precipitation of plagioclase begins, the quotient $CaO : Na_2O$ must have a lower value than in the original melt, and a correspondingly less anorthite-rich plagioclase must be deposited.

The above considerations imply rather peculiar consequences. We have seen that an enrichment in iron will tend to bring about a doleritic texture, instead of the ophitic one which would have been displayed on crystallization of the original magma. On p. 140—141 I have argued that the doleritic texture of the contact rocks was a result of an enrichment in silica. Thus, starting from a magma that would normally solidify as an ophitic rock, an enrichment in silica will, curiously enough, lead to the same result as an enrichment in iron, *viz.* to quite another order of crystallization, resulting in the development of doleritic texture. In a previous paper (KROKSTRÖM 1932 b) I have stated as my opinion that the ophitic texture is met with only in undersaturated rocks and NORIN (1934, pp. 136—144) from a study of the

Scanian basalts arrived at much the same result. A quotation from my paper above-mentioned will show on what grounds my opinion was formed:

»The difficulty is avoided if we assume the original magma to have been undersaturated. The plagioclase and olivine crystallized almost simultaneously and not before the saturation point was reached, pyroxene began to separate. At this time the very greatest part of the plagioclase had already consolidated and the residual liquid *of a pyroxenic composition* when congealing could embed the plagioclase laths ophitically or subophitically.» (*Loc. cit.* p. 210.)

It is quite clear that an enrichment in silica will tend to prevent the crystallization of olivine or at any rate shorten its duration. Consequently, pyroxene will get the opportunity of crystallizing rather early and the conditions leading to an ophitic texture are no more existing. As a matter of fact, the development of the latter is entirely dependent on whether at an early stage olivine is precipitated in considerable amounts or not. Turning now to the doleritic texture displayed by the iron-rich central Hällefors rocks, we find that just the same interpretation is valid here. Recently BOWEN and SCHAIRER (1935, p. 212) have emphasized that when olivine and pyroxene have a high iron content, pyroxene will separate in advance of olivine. Indeed, in some Greenland basalts BACKLUND and MALMQVIST (1932, p. 45) found this order of crystallization clearly indicated. In the present case the place of olivine in the sequence of crystallization could not be directly established, as the mineral in question is nowhere preserved and the secondary products give no unambiguous evidence. It is very interesting to find, however, that the general textural relations of the rock clearly lead us to assume the very order of deposition that is theoretically to be expected in these extremely iron-rich magmas.

It will appear, then, that the development of the typical ophitic texture is confined to rocks of rather limited chemical composition, *viz.* to rocks undersaturated in silica and not extremely rich in iron. The word »extremely» is chosen on purpose, for even the marginal rocks of the Hällefors dike are fairly rich in iron, but still exhibit a beautiful ophitic texture. Only when the iron content attains the very high values of the central types can this texture no longer be developed. Consequently, the ophitic texture, in its original conception as given by ROSENBUSCH (1887, p. 191) is not only of importance as a descriptional textural term, but may also give certain rather distinct indications as to the chemical composition of the rock in question. For that reason I wish to emphasize once more that a discrimination should certainly be made between this texture and the doleritic one. In this respect another view is held by most British petrologists, which, according to A. G. MACGREGOR (1928, p. 329) have found it undesirable to base a distinction on these differences. Thus BAILEY (1911, pp. 137—139) found it convenient to include under the term »Jedburgh basalt» rocks of both textural types and even to reject the discrimination made by WATTS (GEIKIE 1897, p. 417) between ophitic Kilsyth dolerite and »microlitic» Markle dolerite. It may be true that sometimes, especially in fine-grained rocks, it may be rather difficult to carry through such a discrimination, but, nevertheless, in view of the above considerations it seems to be highly desirable that due attention should be given to its significance.

In this connection a few words should be added concerning the nomenclature that was proposed by me for basaltic and doleritic rocks (KROKSTRÖM 1932 b, p. 199) and which has been used throughout this paper. In a personal communication in 1934 Mr. W. CAMPBELL SMITH of the British Museum called my attention to the fact that the term »doleritic» as proposed by me would be very difficult to accept in Britain as the ophitic texture is, indeed, considered as a characteristic of dolerites. I frankly admit that in such a case the term is not altogether appropriate and I am quite willing to reject it for a better one. Instead of my »doleritic» British petrologists seem to use the term »intergranular». It is true that this term can be used internationally, but it becomes very cumbersome if the prefix »sub-» is added and it is my opinion that there is certainly a need for such a distinction as implied in my »sub-doleritic». In any case I maintain that the four-fold division proposed by me is necessary in order to bring any clearness in the jungle of textural terms concerning basaltic rocks. I am not able myself to find any good substitute for my »doleritic», but will welcome one with satisfaction. Until then, however, I feel compelled to use the term in the sense previously proposed by me.

Before concluding this chapter on magmatic evolution, attention should be called to some features of the variation diagram (Fig. 28 on p. 230). The curves have been traced so as to satisfy as well as possible all the analyses of the central series. As some of the iron recorded by analysis most probably belongs to accumulated crystals not completely resorbed, the curve $FeO + Fe_2O_3$ is likely to be a little too high in the basic part of the diagram, but this fact is of no vital importance in the interpretation of the curve. Starting from the left side of the diagram we find that in the first stages there is a slight decrease in TiO_2, $FeO + Fe_2O_3$ and MgO whereas CaO and Al_2O_3 are almost constant or show very little decrease. Finally, alkalies and P_2O_5 are increasing markedly. This part probably corresponds to the period of early pyroxene crystallization. Although the P_2O_5-curve shows a rather strong scattering of its points, its general tendency is evident and it seems to support the assumption that in the early stages no apatite was deposited.

At about 50 % of silica the decrease of the iron curve becomes rapidly more prominent, the magnesia-curve flattens out, the lime-curve begins to fall a little steeper and the alumina-curve passes a minimum and begins to rise. This interval corresponds to the stage when olivine begins to separate, accompanied by iron ore. Probably some plagioclase was also separating, but in comparison with the mafic minerals its amount was insignificant and thus the alumina was, in point of fact, concentrating in the melt, as were also the alkalies. The P_2O_5-curve at this stage passes a maximum and begins to fall, indicating the beginning of the apatite deposition.

From this stage on, the curves in general retain the same tendencies, with the exception of the alumina-curve which in the acid part of the diagram passes a maximum and begins to fall — owing to the increasing role played by feldspar among the minerals deposited. The contrasted shape of the iron- and magnesia-curves is of great interest, signifying the successive change to more iron-rich compounds among the crystals.

As to the marginal rocks, with the exception of lime and alkalies, their analyses do not fit the curves. The fairly good agreement concerning the oxides mentioned is easily understood. The alkali content of the melt is hardly influenced at all by the different order of crystallization in the early period, for under all conditions alkalies must tend to increase during the mafic crystallization. As to lime, one might possibly expect a steeper initial fall of the marginal curve, owing to the early precipitation of rather basic plagioclase. Such a tendency, however, is counterbalanced by the separation of olivine, and thus the lime-curve must assume about the same shape as that of the central rocks which is controlled by the lime-content of the separating augite.

VII. The Breven and Hällefors dikes — a comparison.

In the preceding pages an attempt has been made to follow the magmatic evolution within the Hällefors dike. The field and laboratory data have shown that in the formation of the dike two different *magma-types* were concerned, and it has been concluded that they were formed from a common parental magma by crystal sorting and subsequent remelting. Moreover, the field relations indicate that at least two distinctly different intrusions have taken place — an earlier of the marginal type and a later of the central type. This order of intrusion was supported by the chemical data and the hypothesis of differentiation accepted. Further there are some indications that a granitic magma may have played some role, although there are no definite proofs of its existence. The sequence of intrusion, consequently, should be represented by the following phases:

1. *Marginal dolerite magma.* Probably two manifestations with a very slight *hiatus.*

2. *Central dolerite magma.* Intruded in several paroxysms of rapid succession and differentiating during intrusion in the direction from dolerite to porphyrite.

3. *Granitic magma(?)* The existence of this magma is indicated by circumstantial evidence only. (See pp. 213 and 221).

Turning now to the Breven dike the following intrusion-series was deduced (KROKSTRÖM 1932 a, p. 323):

1. Olivine dolerite
2. Olivine-free dolerite
3. Granophyre
4. Olivine dolerite.

It is at once evident that there exists a marked agreement between the two sequences. The marginal dolerite of the Hällefors dike is practically identical with the olivine dolerite of the Breven dike and the variation diagram of Fig. 28 shows that the olivine-free dolerite of the latter fits the curves of the central series rather well. There is also a marked mineralogical agreement between the two types of rock. In the Hällefors dike there has been found no rock corresponding to the late olivine dolerite of the Breven dike, but it must be borne in mind that even in the Breven dike this rock is very restricted in its occurrence. Moreover, its position in the sequence is by no means reliably established, although a great deal of circumstantial evidence speaks in favour of its late magmatic manifestation.

It seems necessary, then, that any hypothesis of differentiation deduced for one of the dikes must apply as well to the other. In neither case, however, has it been possible to form a definite opinion as to the position of the granophyre magma in the differentiation-series. It is true that in the Breven paper I have been able to show that the granophyre analysis conforms rather well with the curves of the variation diagram, but I have also stressed, firstly, the difficulty of making definite conclusions from such a limited number of analyses and, secondly, the fact that a great many granite analyses would most probably fit the curves quite as well.

The rather common association of sharply contrasted acid and basic rocks has of late years been the object of much discussion. The extreme adherents of the theory of differentiation by crystallization claim that granitic magmas are generated from basaltic ones by crystallization only. The process is, however, a rather complex one. Normally the residual melt of a basaltic magma tends in a trachytic rather than a granitic direction (BOWEN 1928, p. 236; HOLMES 1931, p. 250). The condition for the generation of a granitic residual is that olivine is precipitated in excess of its stoichiometrical amount and afterwards for some reason or another fails to react with the melt. In a previous paper (KROKSTRÖM 1932 b) I have stressed the great difficulties that this theory has to meet when the quantitative relations between dolerite and granophyre in the Breven dike are taken into consideration, and these arguments need not be repeated here. It is my opinion that although the theory may explain the micropegmatitic interstitial material found in many dolerites it is hardly sufficient to account for such great granophyre masses, as for instance the Breven one.

As to the hypothesis of liquid immiscibility, I have previously (*loc. cit.* pp. 212—213) pointed out that it would provide a rather good explanation of the rock association in question. I do not claim, however, that such processes have actually been in operation, for in view of the strong laboratory evidence against the existence of immiscibility relations in silicate melts it seems essential that more weighty arguments should be offered before such an hypothesis is accepted.

A few years ago KENNEDY (1933) advanced a theory concerning the trends of differentiation in basaltic magmas and his views in this connection are of great interest. He claims the existence of two parental basaltic magmas, the *olivine-basalt magma-type* and the *tholeiitic magma-type*.

Starting from the former, differentiation should proceed in an alkaline direction, whereas from the latter acid differentiates should result. KENNEDY has compiled a fairly exhaustive amount of analytical data concerning the late segregation veins in basaltic rocks of different types, and the result seems to confirm his views strongly.

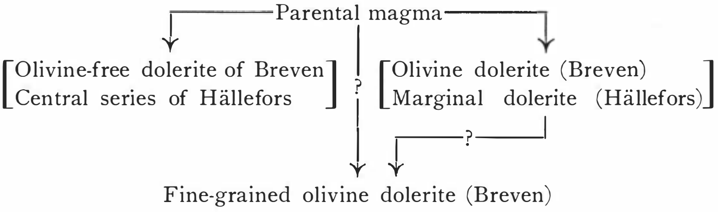
Mineralogically the rock representatives of the two contrasted *magma-types* are quite distinct. The olivine-basalt magma-type gives rise to rocks with abundant olivine and a diopsidic, often titaniferous pyroxene. Their texture is typically ophitic and the residual interstitial base is alkaline. The tholeiitic magma-type on the other hand gives rocks with little or no olivine and a pyroxene of the pigeonite series. The texture is doleritic and the interstitial residuum is of an acid, quartzo-feldspathic composition. (KENNEDY 1931, p. 63; 1933, p. 241).

When this distinction is applied to the Breven-Hällefors rocks it is at once evident that they must be incorporated in the olivine-basalt magma-type. It is true that the optical determinations seem to indicate that the pyroxene tends slightly towards a pigeonitic composition, but it has already been stressed that the chemical data do not seem to support this opinion and it may be questioned whether the optical properties determined are quite conclusive on that point (see p. 137). Further, there are certainly interstitial infillings of an acid character in the marginal rocks, but they are most probably to be ascribed to the above-mentioned effect of excess olivine precipitation, and consequently, do not give an indication of the normal development. Thus it may be quite safely concluded that the rocks in question are fairly good representatives of KENNEDY's olivine-basalt magma-type

According to KENNEDY this magma-type should normally give alkaline differentiates and he states that not a single case is known to him in which olivine-basalt magma has produced a quartzose differentiate. As regards the Hällefors dike the observations tend to support this opinion. We have seen that the porphyritic types show a groundmass of mainly feldspathic composition whereas quartz is seldom present and then in very small amounts. As this groundmass very often exhibits a texture indicating very rapid cooling, sometimes even a devitrification from an originally glassy state, it probably represents rather closely the composition of the residual melt and, consequently, its character ought to bear witness to the direction of differentiation in the magma. Under such circumstances it is very peculiar indeed to find in the Breven granophyre such a conspicuous exception to a rule that seems to be rather convincingly established. This inconsistency has led me to the opinion that the granophyre is not directly consanguineous with the doleritic rocks. An attempt to explain rock associations of the kind just treated without involving differentiation was made by HOLMES (1931) who assumes the granitic phase to have been generated by a remelting of the country rocks. Discussing the results of recent petrological work in N.W. Scotland, especially in the Ardnamurchan peninsula (RICHEY and THOMAS 1930) HOLMES concludes that the cone-sheets and ring-dikes of that region have emanated from cupola-shaped magma reservoirs rising from the upper parts of a regional magma layer within the earth's crust. By means of convection currents even the uppermost parts of these magma cupolas may always maintain a temperature sufficiently high to permit a remelting of their roof, and »the ultimate result provides the required conditions — co-existence of acid and basic magmas in a cupola-shaped reservoir» (*loc. cit.* p. 249).

There are a great many facts speaking in favour of this hypothesis and in the present case it gives a very simple explanation of the apparent inconsistency just referred to. It may be objected that in such a case the acid magma must have occupied the upper part of the reservoir and thus it would likely form the earliest phase of intrusion, whereas in the Breven dike as in many other composite intrusions it is found to represent a rather late phase. It seems, however, by no means necessary to suppose that the intrusions were always fed from the uppermost part of the cupola, and, moreover, we must take into consideration the probability that such an acid magma had far greater viscosity than the basic one and, consequently, was less apt to be immediately raised in response to a release of the intrusive forces. Indeed, some observations within the Breven dike of diffuse granophyric inclusions in the distinctly older dolerite (KROKSTRÖM 1932 a, p. 300 and 310) seem to indicate that the two magmas at some time or other coexisted at deeper levels.

In view of the above considerations I am inclined to accept for the Breven granophyre and its possible Hällefors equivalent the theory advanced by HOLMES. It should be stressed, however, that it is hardly possible to give a definite solution of this problem, as the evidence that has so far been gained cannot be considered as conclusive. For this reason a scheme of evolution including all the different phases of the Breven-Hällefors rock association cannot be given. The mutual genetic relations of the doleritic rocks, however, may be illustrated as follows



We have found that the analogies between the Breven and the Hällefors dikes are very conspicuous, but although their magmatic history must have been much the same there are certain differences which must not be overlooked. These differences are presented mainly by the structural development of the rocks. Whereas in the Breven dike all rocks — except the picritic type which is very restricted in occurrence — are coarse-grained, evengrained, and always holo-crystalline, we have met among the Hällefors rocks strongly porphyritic types. The groundmass of these porphyrites most probably represents a devitrified glass or at least a product of very rapid crystallization. In some of them indubitable glass portions are even still preserved. Another feature of interest is presented by the structure of the outcrops. In the Breven dike a few exposures of picrite and fine-grained olivine dolerite exhibit a *habitus* that was considered as indicative of solidification under effusive conditions, but otherwise no such structures are observed. In the Hällefors dike, on the contrary, a great part of the porphyrite outcrops show rugged and almost scoriaceous surfaces strongly reminiscent of those found in lava exposures. Of course, these surface phenomena are due mainly to processes of weathering, but at the same time it would appear that the rock is not very compact.

Thus both microscopical and megascopical structures seem to suggest that the rocks now exposed in this dike represent a rather shallow section through the intrusive body, or might even in some cases be considered as effusives.

There is, further, a mineralogical difference between the marginal Hällefors dolerite and the Breven olivine dolerite which might perhaps be connected with the different depths of the two sections. In the Breven olivine dolerite two kinds of pyroxene are found — monoclinic and ortho-rhombic — whereas in the closely related marginal dolerite of the Hällefors dike only monoclinic pyroxene is represented. Of course, this difference may depend on a slightly different initial composition of the magmas of the two areas, but a comparison between the analyses 113 and B 1 of table XXIV will show that in the Hällefors rock the content of MgO+FeO is even greater than in the Breven one and, consequently, there ought to have been still better opportunities for the formation of ortho-rhombic pyroxene. Now it is quite possible that the higher quotient $FeO:MgO$ of the Hällefors rock may account for the difference, for even in the Breven rock, which is much poorer in iron, the ortho-rhombic pyroxene was found to contain no less than *43 %* $FeSiO_3$ and an increase of the above-mentioned ratio may very well have brought the melt out of the stability area of the ortho-rhombic series.

There is, however, another possibility that deserves attention, although it must be considered as purely conjectural. TSUBOI (1932) has advanced a theory concerning the crystallization of pyroxenes from rock-magmas, according to which »the pyroxenic components are only partially miscible in the intratelluric stage while they are completely miscible in the effusive stage» (*loc. cit.* p. 81). Concerning the cause of this difference he offers no explanation, but it seems rather reasonable to suppose that temperature and — perhaps above all — pressure should be the controlling factors. Under such circumstances the result would be that a deeper level of crystallization would tend to promote the deposition of two pyroxenes, whereas in a more shallow position only one kind would be expected. Consequently, if this theory of TSUBOI's is to hold good, we might find in the mineralogical difference, just referred to, another indication of the higher position of the Hällefors section. It is frankly admitted, however, that this argument is of no great weight.

VIII. **Faulting. Dip and form of the dike.**

A. **The Norrkärr fault.**

At the southern shore of Lake Örhammaren, just N. of the farmhouse of Norrkärr, two dolerite outcrops are separated by a rather conspicuous valley which continues from the shore in a southerly direction, becoming rapidly less well marked towards the south. In the eastern wall of the valley a normal mottled dolerite is exposed, whereas the western slope is occupied by a strongly brecciated rock. Almost the whole outcrop at this side of the valley consists of a coarse breccia formed *in situ*, and is abundantly littered with angular rock fragments of varying size. This breccia zone may be followed for some distance towards the south. A specimen of the breccia [83] was subjected to a microscopical examination which brought out the following results.

The original rock most certainly represented a mottled marginal dolerite. The minerals present are *plagioclase, pyroxene, iron ore,* and some *chloritic material,* and they are all strongly affected by mechanical deformation. The plagioclase is clouded and fractured, and the pyroxene likewise. The iron ore occurs in rather large individuals which are, however, intersected by numerous irregular veins, filled by secondary products, mainly *epidote.* To some extent the iron ore is also drawn out so as to form long streaks.

These parts of the rock must, however, be considered as relict portions that have been only slightly affected by the crushing. Other parts are developed as fairly wide zones with a prominently streaky structure and of slightly irregular shape. They consist of an extremely fine-grained isotropic base that cannot be resolved by the microscope and all over this mass numerous small angular fragments of all the minerals of the rock are scattered. These zones seem to be quite identical with those described by BEARTH (1932, p. 164) from the dolerites of the Silvretta mountain chain and must be considered as the extreme results of shearing.

The existence of the breccia is in itself a strong indication that the dike has been affected by a fault at this locality. There are, however, several other facts confirming this conclusion and they will be briefly mentioned below.

1. A glance at the map of plate I or, still better, at the geological map-sheet Hällefors (KUGELBERG 1864) reveals that at this place the width of the dike undergoes a very abrupt change. Moreover, on the little peninsula immediately east of the islet in Lake Örhammaren, dolerite is exposed, whereas the islet itself shows only gneiss. This would imply a sudden deviation of the northern boundary of the dike from an east-westerly to an almost north-southerly direction. At the southern boundary the relations are still more conspicuous. Indeed, E. of the presumed fault the dike boundary is located no less than 800 m. north of the corresponding line W. of it.

2. In all probability a continuation of the valley referred to above may be traced northwards, as indicated by the rectilinear western shore of the little inlet at the opposite side of Lake Örhammaren. Farther northwards in the same direction a small depression is again encountered which is filled by a small elongate lake (see map).

3. On the islet in Lake Örhammaren the gneiss strikes N. 50° W. At a small isolated rock immediately N.E. of the islet, however, the strike is seen to become very irregular but is mainly directed N. 10° E. Such a change of direction may possibly be explained as a distortion along a more or less transcurrent fault.

4. To the east of the presumed fault no porphyritic rocks are observed. A little westwards, however, they immediately make their appearance. This seems to indicate a somewhat different position of the present section at different sides of the critical zone.

The observations listed above, together with the actual occurrence of a breccia, must be considered to prove irrefutably that at this locality the dike has been subjected to faulting. The fault line must have had a roughly north-southerly direction and the movement of the western parts should have been southwards (points 1 and 3 above) and downwards (point 4 above).

B. Indications of faulting at Lake Norrtorpsjön and S. of Svalbo.

There are a few indications of faulting at two other places but it must be admitted that the evidence is too scarce to be fully conclusive.

Lake Norrtorpsjön is situated in a narrow valley of N.N.W. direction which is well marked in the topography and most probably lies along one of the system of fissures that intersect this region (*cf.* ASKLUND 1923). It may be traced for a distance of about 10 km. and is occupied by several elongate small lakes. At the eastern shore of Lake Norrtorpsjön a number of rather high dolerite exposures are seen to plunge steeply down into the lake. At this shore the boundary between the marginal and the central rocks may be exactly located about 100 m. south of the northern end of the lake. About 250 m. westwards, west of the lake, the dike is again exposed, but here the boundary in question is found no less than 300 m. farther to the north. It is of course possible that the boundary may be rather irregular, but certainly this would imply a very surprising change in its general east-westerly direction. I am inclined to think that the observations tend to favour the conception of a slight fault also at this locality.

S. E. of the Svalbo inlet a very conspicuous change in the direction of the dike is observed. In the eastern parts it runs east-west or nearly so, but in this neighbourhood it curves gently round to a north-westerly direction and then very abruptly changes back to the former east-westerly one again. The general impression is that the dike has been faulted and the parts immediately east of the fault have been distorted. It is very interesting, then, to find that at the very locality where the dike takes up again its east-west direction it is bounded eastwards by a rather steep escarpment, running N. W. or N. N. W. In all probability this escarpment is a direct continuation of the Svalbo inlet which is undoubtedly bounded by faults.

As additional evidence it may be mentioned that at the northern dike boundary, immediately west of the presumed fault line, a rather strong jointing is observed in the mottled marginal dolerite, a feature which is otherwise never observed in this rock.

West of the presumed fault no porphyrites are found. As a matter of fact they are entirely restricted to the area between it and the fault at Lake Örhammaren. This would indicate that the relative movement of this part of the dike has been downwards also at the locality last treated.

C. **Concluding remarks.**

In this connection a few words should be added concerning the dip and the form of the dike. At the localities where the contact line between the dike and the country rock is exposed no sections of great vertical extension are found and, consequently, the dip cannot be ascertained from direct observation. Nor is it possible — owing to the small differences of level within the area — to draw any definite conclusions from the relations between the position of the dike boundaries and the topography. The fairly regular strike of the dike seems to indicate, however, that the deviation from a vertical dip cannot be very great in either direction.

The above considerations concerning the faults seem, however, to provide somewhat more conclusive evidence. We have found that for petrological and topographical reasons the part of the dike which is situated between the Örhammaren fault and the presumed Svalbo fault must be assumed to have moved downwards. If the faulting implied a vertical movement only — which is perhaps most probable — this would indicate a dip towards the north, since the boundaries of this part of the dike are in both cases replaced southwards. However, it cannot be entirely ruled out that a horizontal movement has also been effected and, consequently, the conclusion is by no means irrefutable.

At both the above-mentioned fault-lines a marked change in the width of the dike is observed, and in both cases the sunken part is wider than the adjacent ones. This would indicate that at least at higher levels the intrusion has the form of a wedge widening upwards. Such a form seems indeed quite probable as the dike was no doubt injected along a successively widening fissure.

IX. **Age relations of the great dikes.**

As is well known, the main strike of the gneiss region into which the Breven and Hällefors dikes are intruded is an east-westerly one, and thus the dikes run roughly parallel to the strike direction. If the relations are studied in more detail, however, it will be found that at several localities the dolerite cuts across the structures of the gneiss.

I have given some attention to the internal contact phenomena displayed by the dolerite and found that assimilation of the wall rock must to some extent have taken place. At several localities, moreover, the gneiss is seen to have been strongly affected by the dolerite, developing contact modifications of varying types, very often »baked» in appearance and reminding one slightly of the Swedish hälleflintas. Of course a closer study of these rocks would be of great interest, but owing to the great extension of the dike and the rather heterogeneous character of the country rock such an investigation must necessarily turn out to be a very far-reaching one, and must be considered to fall beyond the scope of this paper.

We have found that at some places the dike has been subjected to mechanical deformation, but only of a very local kind and always due to faulting. With the exception of these local phenomena the rocks are quite unaffected by any tectonic processes such as those intensely displayed by the country rocks.

The above-mentioned data all prove that the dikes are younger than the Archaean, a fact that has long since been recognized by Swedish geologists and which is stated here only for the sake of completeness. If there is thus no great difficulty in fixing the lower limit, it is not so with the upper one. In the most recent comprehensive treatise of Fennoscandian geology (RAMSAY 1931) ASKLUND concluded that the Breven and Hällefors dikes are of post-Jotnian age. His reasons for this opinion have been previously stated (ASKLUND 1923) and in my Breven paper I ventured to express some doubt as to their definite validity. It is hardly necessary to repeat my arguments here, but I will stress one point only.

I have shown above that the Hällefors dike is traversed by at least one and probably three faults striking in a N.N.W. or N. direction. The same applies to the Breven dike where the fault is even still better indicated. Consequently, there seems to be no possibility of maintaining the opinion announced by ASKLUND (1923, p. 278) that the Hällefors dike probably cuts the N.W. system of fissures. On the other hand there is the well-known observation at St. Sidus where an olivine dolerite of the Hällefors system cuts some bronzite dolerites of the N.N.W. system (STOLPE 1879, p. 16; ASKLUND 1923, p. 279). If the conclusions based on petrological agreement and fissure systems should both be valid, there seems to be no possible explanation of this inconsistency. Consequently, either of the two methods of correlation must be considered as unreliable and I have previously pointed out that, indeed, grave objections may be raised against both (KROKSTRÖM 1932 a, p. 325).

Two matters are settled, however. Firstly, there is no doubt that two different types of dolerite — bronzite-dolerite and olivine-dolerite — were intruded in post-Archaean but pre-Cambrian time. As a matter of fact they correspond rather closely to the two magma-types claimed by KENNEDY (see p. 246). Secondly, ASKLUND's investigations (*loc. cit.*) prove beyond doubt that in the region now in question the former are found to occupy *preferably* the north-west system of fissures whereas the latter are generally found to strike east west. The observations referred to above, however, seem to prove that fissures of a certain direction may have originated at different times, or at least that movements along them may have taken place at long intervals. As concerns the great fault lines of the Lake district of Middle Sweden this fact has already been emphasized by A. G. HÖGBOM (1913, p. 4). Consequently, it is also to be expected that dikes belonging to the same system of fissures may have been intruded at different periods. Thus the connection between intrusives and fissure directions in this region pointed out by ASKLUND may generally hold good, but must not be considered conclusive in such a manner that the age of a dike might be inferred from its direction only.

It is of some interest in this connection to find that one of the large fault lines which are held responsible for the formation of the basins of Lake Hjälmaren and Lake Mälaren intersects the Hällefors dike in close vicinity of the epidote rocks at Äs and the breccia at Källarboda (see S. DE GEER 1910, map, and map Pl. I). As, according to DE GEER, the

Silurian of Närke is faulted along this line, post-Silurian movements should have occurred along it. Now it is by no means proved that the Källarboda breccia is a result of real tectonic movements, but if that be so it must most probably be connected with the fault line in question. In such a case it seems necessary to assume movements along it having been effected already in pre-Cambrian time, as the rock development at Källarboda clearly indicates that the mechanical deformation took place at a time when the magmatic activity leading to the formation of the dike had not yet died out.

As the Breven and Hällefors dikes are altogether isolated from any sediments or eruptives of known age, the only other hint as to the probable age of the intrusions might be given by their petrological character. Previously I have emphasized that while the olivine dolerites are of Åsby type, and for that reason are considered likely to be of post-Jotnian age, the character of the Breven granophyre seems to be more compatible with a sub-Jotnian age, a fact which had been already pointed out by GEIJER (1922, p. 417). In my present investigation, however, I have reached the conclusion that the granophyre is not actually consanguineous with the dolerites (see p. 248) and, consequently, this argument is not valid. For this reason I have no longer any objections to offer against assuming the dikes to be of post-Jotnian age. It should be borne in mind, however, that their position is by no means reliably established as it is inferred only from analogies with other districts (Åsby, Nordingrå).

X. **Summary of contents.**

The Hällefors dolerite dike is situated in the southern part of Middle Sweden, about 30 km. N.E. of the Breven dike (KROKSTRÖM 1932 a). It has a length of about 40 km., an average width of 1 km., and strikes approximately E.—W.

Within the dike two different rock series are represented. Almost the whole western half of the dike, and the marginal portions of the eastern part are occupied by types which are referred to as the *marginal series*. Its main representative is a medium-grained olivine dolerite of Åsby type with excellent ophitic texture. A somewhat coarser variety of essentially the same type and clearly also belonging to the marginal series is believed to represent a slightly later intrusion inside the medium-grained one. This coarse-grained type at some localities shows a glassy development of its interstitial material. The plagioclase of the marginal rocks is a *labradorite* $Ab_{35}An_{65}$.

In the central parts of the eastern half of the dike another rock series is represented which is referred to as the *central series.* This suite displays a marked and apparently continuous variation from coarse-grained, evengrained types, the Hällefors dolerites, to markedly porhyritic types, the Hällefors porphyrites, with very fine-grained groundmass of about trachytic composition, which represents in many cases the result of devitrification. Fresh olivine is never present, but numerous pseudomorps after this mineral are found. The plagioclase of the central rocks is an *andesine*, $Ab_{60}An_{40}$, and this mineral also constitutes the commonest phenocryst of the porphyrites, olivine pseudomorphs and pyroxene being as a rule restricted to the groundmass.

Especially the porphyrites, but to some extent also the Hällefors dolerites, have locally been subjected to marked albitization, which is interpreted as a result of late magmatic processes. The distribution of the albitic rocks is considered to indicate a streaky distribution of the material of the magma (especially the volatiles) during intrusion.

A few small dikes of adamellitic affinities which intersect the marginal dolerite are interpreted as consanguineous with the central series, and, most probably, point at a *hiatus* in the intrusive activity.

The chemical and petrological data seem to bring out that the two magmas responsible for the marginal and central rock series respectively have been generated from a common parental magma by gravitative settling and subsequent remelting of mainly titaniferous iron ore and apatite. The Breven and Hällefors dikes are found to be consanguineous, but the granophyre of the latter is concluded to have been generated by remelting of the country rocks in accordance with the hypothesis advanced by HOLMES (1931). The present section through the Breven dike is considered to be a deeper one as compared with that through the Hällefors dike.

In the western part of the dike a few exposures of helsinkitic rocks and an epidote breccia are found. They are interpreted as results of pneumatolytic action in connection with mechanical deformation.

The dike is traversed by at least one and most probably by three faults which seem to belong to the N.N.W. system of fissures of the region. The field relations in the vicinity of these faults may possibly indicate a steep northerly dip of the dike.

The age-relations of the dike cannot be irrefutably established, but there seems to be no reasonable objection to the prevailing opinion that it is of post-Jotnian age.

List of references.

Abbreviations.

A.J.S. = American Journal of Science.
B.G.I.U. = Bulletin of the Geological Institution of the University of Upsala.
G.F.F. = Geologiska Föreningens i Stockholm förhandlingar.
N.J. = Neues Jahrbuch für Mineralogie, Geologie und Paläontologie.
N.J.B.B. = » » » » » » » , Beilageband.
Q.J.G.S. = Quarteraly Journal of the Geological Society of London.
S.G.U. = Sveriges Geologiska Undersökning.
T.M.P.M. = TSCHERMAK's mineralogische und petrographische Mitteilungen.

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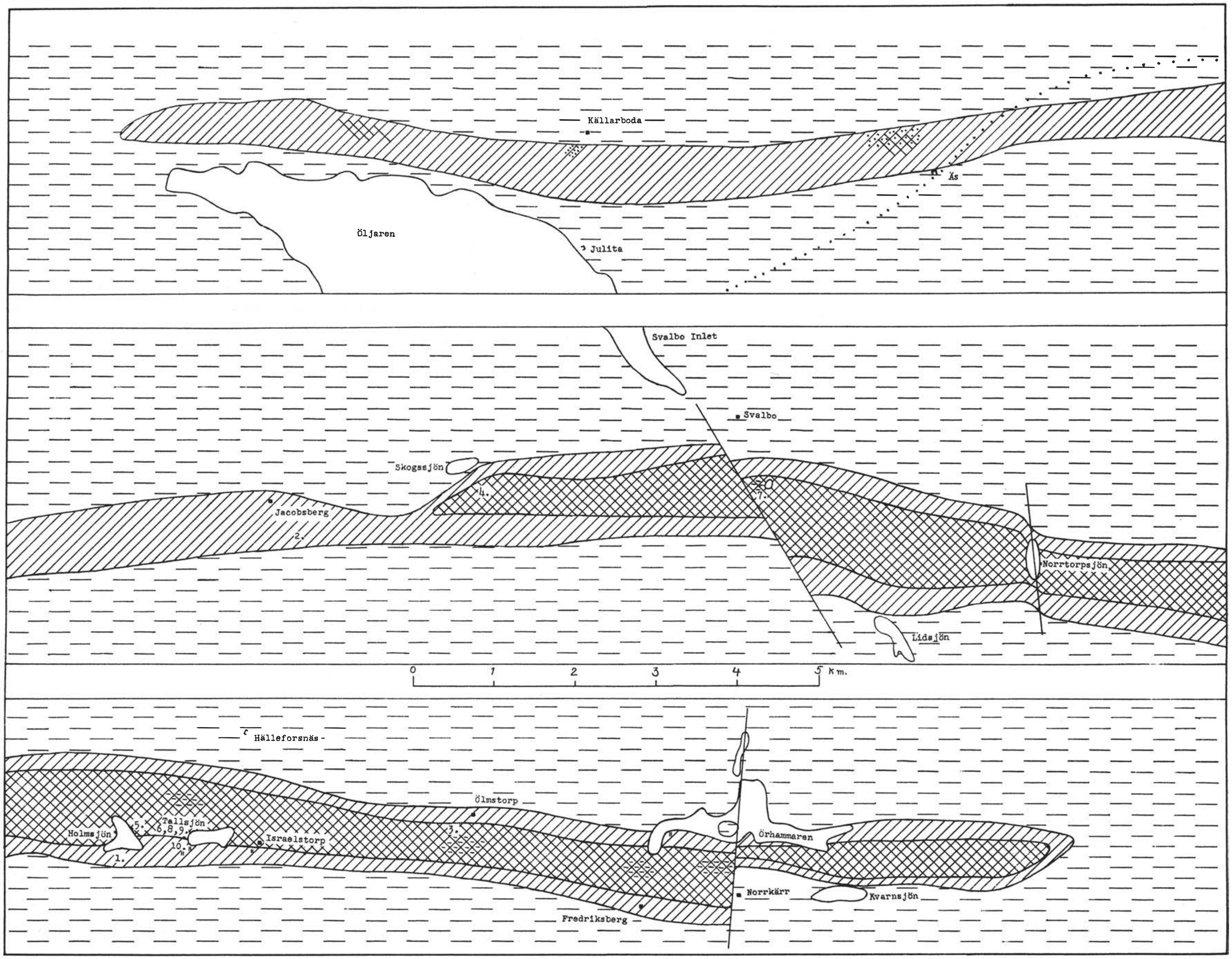

Scale 1 : 50 000

PETROLOGICAL MAP OF THE HÄLLEFORS DOLERITE DIKE.

Horizontal broken lines = Gneiss.
Oblique hatching = Hällefors marginal series.
Cross-hatching = Hällefors central series.
Dots indicate the position of the epidotized rocks at Äs and the epidote breccia at Källarboda.
Small horizontal lines within the cross hatching indicate the main areas of albitic rocks described in the text on p. 191 ff.

Small vertical lines in the vicinity of Lake Tallsjön and S. of Lake Örhammaren represent dikes of adamellitic or quartz-albite composition. See text pp. 208 ff. and 212 ff. The dimensions of the dikes are necessarily somewhat exaggerated.
Full-drawn straight lines indicate faults.
The dotted line represents one of the great fault-lines of Middle Sweden according to S. De Geer (1910).

The small cross-hatched areas within the western part of the dike (upper part of the map) are possibly somewhat exaggerated in their extension, as rocks of the central series are at these localities encountered in one or two outcrops only.
The numbers refer to the numbers of the analyses in the text and are inserted approximately at the locality of the specimen analysed.