7. The Breven Dolerite Dike.

A Petrogenetic Study.

By

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(With Pl. XII.)

Contents.

Preface.

The field investigations for this paper were carried out during the summer months 1929 and 1930 *viz.* about three weeks in 1929 and about six weeks in 1930. Furthermore some localities of special interest were revisited in 1931. The laboratory research was executed in the Mineralogical and Geological Institution of Upsala during the winter months 1929—1930 and 1930—1931.

As to the formal aspect it has been considered convenient to make a division into a descriptive and a discussing part. In this way it has not been possible to avoid some repetitions, but the author is fairly convinced, that this inconvenience is more than counterbalanced by the greater perspicuousness gained by such an arrangement of the material. On the other hand all the data given in the descriptive chapters have not been discussed in the second part, but nevertheless it might be convenient to present them, as they may be of some importance for other purposes than those aimed at in this paper.

For shortness some explanations of methods used in the course of the microscopical investigations may be given here:

The refraction indices were determined on optically oriented thin sections by means of standardised liquids of immersion.

The determinations of double refraction were made with the aid of a BEREK's compensator, the thickness of the thin sections — when not otherwise stated — being directly measured with an ocular screw micrometer.

For works with the universal methods a FEDOROFF stage of LEITZ' construction was used. In course of the feldspar determinations by that method, the corrected values of observed angles have been given, because the standard values of differerent authors still diverge and lead to various compositions.

The numbers within brackets in the text below refer to the list of references on pp. 326—329 and to the page of the paper cited respectively.

Introduction – Earlier investigations in the area.

The dike, that is to be treated on the following pages, forms a typical example of a composite dike, consisting of a great many rocks of different types, varying from an abundantly olivinebearing dolerite through various intermediate types to a pure alkalic granophyre. The dike, having a length of a about 30 km. and a width of 0,3 to 1,2 km., extends from Lake Rävsjön in the parish of Hallsberg (Örebro län) in an easterly direction to the neighbourhood of Lake Storsjön in the parish of Regna (Östergötlands län). The situation of the dike is moreover indicated on the sketch map, Fig. 1 on page 246. Having its main extension within the geologic map-sheet »Brefven» (**14**), it was named the Brefven dike by WINGE (**60**: 189), and this name has also been admitted into the literature. Only the very eastern part of the dike falls within the geologic map-sheet »Claestorp» (**26**).

As far as the author knows, the Breven dike is first mentioned in the literature by TÖRNEBOHM, who devotes a few lines to it in his paper on the diabases and gabbros of Sweden (**50**: 19). TÖRNEBOHM seems to pay his attention only to the western, olivinebearing part of the dike, and he gives a short description of the mineral composition of these rocks.

Two years later, in the year 1878, E. ERDMANN published a somewhat more detailed description (**14**: 36—44), and as his concluding remarks are rather interesting, they are quoted below:

»It has been previously mentioned, that the diabase in the eastern parts of the great dike and the granite (the diabase granite), occurring close by, have a somewhat similar composition but are perceivably different from the rock in the western part of the dike. Particularly in the vicinity of the boundaries between the diabase and the granite in the eastern part of the dike, where a real transition between the two rocks exists, both rocks seem to have been influenced, the one by the other, an influence appearing mainly in the mineral composition. The diabase has there been enriched in silica, by which quartz has separated and part of the feldspar has changed to orthoclase. One could rather say that the diabase in the western part of the dike, the one occurring in the eastern part, and the diabase granite form together a series of different types of one and the same rock.» (*Loc. cit.* page 44. Translation by the present author.)

In the year 1882 TÖRNEBOHM describes again with a few words the types of rocks in question (**49**).

The most recent treatise on the Breven rocks is to be found in a paper by WINGE 1896 (**60**). WINGE gives a rather detailed microscopical analysis of the types of rock, and besides, three chemical analyses are communicated. As an introduction the author gives a comparing account of the various theories set forth in order to explain the mode of formation of composite dikes, and finally in some concluding remarks he gives expression to the opinion gained by him during the research as to the probable genetic relations of the dike rocks:

»Thus ascertained, that the diabase and the granite making up the Breven dike are genetically associated, another question is, how the

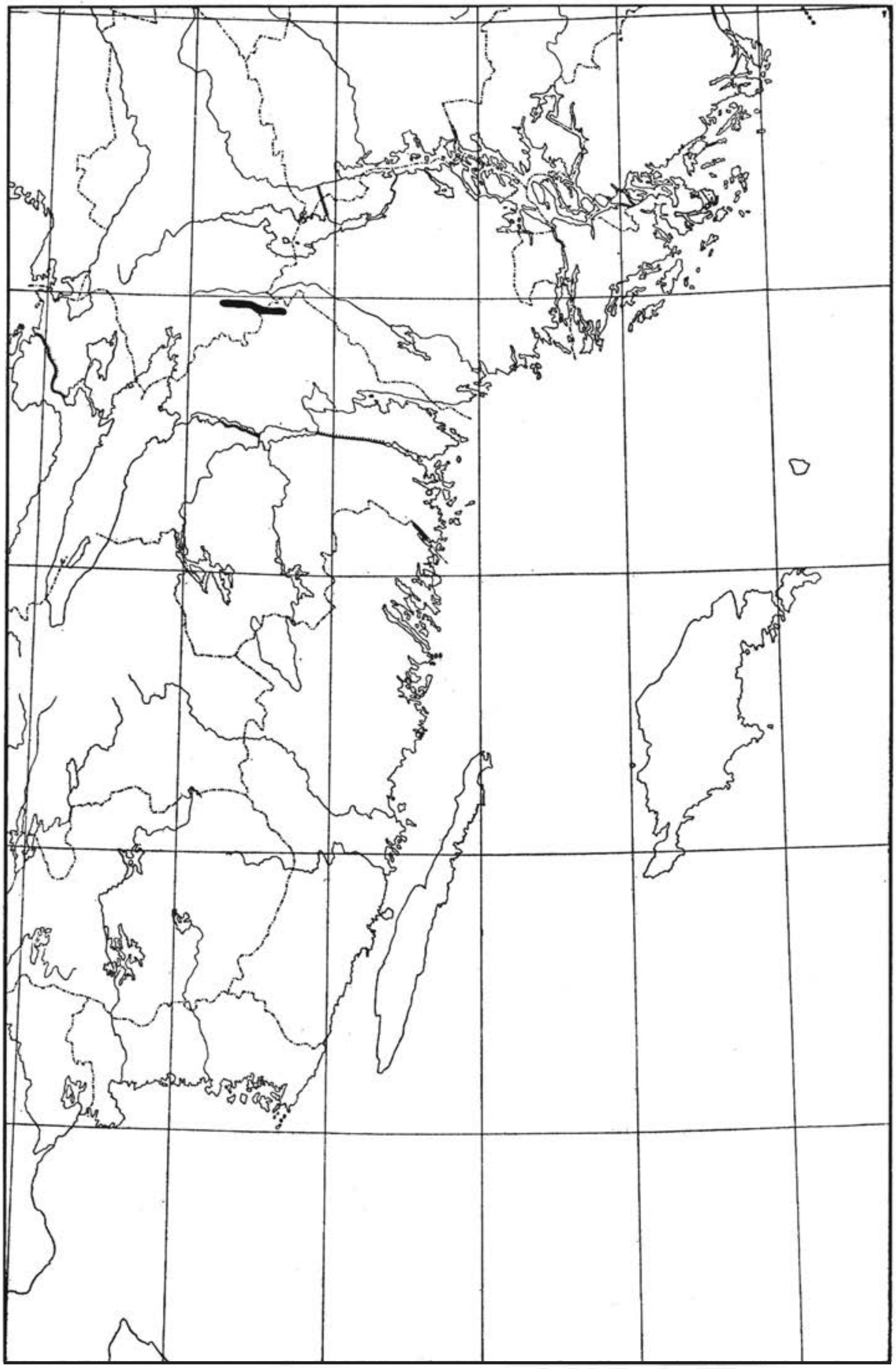


Fig. 1. Sketch-map showing the situation of the Breven dike.

formation of the dike has taken place. It seems to me, that this formation could have taken place in one way only, *through an eruption of an already previously heterogeneous magma, differentiated in the magma reservoir.*» (*Loc. cit.* page 198. Translation and italics by the present author.)

Among the authors cited it is thus only WINGE who has devoted a somewhat detailed study to the rocks in question, and he has also carried out with a great consciousness the field investigations as well as the microscopical analysis. Yet it seems to the present author, as if the opinion expressed by WINGE about the formation of the dike, was not entirely well-founded, there being no really logical connection between the premises gained during the investigation and the conclusions finally arrived at. It has therefore been considered convenient to make this problem the object of a renewed discussion in connection with a detailed laboratory research with the intention of comprehensively elucidating the question. Moreover it must be kept in mind, that 35 years have elapsed, since WINGE's paper was published, and that within that time the methods as well as our knowledge of the laws governing differentiation, and rock formation have been excessively improved and enlarged. Consequently the aim of this paper is to weigh critically — the mineralogical, petrological, chemical and geological data equally considered — the reasons *pro et contra* of every explanation available, thus finally arriving at the interpretation, that ought to be the most probable one according to our present knowledge.

I. Descriptive part.

A. Description of the general geologic features.

The situation, extension and dimensions of the Breven dike have already been considered in the introductory chapter. As a rule the rocks are fairly well exposed in the whole extension of the dike. The only exception of importance is offered by an area situated at both sides of the highway Pålsboda—Finspång, having a length of about 800 m. and being wholly devoid of outcrops. This is the more to be regretted as this very part of the dike is one of the most critical localities, and of a great significance for an understanding of the mutual relationships between the different types of rock.

Partly the dike stands out very sharply in the topography, that being the case especially in the western part, and at Uvberget to the north of Boo. An attempt was made to ascertain the dip of the dike by means of studying the relations between the dike boundaires and the topography, but no reliable result could be obtained. An indication of a dip to the south may perhaps be traced, an assumption that is, moreover, fairly well in accordance with some petrological observations to be mentioned later on (p. 292). At the northern boundary *e. g.*, the author has at some places found olivinebearing rocks — which are already mentioned by WINGE (**60** : 197) — in the otherwise olivinefree part of the dike, whereas no such rocks have been found at the southern boundary. (About a questionable specimen cf. page 301.) On the other hand anorthosites have been met with at one or two localities at the southern contact.

Anyhow it must be assumed, that if the dike really deviates from the vertical position — which is by no means reliably stated — the hade is likely to be very slight.

In the central part of the dike, the latter has been subjected to a fault, the traces of which are to be seen at Uvberget and a little south of the mansion of Deje, both localities showing a well developed fault-breccia. At Uvberget the fault has also produced a steep wall, forming the southwestern boundary of the little mountain, as already observed by WINGE (**60**: 189).

The contact between the dike and the wall rock is exposed only at one locality, viz. close to the farm building at Bottorp within the western olivinebearing dolerite, and here the nothern as well as the southern contact is to be seen. Both contacts, especially the northern one, are disguised by assimilation phenomena, and they are most strictly characterized as contact zones. At other localities one may approach the contact rather closely, marginal modifications may be observed and so on, but the very contact line is everywhere hidden except in the area just mentioned.

With a single exception the rocks constituting the dike are holocrystalline and coarsegrained and ought to have congealed at an intermediate depth. As to the probable depth of congealing of the granophyre the reader is referred to page 321. The exception referred to, is found in a few outcrops at Bottorp, the rocks of which are described later on as »the finegrained olivine dolerite». This row of outcrops, the extension of which is indicated on the sketch-map fig. 7 on page 263, ends (at point 10 on the sketch-map) with a vitreous picritic rock, and, moreover, its rocks texturally all differ very distinctly from the adjacent main rock. One could say, that the rock in question conveys the impression of having congealed at a considerably higher level than the other rocks, perhaps at the very surface. This conception is highly strengthened by the peculiar morphologic development of the outcrops numbered 125 and 126 on the sketch-map on page 263, the latter being represented on the figures 2 and 3 on page 249. A somewhat detailed investigation brings out rather a lot of such planes, exposing an unmistakeable *habitus* of surface congealing, the planes being arranged as banks or beds behind one another. Especially in fig. 2 two or three such planes are to be

Photo. T. Krokström 27/5 1931.

Fig. 2. Planes with an *habitus* of surface congealing. Bottorp.

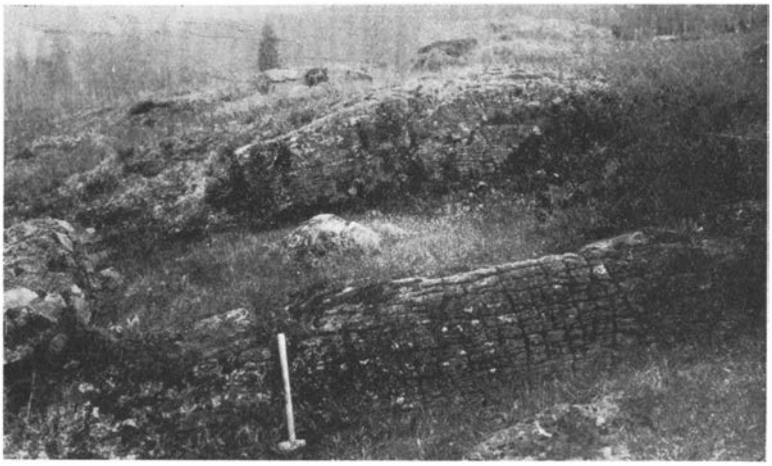


Photo. J. Öster 27/5 1931.

Fig. 3. Planes with an *habitus* of surface congealing. Bottorp.

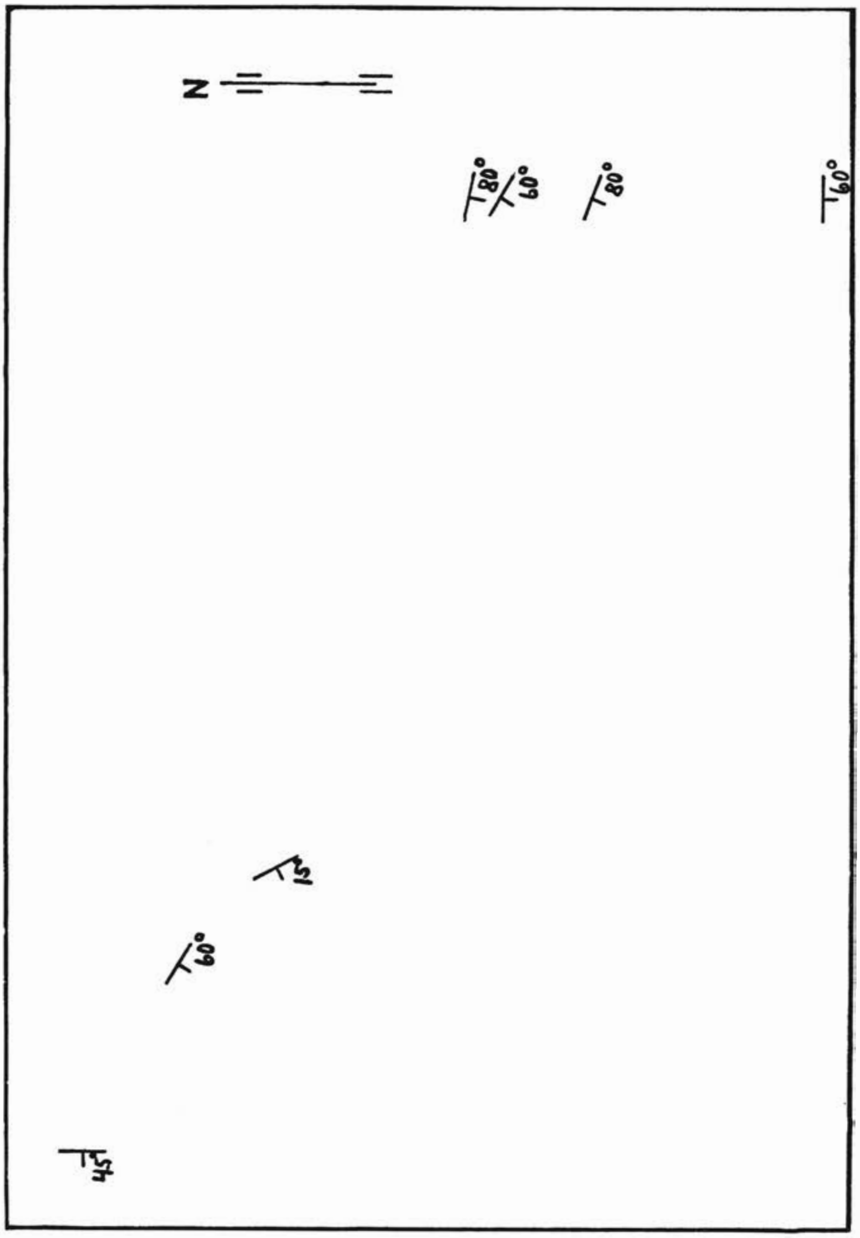


Fig. 4. Sketch showing the distribution, strike, and dip of the planes with an *habitus* of surface congealing at Bottorp. The sketch represents the southern part of the outcrop 125 of the sketch-map on page 263. Scale 1 : 320.

seen most clearly. In fig. 4 on page 250 a sketch is given of the situation and orientation of the most prominent planes, the former being referred to the same level, and in fig. 5 below a stereogram is reproduced,

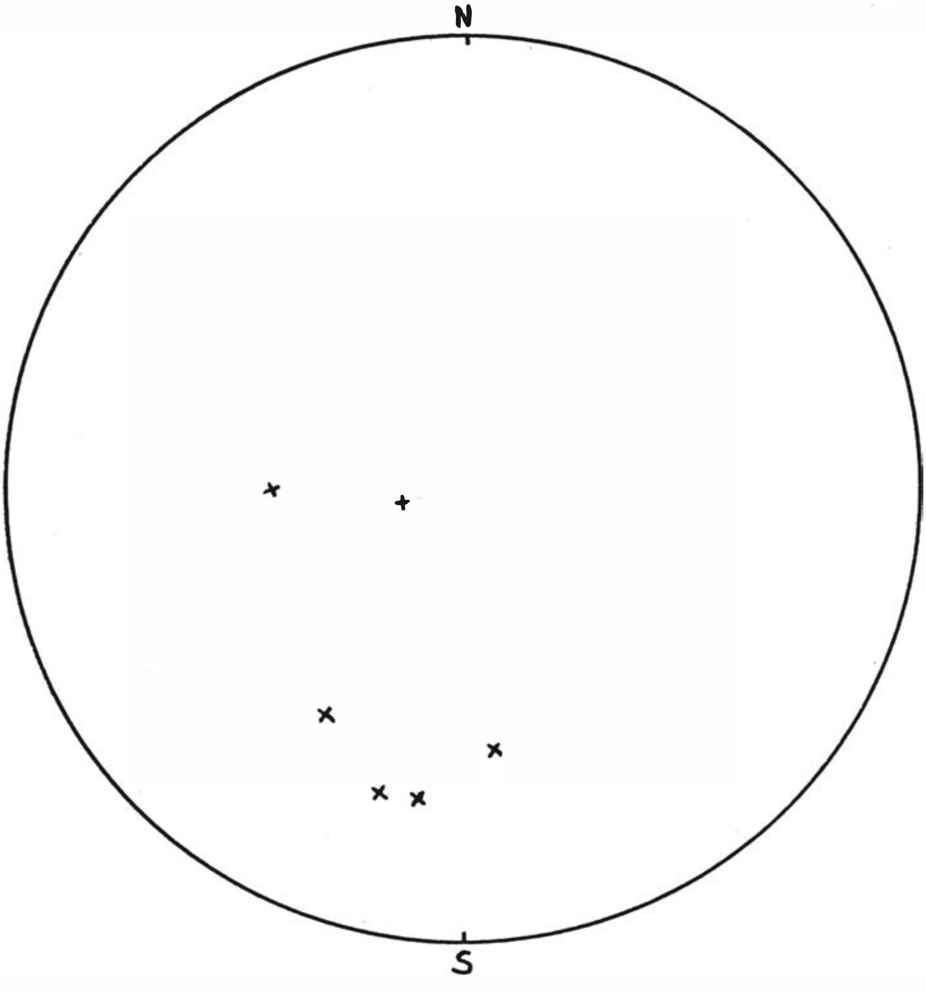


Fig. 5. A stereographic projection of the planes indicated in fig. 4. The crosses represent the poles of the planes. Two of the seven planes of fig. 4 coincide.

indicating their strikes and dips. It appears to be quite evident, that superficial phenomena are really met with here, and the bearing of this fact upon the interpretation of the rock genesis will be discussed later on (page 320 foll.).

B. Mineralogical and petrological description.

a. The western olivinebearing dolerite.

1. The area between the railway and Lake Rävsjön.

The rocks within this area with a few local exceptions are of a very uniform aspect. Megascopically they are mediumgrained, evengrained, and of a dark gray colour, obtaining a rather characteristic appearance from

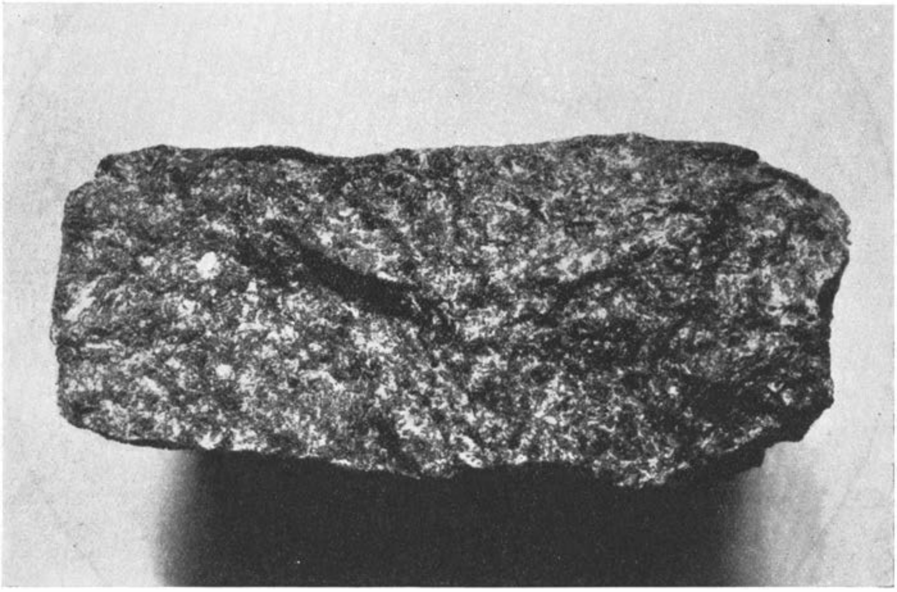


Fig. 6. A hand specimen of the western olivine dolerite. Half natural size.

the tabular feldspars. Microscopically they show a well developed ophitic texture, and their main constituents are *plagioclase, orthopyroxene, clinopyroxene* and *olivine*. As accessory constituents *titaniferous iron ore*, *biotite* and *serpentinic, chloritic* and *talcose products of alteration* are found. In the interstices *alkalic feldspar* in small quantities is sometimes observed, generally in the form of an anorthoclase with signs of a beginning perthitisation. Finally in some thin sections a few individuals of *apatite* are found. A rather characteristic picture of the megascopical aspect of these rocks is given by fig. 6 above.

The author has examined thin sections from nine different localities within this area. An attempt was made to ascertain by means of geometrical analyses the mineral composition of the rock, but because of the irregular distribution of the olivine, even in different sections of the same hand specimen, very widely differing values were obtained, and the reliability of the result for the purpose of drawing general conclusions must be highly doubted. Nevertheless, some analyses are put together in the table below. (Table I). The measurements have been extended in every case over an indicatrix of a length of 30 cm., and when two analyses are given of one rock specimen, they are made on different sections of the specimen. The measurements were made by means of an integration table of LEITZ' construction, which unfortunately does not permit a rotation of the object in the course of measuring. Thus sometimes difficulties arose to distinguish reliably the orthopyroxene from the clinopyroxene, and in order to avoid another source of error, they are comprised in the table below under the collective heading of pyroxene.

Table I.

Geometrical analyses of the western olivine dolerite.

No.	Plagioclase		Pyroxene		Olivine		Accessories	
	Vol.-%	Weight-%	Vol.-%	Weight-%	Vol.-%	Weight-%	Vol.-%	Weight-%
1	66,1	59,9	16,9	19,9	15,8	18,4	1,3	1,7
1	70,4	64,0	10,5	12,4	13,0	15,4	6,1	8,2
2	68,7	62,5	8,2	9,7	19,9	23,5	3,2	4,3
2	69,5	63,7	16,6	19,8	13,8	16,4	0,1	0,1
5	70,4	64,3	5,9	7,0	19,9	23,5	3,8	5,2
6	72,7	67,0	13,3	15,9	11,5	13,7	2,5	3,4
7	48,8	42,3	10,5	11,8	39,8	44,7	0,9	1,2
8	66,7	60,3	19,5	22,9	9,2	10,7	4,6	6,1

1. Olivine dolerite, Kortorp.
2. » » » . Another outcrop.
5. » » near the path Berget-Gubbhult.
6. » » Berget.
7. » » Krustorp.
8. » » » . Another outcrop.

For the calculation of the weight percentages the following values of the spec. weights were used:

Plagioclase 2,7; olivine and pyroxene 3,5; accessories 4,0 (ore).

As a hint it may be mentioned, that the orthorombic pyroxene generally seems to make up about one third of the total pyroxene quantity, the mutual proportions, however, varying rather widely in different sections.

As seen from the table, the different analyses show great variations as to the mutual proportions of the femic constituents, but these variations being equally well marked even within the same specimen, when measured in several sections, they can hardly be considered as indicating different mineral composition at different localities. The only value varying within rather narrow limits is that of the plagioclase, and in this case it may be justificable to assume that the rock holds about *68 vol.-% of plagioclase.*

The *plagioclase* is remarkably fresh everywhere in this area. Twinning occurs abundantly, the most usual laws being the albite-, the Karlsbader- and the pericline-laws. A few Baveno twins, however, have also been observed. Zonary banding is almost everywhere strongly developed, sometimes quite continuously, sometimes with discontinuous changes, the boundaries of the different zones then often showing very irregular outlines, conveying the impression that the crystal growth was interrupted by several periods of strong corrosion. Because of that irregular zonary banding, the determinations according to the universal methods were met with great difficulties and above all involved a great loss of time, as a fairly large number of measurements must be made in order to ascertain the composition of the plagioclase. Because of this, those determinations were substituted by the measurements of extinction angles, and the results are given in the table below (Table II on page 255). The extinction angles $\perp$ M and P are interpreted according to the diagram of KÖHLER (**29** : 63), the extinction angles $\perp \gamma$: M according to SOKOL (**42** : 64), whereas for the interpretation of the optic axial angles the curves deduced by DUPARC and REINHARD (**13**) were used. As seen from the table the different individuals, even when seemingly homogeneous, show slight variations reciprocally, but the average value ought to be *about 68 % anorthite* in the western parts of the area, increasing to *about 76 %* towards the eastern boundary, in the neighbourhood of Krustorp. In the last mentioned eastern part of the area the cores of some crystals with zonary banding have been determined as all but pure anorthite, the margin, however, showing only *70 %*, in one case even only *60 %*. At the western end of the dike the corresponding values are *82* and *53 %* respectively. In a few cases an inverted succession of zones was observed, as is seen, e g. from the following figures, referring to an individual from the rock no. 2 of table II: Kernel 64 %, a middle zone 71 %, margin 53 % anorthite. Yet generally the succession is the normal one. As to the development, the plagioclase individuals are distinctly idiomorphic against the two pyroxenes. On the other hand their relation to the olivine is not quite so clear, as will be mentioned later on.

Table II.

Determinations of plagioclase in the western olivine dolerite.

No.		Angles	Composition in Mol.-% An	Average of the individual	Average of the slide
1	⊥ M and P	29—35°	56—69	62,5	
1	»	32°	62,5	62,5	
1	»	34°	66,5	66,5	65 %
1	»	33°	64,5	64,5	
1	»	32—37°	62,5—73,5	68,0	
2	⊥ γ : M	38°	71,0	71,0	
2	⊥ M and P	35—40°	69—82	75,5	69 %
2	»	27,5—36°	52,5—71,5	62,0	
2	»	34°	66.5	66,5	
4	2 V (FEDOROFF stage)	90°	68,0	68	
4	⊥ M and P	35°	68,0	68	
4	»	37°	73,5	73,5	69 %
4	»	36°	71,5	71,5	
4	»	34°	66,5	66,5	
4	»	33°,5	65,5	65,5	
5	»	36°	71,5	71,5	
5	»	34°	66,5	66,5	69 %
5	»	35°	69,0	69,0	
5	»	35°	69,0	69,0	
6	»	31°	60,0	60,0	
6	»	38°	76,0	76,0	
6	»	33°,5	65,5	65,5	68 %
6	»	35°,5	70,0	70,0	
6	»	36°,5	72,5	72,5	
6	»	33°,5	65,5	65,5	
7	»	36°	71,5	71,5	
7	»	39°	79,0	79,0	
7	»	36—41°	71,5—84,5	78,0	78 %
7	»	40°	81,5	81,5	
7	»	36—43°	71,5—91,5	81,5	
8	»	36—40°	71,5—81,5	76,5	
8	»	39—44°	79,0—96,0	82,5	79 %
8	»	38°,5	77,5	77,5	

1. Olivine dolerite, Kortorp.
2. » » , » . Another outcrop.
4. » » , Berget.
5. » » near the path Berget-Gubbhult.
6. » » , Berget.
7. » » , Krustorp.
8. » » , » . Another outcrop.

The *olivine* generally occurs in rather large (up to 4 mm.) isometric grains, sometimes with rounded outlines, sometimes with fairly well developed crystal forms. In some cases they are clearly idiomorphic against the plagioclase, the laths of the latter arranging themselves along with the outlines of the olivine individuals; in other instances, however, the relations are more obscure, and it cannot be wholly denied, that the case may be just the opposite. Probably the olivine and the plagioclase have crystallized simultaneously, perhaps with a slight difference in favour of the former. Against the pyroxenes the olivine is, however, quite clearly idiomorphic. In other respects the development of the olivine seems to be a somewhat different one in the western parts of the area as compared with the eastern. To the west the olivine is generally wholly fresh, and coronas are hardly to be observed. The veinlets of serpentine and iron ore dissecting the mineral are few in number and rather narrow. At the eastern localities on the other hand — *e. g.* at Krustorp — the aspect of the olivine is quite different. Here one finds well developed and fairly broad reaction rims, the original crystal being in extreme cases wholly replaced but for a small strongly corroded kernel. The reaction rims generally consist of talc. The parts of olivine not changed are dissected by numerous veinlets of iron ore. Indeed even in the western rocks the pyroxenes may sometimes be apparently developed as rims around the olivines, but probably the former here only form fillings in the interstices between the olivine and the plagioclase. Any regularity in the mutual orientation of the olivine and the pyroxene has not been found in those cases.

In order to ascertain the composition of the olivine a determination of the refraction indices was made on an individual from a specimen taken near the path Berget— Gubbhult.

Result:

$$N_\beta = 1{,}721 \pm 0{,}001 \qquad N_\alpha = 1{,}696 \pm 0{,}001.$$

The two values obtained agree fully with each other according to BACKLUND's diagram (3) and indicate a composition of *32 % fayalite*, *68 % forsterite*. In order to control, whether the olivine is of the same composition all over the area, measurements of its relative optical retardations were made in all thin sections available, and the optic axial angles were calculated from the values thus obtained. The course of determination was as follows. On the FEDOROFF stage the relative retardations were measured in the directions of two optical axes of symmetry or — two of them being in some cases not accessible — in the direction of one symmetry axis and in one help direction. The calculations were made in accordance with the formulas given by BEREK (**8**: 99—108). As a result of twenty-three measurements the values of Table III were obtained.

Table III.

Measurements of optic axial angles according to the method of relative retardation on the olivine of the western olivine dolerite.

Locality	Slides examined	$2\ V_\alpha$	Average
Kortorp . .	1	78°, 79°, 82°, 82°, 83°, 84°	81°
Berget . .	3	75°, 78°, 79°, 82°, 83°, 85°, 85°, 87°, 88°	82°
Krustorp .	3	82°, 83°, 84°, 84°, 85°, 85°, 86°, 86°	84°

The values of the first series and those of the third show but slight deviations from the average values of the series, those being 81° and 84° respectively. On the other hand, the second series shows a remarkable lack of agreement in the values of the optic axial angles, the fact that the two extreme values, 75° and 88°, were measured in the same thin section, being especially peculiar. Either there must be some methodical error, or the olivine displays a rather astonishingly wide range of variation, the two extreme values indicating — according to BACKLUND, *loc. cit.* — 43 % and 16 % fayalite respectively. In order to verify the data obtained, a mineral separation was made by means of the CLERICI solution. To that purpose part of the specimen in question was ground down to a granularity of $0{,}_1$—$0{,}_4$ mm. and was then treated with liquids of a specific weight of $3{,}_{60}$ and $3{,}_{28}$, and thus a mixture was obtained, containing only pyroxene and olivine. The purity of that fraction was microscopically controlled, and finally it was brought into a liquid of the sp. weight $3{,}_{60}$, which was successively diluted by a somewhat lighter one. Every fraction sinking during the course of diluting was separated and microscopically tested. From this investigation it became clear, that the olivine occurred in one fraction only, *viz.* that of the sp. weight $3{,}_{55}$, which according to BACKLUND *(loc. cit.)* fully agrees with the refraction indices previously determined, indicating an optic axial angle of 81° ($2\ V_\alpha$). It seems, thus, as if the extreme angle values were due to some methodical error, and indeed, leaving the three values 75°, 87° and 88° aside, the average for the remaining six results at 82°, which is fairly in accordance with the refraction indices and the specific weight. On the whole, it appears from the figures that determinations, according to the universal methods, of minerals with high refraction and high double refraction, should be made only with a very great discrimination. Especially great difficulties arise in the case related, as the optic axial angle is an extraordinarily sensible property of the olivine minerals. To outline satisfactorily the variations of the olivine of this rock, it would be necessary to make a great many determinations of refraction indices, but in the writer's opinion the value of the result — as far as the aim of the present paper is concerned — would hardly correspond to the timeconsuming work involved in such an investigation, and, thus, this project was given up. Nevertheless it may be justificable to draw the conclusion from the numbers given above, that the percentage of fayalite silicate decreases towards the eastern limit of the area, as the rather well coinciding values of the observation series from Krustorp show a marked difference from the determinations of refraction indices and specific weight at Berget. At Krustorp the average is:

$$2\,V_{\alpha} = 84^{\circ} \pm 2^{\circ} \text{ corresponding to } 24\,\% \text{ fayalite silicate.}$$

This decreasing percentage of fayalite towards the east is further verified by the investigations in the Bottorp area, the results of which will be given below. (Page 262 foll.)

Orthopyroxene. In his description of the olivine dolerite of the Breven dike TÖRNEBOHM mentions (**49**: 31, **50**: 19), that hypersthene occurs subordinately. WINGE quotes this statement (**60**: 191), but seems not to have been able to verify it by observations of his own. He describes, however, as augite a mineral which is evidently the orthopyroxene found by TÖRNEBOHM. A critical examination of a great number of thin sections has brought out, that the orthopyroxene is not at all subordinate but sometimes even occurs more abundantly than the clinopyroxene. Generally, however, it makes up about one third of the total pyroxene quantity. It is microscopically of a bright appearance, showing a slight pleochroism with *γ colourless or of a faintly green colour, β slightly reddish.* Cleavage planes are generally developed parallel to the basis, the front pinacoid and the prism. The optic axial angle was determined in thin sections from several localities, the same method being used, as was described in the chapter on olivine. Within the limits of observation errors the angle seems to be of a constant value.

Result:

$$2\,V_{\alpha} = 61^{\circ} \pm 2^{\circ}$$

According to WINCHELL (**59**: 177) this value indicates a composition of *43 %* $FeSiO_3$. In the course of the olivine separation described above, the specific weight of orthopyroxene was also obtained:

$D = 3{,}50$ Composition according to WINCHELL *(loc. cit.)* *42 %* $FeSiO_3$.

The idiomorphic relations of the orthopyroxene are quite similar to those of the clinopyroxene, which are to be described below.

Clinopyroxene. The clinopyroxene microscopically shows a somewhat dull grayish colour and is not pleochroic. It occurs as a typical interstitial mass without any crystallographical contours of its own. Quite frequently, too, a single clinopyroxene individual occupies the whole field of sight, the optical orientation being exactly the same in the different parts. According to BOWEN (**10**: 64—91) the pyroxene in magmas of such a composition as must be assumed here, should crystallize very early, sometimes even earlier, but at least simultaneously with the plagioclase. The extremely ophitic texture seems to contradict such an opinion, but this difficulty is avoided by explaining the texture in question as a result not of an earlier crystallization of the feldspar but of the stronger tendency of the plagioclase to develop crystal forms of its own (**10**: 68). It seems, however, very difficult even with that assumption to interpret the texture of the rock just described in accordance with this opinion of BOWEN's. The absolute absence of every sign of idiomorphic development of the pyroxenes as also above all the fact, just pointed out, that all over a thin section the pyroxene fields may belong to the same individual unity, strongly favours the opinion, that the crystallization of the pyroxenes is distinctly later than that of the feldspar.

Determinations of optic axial angles according to the method of relative retardations previously described have been executed also on the clinopyroxenes in thin sections from several localities, and here, too, the angle seems to be constant all over the area within the limits of observation errors. In a thin section from Krustorp the refraction indices were also determined.

Result:

$$2\,V_\gamma = 46^\circ \pm 2^\circ \qquad N_\gamma = 1{,}708 \pm 0{,}002 \qquad N_\beta = 1{,}681 \pm 0{,}002.$$

According to the diagram of ASKLUND (**1** : 29) those values of the refraction indices and the optic axial angle would conduct the pyroxene to a position within the area of discontinuity, deduced by the same author (*loc. cit.* page 77). However, the values given above have been repeatedly checked and must be considered as very reliable. Thus the only explanation available seems to be, that the N_γ-curves, deduced by ASKLUND and set down in his determination diagram are not wholly valid. According to a personal communication of Dr. ASKLUND, that may also be the case, too few data having been obtainable as for a tracing of these curves with the accuracy desirable. The deviations probably not being very great, the curves, however, ought to allow of an approximate determination, and thus from the values given above the following composition is obtained:

$$45\ \%\ MgSiO_3 + 30\ \%\ CaSiO_3 + 25\ \%\ FeSiO_3.$$

It must, however, be pointed out that quite recently BARTH (**6**: 207—208) has found a complete series of solid solutions in the natural basaltic pyroxenes his investigations thus failing to demonstrate the discontinuity area proposed by ASKLUND.

The *accessory minerals* occur as is seen on the table of geometric analyses (Table I on page 253) only in very subordinate proportions. Most important is *ilmenite*, generally surrounded by a strongly pleochroic *biotite*. The latter mineral also occurs independent of the ilmenite and even then it shows the same strong pleochroism, *γ being of a dark reddish brown* and *α of a straw-yellow colour*. The mineral ought to be rather rich in iron. *Serpentine* occurs sparingly and chiefly as veinlets in the olivine. Sometimes, however, it is also found as independent aggregates of a somewhat larger size. *Chlorite* seems to be a not quite unusual product of alteration of the pyroxenes, and the talcose rims surrounding the olivines have already previously been mentioned.

Comparing the results given above about the main minerals of the rock treated, we may consider the following facts:

1. The *percentage of anorthite* in the plagioclase increases from *68 %* in the western part of the area to *76 %* in the eastern part.
2. The *percentage of forsterite* in the olivine increases from *68 %* in the western part of the area to *76 %* in the eastern part.
3. The *pyroxenes* maintain the same composition all over the area.

The variation of the olivine and the plagioclase is of the same kind — one finds towards the east an enrichment of the higher melting component, forsterite and anorthite respectively. The relations between rock composition and the composition of the ferro-magnesian minerals have been the subject of several investigations. Thus Miss AMALIE WEICH on the basis of a great choice of optical and chemical determinations proved, that in pyroxene rocks the percentage of $FeSiO_3$ of the orthopyroxene always decreases with increasing basicity of the rock (**58**). In the same way STARK showed, that the percentage of fayalite silicate of olivine also decreases with increasing basicity of the rock (**44**). Finally VOGT has treated the question in several papers (**52**, **53**, **54**). VOGT holds the view, that the phenomenon is of a general significance, the formation of basic rocks (differentiation in »proto»- or anchi-monomineralic direction) being accompanied by an enrichment of the higher melting component.

The variation of olivine and plagioclase stated above is thus in full conformity to experience, provided that the rock of the eastern part of the area just treated, is of a more basic composition than that of the western part. The difficulty of proving such a variation by means of geometrical analyses has already been pointed out (page 253), but on the other hand there are no facts contradicting such an assumption. The rocks of the still more eastern parts of the dike are of a markedly higher acidity but as will be seen later on (pp. 312 and 321) it is perhaps most probable, that this area and the Bottorp area must be kept apart from the rest of the dike.

Another question that arises is, however, why there is no variation to be found in the pyroxene determinations. The distribution of Mg and Fe between olivine and orthopyroxene has been statistically treated by SCHILLER (**41**) who found that in rocks with no feldspar, Mg and Fe show about the same proportions in the two minerals, whereas, when feldspars enter into the mineral composition of the rock, the olivine always becomes richer in Mg than the orthopyroxene. Even that result is checked by the present rocks but there is still no clue to the different behaviour of the olivine and the pyroxenes.

An attempt to unravel this complicated question would lead away from the subject of this paper, but the author will not omit the following hints as to a problable solution. The geometrical analyses given above (Table I on page 253) are not easily interpreted, but it seems as if the proportion *plagioclase : femic minerals* were fairly constant all over the area. Then it is perhaps also most probable, that the mutual quantitative relations between the femic minerals proper are not subjected to great variations. If this assumption holds good, the varying composition of olivine and plagioclase must be ascribed to an initial chemical inhomogeneity of the magma. No matter how to explain such an inhomogeneity — that ought not to be impossible — it may be assumed, that the components of early crystallization, *viz.* olivine among the femic minerals, must display variations of composition due to the variations in the magma, the latter thus being adjusted to a chemical homogeneity, which is wholly established, when the pyroxenes begin to crystallize. If this explanation is valid, there is consequently another reason strongly speaking for a late crystallization of the pyroxene, if the opposite being the case, great difficulties would arise as to an explanation of the uniform composition of this mineral all over the area.

The »hypothesis» suggested above is by no means to be considered as the author's definite opinion — it is only an attempt to give a possible explanation of the phenomena met with, and any other explanation that is more fully in accordance with the facts stated, will be accepted with great satisfaction. Anyhow an observation of those and related phenomena ought to be of great importance.

2. The Bottorp area.

The small Bottorp area comprises the part of the dike between the railway Pålsboda—Finspång and the main road immediately to the east of it, just around the name of Bottorp on the geological map-sheet. It has an extension of only a few hundred meters in the east-west direction, but nevertheless it has been considered convenient to devote a rather detailed study to it, because a great many interesting facts have been observed. Figure 7 on page 263 gives a sketch-map of this little area. To the west of the railway it is bounded by the part of the dike previously described, the rocks of which are of a fairly uniform aspect, except the variations of the composition of some minerals as has been stated above. Within the Bottorp area, however, the rocks show a rather strong variation, and it has not been easy to fit those variations into a uniform system. At last, however, the author has arrived at an opinion of the petrological structure of the area, and this opinion is mainly represented on the sketch-map. The boundary lines traced on the map between the wall rock and the contact zones as also between the latter and the coarse-grained olivine dolerite are not sharply defined. Firstly the number of exposures is quite insufficient for an accurate fixing of the boundaries, secondly the latter are in many cases diffuse and replaced by zones of transition between the different rocks. For sake of perspicuousness it has, however, been considered convenient to draw a boundary line though in that way the map is not in full accordance with the field relations. Those somewhat undefinite boundaries have been marked by a broken line. The boundary between the two olivine dolerites, on the contrary, ought to be ascertained with a sufficient exactness.

α. *The coarsegrained olivine dolerite.*

This rock is principally quite similar to the olivine dolerite previously described. Exactly as the latter it shows a coarse ophitic texture, the olivines attaining a diameter unto 4 mm. and the tabular feldspars sometimes attaining a length of 5 mm. For a picture of the microscopical aspect of the rock the reader is referred to figure 8 on page 264. The plagioclase just as in the rock already described shows a strong zonary banding, this banding, however, being perhaps a little more regularly developed. The same kinds of twins are also to be seen, and in full accordance with the tendency

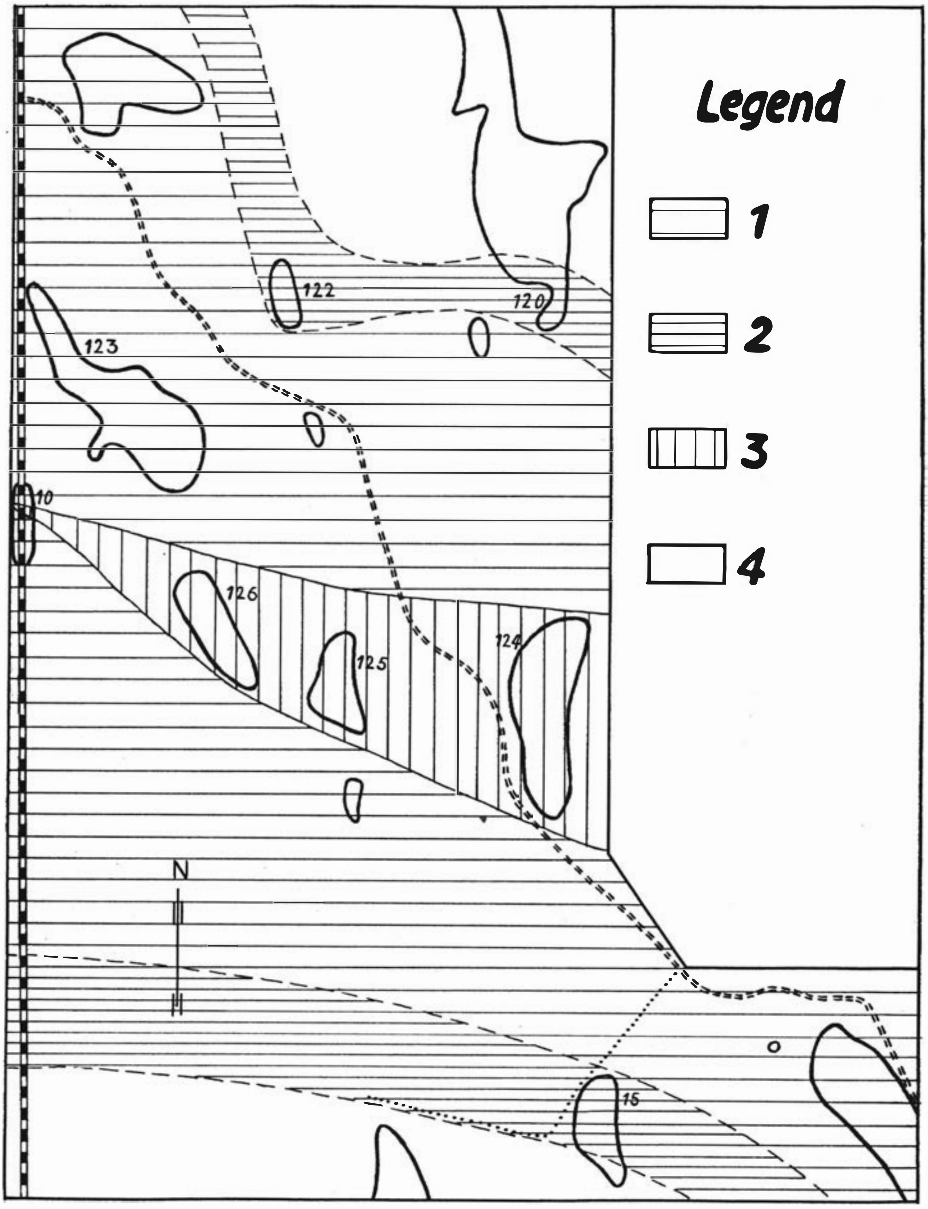


Fig. 7. Geological sketch-map of the Bottorp area. Scale 1 : 4000.
1 = Coarsegrained olivine dolerite.
2 = Zone of contact.
3 = Finegrained olivine dolerite. 4 = Wall rock.
Outcrops are indicated by heavy lines.

already stated of an increasing percentage of anorthite towards the east, the plagioclase has here a composition of *75—81 % anorthite.* Because of the zonary banding the determinations have as before been made by means of extinction angle measurements, and in order to give an idea of the variations, the values obtained are put together in the table below (Table IV on page 265). They are all measured ⊥M and P and are interpreted according to KÖHLER's diagram (**29**).

Generally this type of rock is fresh and unaltered, but at some places rock portions are found, which display a rather strong alteration mainly affecting the olivine. A description of such a rock (from point 123 on the sketch-map) is given below.

Rock 123 shows a coarse ophitic texture and has the following mineral composition: *Plagioclase, olivine, orthopyroxene, clinopyroxene, talc, amphibole, biotite, titanite, epidote, apatite, serpentine, iddingsite* and *ore*.

Microphoto by the author.

Fig. 8. Microphotograph of the coarsegrained olivine dolerite at Bottorp, showing its rather coarse ophitic texture. Nicols +, magnification 16 diameters.

Plagioclase is as usual the dominant constituent. It has a composition of *62% anorthite* as ascertained by the FEDOROFF method.

Olivine quantitatively comes next to the plagioclase. Its optic axial angle was measured on the FEDOROFF stage, the following result being the average of four slightly deviating determinations:

$$2V = 90^\circ$$ corresponding to *12% fayalite silicate* (**3**).

The mineral is strongly dissected by veinlets of serpentine, which often penetrate the surrounding plagioclases. Thereby it may be observed, that not only the feldspar individuals close to the olivine are dissected by the veinlets, but that the latter on the contrary without being in any way affected extend into individuals far away from the central olivine. This observa-

Table IV.

Determinations of the plagioclase of the coarsegrained olivine dolerite of the Bottorp area.

Extinction ⊥ M a. P	Composition in mol.-% of anorthite	Average of the individual	Average of the slide
41°	84,0	84,0	
41°	84,0	84,0	81 %
33°,5—40°,5	65,5—82,5	74,0	
38°	76,0	76,0	
38°	76,0	76,0	
38°	76,0	76,0	
36°,5—42°	72,5—88,0	80,0	77 %
31°—44°	60,0—96,0	78,0	
35°,5—44°	70,0—96,0	78,0	
35°—42°	69,0—88,0	78,5	
37°	73,5	73,5	
38°	71,0	71,0	76 %
38°	71,0	71,0	
41°	84,5	84,5	

tion seems to prove, that the serpentinic alteration and the material transport, which was possibly connected with it (cf. below on pp. 286—287) took place after the plagioclase had got wholly or partly consolidated.

The olivine shows alterations of two different kinds. The earliest one seems to be an irregular alteration into *iddingsite* of a rather high double refraction and with a faint pleochroism in yellow and yellowish brown. Those products of alteration have not been optically determined, but it seems probable, that they contain a rather high percentage of iron. The second and later alteration has led to the formation of *talc* and *amphibole*, the talc being quantitatively dominating. All stages of that alteration may be observed, from a relatively thin talcose reaction rim to the stage, which is illustrated by figure 9 (page 266) and further on to the formation of a perfect pseudomorph, consisting of talc only, but reproducing all details of the structure of the original olivine (figure 10 on page 267). In the course of alteration the iron has seemingly been deposited as ore, the contours of the talc grains being lined by a narrow or sometimes rather broad zone of ore minerals. Generally the talc is developed as a fairly compact, scaly mass as is shown for instance in figure 10, but sometimes also smaller scales of the same mineral may be scattered in the compact groundmass. Those scales generally exhibit a parallel or sub-parallel arrangement, intersecting each others at an angle of about 60°. Most probably those directions are determined by planes of translation in the original mineral.

In some thin sections, however, the pseudomorphs are made up not of talc only, but also of amphibole in rather large quantities. The amphibole is usually developed as needles, which are scattered all over the groundmass in a somewhat similar way as the talc scales described above. Figure 11 on page 268 shows a pseudomorph, consisting of talc

Microphoto by the author.

Fig. 9. Olivine partly altered to talc. Bottorp. Nicols +, magnification 50 diameters.

and amphibole. It is clearly recognized, that the mother mineral must have been olivine. The amphibol is probably *actinolite*.

The pyroxenes, the rombic as well as the monoclinic, are of the same kind as in the fresh olivine dolerite and also occur in a similar way.

Titanite occurs rather abundantly and is generally accompanied by *iron ore*, with which it shows regular intergrowths.

Biotite occurs not too sparingly and is strongly pleochroic.

Apatite is found in subordinate quantities, as is also *epidote*, which latter occurs only as a few individuals, most probably representing the very latest crystallization.

From the field relations of this rock it is made probable, that it constitutes streaky masses in the main rock, from which it can hardly be megascopically distinguished. The rather low content of anorthite in the plagioclase compared with that of the fresh rock is a striking feature; and such a conformability of the anorthite content and the degree of alteration has been observed even in the finegrained olivine dolerite.

β. *The zones of contact.*

Between the coarsegrained olivine dolerite and the wall rock a zone of transitional rocks is developed at the northern contact as well as at

Microphoto by the author.

Fig. 10. Olivine completely altered to talc. Bottorp. Nicols +, magnification 50 diameters.

the southern one. As the relations at the two contacts are rather different, they may most conveniently be described separately.

The northern zone of contact.

The rocks of this zone are exposed at two points only, *viz.* at the markings 120 and 122 of the sketch-map on page 263, and the character of the zone ought to be most clearly understood from a description of those two rocks. The large outcrop at point 120 is made up n its northern part by a reddish gneiss belonging to the wall rock, whereas its southern part belongs to the dolerite dike. Between those two rocks there is no well-defined boundary and thus already in the field the impression is obtained, that a hybridization has taken place here.

Rock 122 shows the usual ophitic texture, the main mineral constituents being *plagioclase*, *augite*, *serpentine*, *amphibole*, *chlorite*, *ilmenite*, *titanite*, *epidote*. In very subordinate amounts *apatite*, *biotite* and *carbonates* are also found.

Plagioclase is the dominating mineral, having a composition of *62 % anorthite* as established by measurements of twinning elements on the FEDOROFF stage. The mineral is strongly altered to *epidote* and in a smaller degree to *sericite*.

Augite occurs rather abundantly. It seems to be a fairly late product of crystallization and often shows an orientation quite uniform all over the

Microphoto by the author.

Fig. 11. Olivine altered to amphibole. Bottorp. Nicols +, magnification 50 diameters.

field of vision. On the FEDOROFF stage the following determinations were made:

$$2V_\gamma = 46^\circ \qquad c/\gamma = 43^\circ.$$

By means of standardised liquids of immersion:

$$N_\beta = 1{,}684 \pm 0{,}002.$$

The augite is to a large extent altered into a colourless or faintly green mineral with an optic axial angle of about 90° and showing low interference colours (white or yellowish white). This mineral, wherever occurring, is dotted by numerous small aggregates of *titanite*, scattered all over the area of the host mineral, as shown by figure 12 on page 269. The original cleavage planes of the pyroxene are fairly well preserved, but it is difficult to determine what kind of a mineral makes up the pseudomorphs. Most probably it is *serpentine*. The rich formation of titanite seems to indicate, that the augite was rather highly titaniferous.

The microscopic study brings out most clearly, that at one time this rock contained in abundance a third mineral now substituted by pseudomorphs, the content of which is colourless or faintly green, and has a small optic axial angle and abnormally low interference colours of a greenish brown. Most probably it is a *chlorite*. Some of these pseudomorphs exhibit fairly well preserved older crystal contours, proving with certainty, that the original mineral was *olivine*. The pseudomorphs in contact with

Microphoto by the author.

Fig. 12. Pyroxene, serpentinized and dotted with titanite. Bottorp. Nicols +, magnification 50 diameters.

pyroxene develop a rim of colourless *amphibole*, which is sharply bounded against the pyroxene with smooth boundary curves, whereas against the chlorite the rim of amphibole shows an irregular boundary with needles penetrating the chlorite mass. In the latter there are also scattered very long and thin needles of amphibole, sometimes showing a subparallel arrangement. Within the chlorite pseudomorphs and above all along their outlines *epidote* occurs abundantly (cf. figure 13 on page 270, where the crystal form of the original olivine is very distinctly marked by an epidote garland). Sometimes the epidote is replaced by *carbonates*, which is especially observed at some distance from the wall rock.

Those two types of pseudomorphs — after pyroxene and after olivine — ought to have been developed rather early, but they do not represent the final product of the alteration. In their turn they may be subjected to a later change, which has taken the form of an *amphibolization* (Fig. 14 on page 271). The pyroxene pseudomorphs are wholly or partly changed into an amphibole identic with the one previously mentioned (page 266), and the same mineral is developed within the olivine pseudomorphs, too, here, however, being restricted to the original ore veinlets of the olivine. Along with those the alteration begins, extending only to a very small degree into the other parts of the chloritic mass. Simultaneously with the formation of amphibole *titanite* is developed here, too, abundantly accompanying all amphibole veinlets but wholly missing in the

Microphoto by the author.

Fig. 13. Olivine, chloritized and surrounded by an epidote garland. Bottorp. Nicols +, magnification 50 diameters.

purely chloritic areas (Fig. 15 on page 272). That ought to indicate, that the ore of the veinlets was *ilmenite,* a mineral which also occurs rather abundantly in other parts of the rock, often strongly pseudomorphosed by titanite along the rhombohedral faces. In that way the ilmenite sometimes disappears almost completely.

The amphibolization described above is probably an indication of a lime supply from the wall rock, an assumption that is furthermore strengthened by the rich development of epidote. The latter is considerably stronger at point 120 (see map on page 263) than at point 122, thus seemingly increasing towards the contact. The fact that even the primary alteration of these rocks has performed in a way different from that of the rocks previously described must most probably be ascribed to a richer supply of gases and solutions.

The southern zone of contact.

The rocks of this zone are exposed only at one place, *viz.* at point 15 on the sketch-map on page 263, and even here the study of the types of rock is made considerably difficult because of the moss coverings. The southern part of the exposure is made up by a real gneiss, while

Microphoto by the author.

Fig. 14. Pyroxene, serpentinized and afterward amphibolized. Bottorp. Nicols +, magnification 50 diameters.

in the northern part a peculiar dolerite variety is found, which is described below (rock 15).

Rock 15 exhibits a fairly well developed ophitic texture, the mineral constituents being *plagioclase, pyroxenes, amphiboles, talc, serpentine, biotite, iron ore* and *quartz.*

Plagioclase is as usual the far most abundant constituent. Generally it shows a rather good idiomorphic development, but it also accumulates as irregular masses, filling the interstices. In the first-mentioned form it ought to be the first mineral crystallized except part of the ore. Zonary banding is not usual, the plagioclase being with a few exceptions quite uniform. Twins occur abundantly above all of the albite-, Karlsbader and pericline laws. On the FEDOROFF stage several optical determinations were made, the result of which are given in table V on page 274.

In this table the twinning elements are given in (α-, β-, γ-)coordinates, the α-coordinate being assigned as positive in the two upper quadrants, the γ-coordinate when positive indicating the two right quadrants and vice versa. As to the indication of the elements the reader is referred to the paper of BEREK (**8** : 81). In the diagram (figure 16 on page 273) the observed values are given in stereographic projection, the determinative curves according to BEREK *(loc. cit.)* being also assigned. The percentages of anorthite indicated by the curves of fig. 16 and by the optic axial angles according to DUPARC and REINHARD (**13**) are put together in table

Microphoto by the author.

Fig. 15. Olivine, chloritized and afterward amphibolized. In the amphibole veinlets (white) titanite is seen to develop (black dots). Bottorp. Nicols +, magnification 50 diameters.

VI on page 274. From this table the following two conclusions may be drawn:

1:o. There are two generations of plagioclase, the one of a very early crystallization containing about *63 % anorthite*, the other of late origin with about *42 % anorthite*. (The relations of age of the two generations are clear from their different idiomorphic development.)

2:o. The very slight deviations of the projection points from the determination curves ought to prove, that there is hardly any potassium in the plagioclase.

In the rock there are further rather large portions, whose present constituent is made up of *talc* with or without scattered *amphibole* needles. The texture as also the resemblance with such aggregates previously described seems to indicate, that the minerals just mentioned have replaced an original *olivine,* but no relics of that mineral have been found. Those pseudomorphs are wholly beset by grains of *ore*, and further in most sections they show very characteristic veinlets also filled by ore. Finally they are cut by a great number of cracks or fissures belonging to several

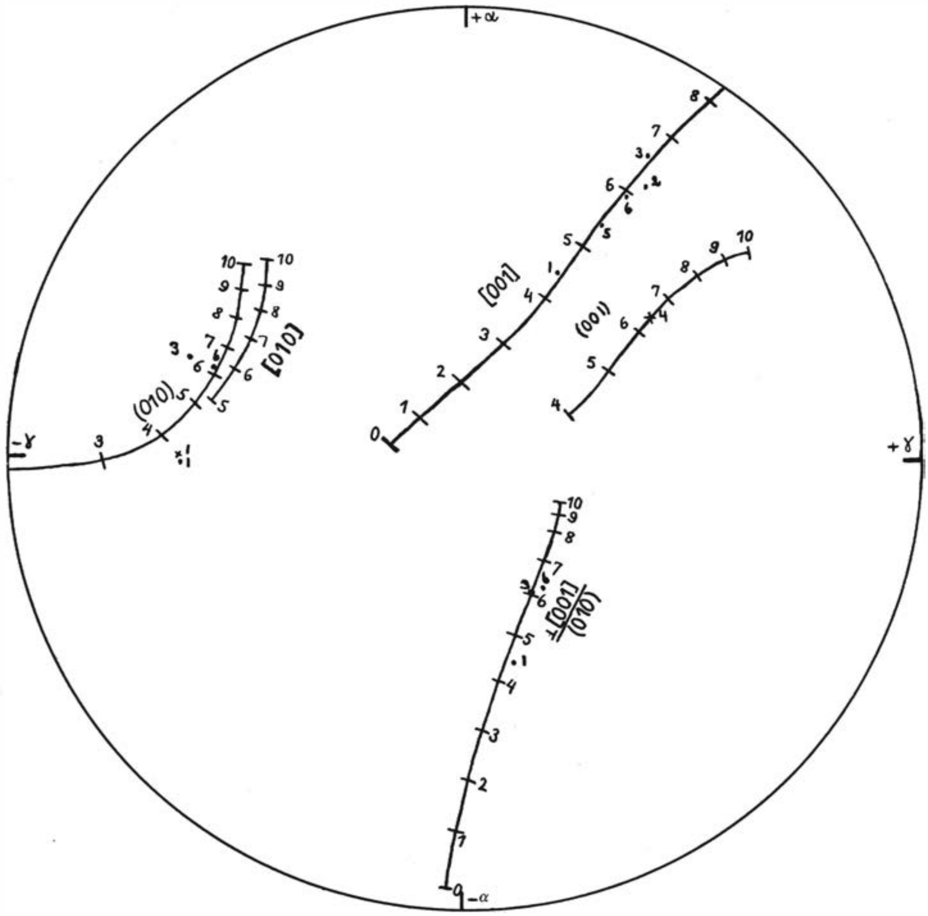


Fig. 16. A stereographic projection of the elements of twinning of the plagioclase in rock 15 at Bottorp. Dots indicate the axes of twinning, crosses the poles of the planes of twinning. The determinative curves are traced according to BEREK.

systems and intersecting each other at an angle of about 60°. Those fissures are most probably due to planes of translation in the talc or in the earlier olivine. In figure 17 on page 275 the irregular veinlets as well as the straight-lined fissures are seen. The amphibole needles are identical with those of rock 123 and, indeed, it seems as if here were met with an earlier stage of the same kind of alteration as in that rock.

The pyroxenes represent at least three different types. Their mutual

Table V.

Determinations according to the FEDOROFF methods of the plagioclase of rock 15 at Bottorp.

No.	Law of twinning	α	β	γ	$2V_{\gamma}$
1	(010)	−89°,5	63°	−26°,5	
	[001]	+47°	50°	+70°	
	⊥[001] / (010)	−42°	50°	+80°	80°
2	[001]	+38°	72°	+58°	85°
3	(010)	+71°	65°	−32°	84°
	[001]	+34°	76°	+60°	
	⊥[001] / (010)	−58°	36°,5	+74°	
4	[010]	+68°	58°	−42°	86°
	(001)	+60°	55°	+50°	
6	(010)	+72°	60°	−36°	82°
	[001]	+38°	69°	+60°,5	
	⊥[001] / (010)	−59°	37°	+72°	

Table VI.

Molecular percentages of anorthite in the plagioclase of rock 15, Bottorp, corresponding to the values of table V.

Law of twinning	Numbers referring to the table V.				
	1	2	3	4	6
(010)	40	64	62	—	62
[001]	44	63	66	—	59
⊥[001] / (010)	44	—	61	—	63
[010]	—	—	—	66	—
(001)	—	—	—	63	—
$2V_{\gamma}$	45	63	62	63,5	60
Average	44%	63%	63%	64%	61%

relations are not easily ascertained, the following statements, however, being the result of a detailed microscopical investigation.

A primary clinopyroxene with high refraction indices and a double refraction varying widely in the different sections (interference colours yellowish green to reddish blue) now occurs only as relics within the two types of pyroxene described below. This early pyroxene has an optic axial angle (2 E) of about 60° (measured by an ocular micrometer) and is colourless of a bright appearance. It has been replaced by other minerals, the alteration seemingly going in three different directions (*cf.* Fig. 18 on page 276):

Microphoto by the author.

Fig. 17. Planes of translation in a talcose olivine pseudomorph. Bottorp. No Nicols, magnification 50 diameters.

1:o *Grayish brown clinopyroxene* with the following optical properties:

$$2V_\gamma = 62^\circ \text{ (FEDOROFF stage)} \quad N_\gamma - N_\alpha = 0{,}016 \quad c/\gamma = 44^\circ.$$

This pyroxene shows an ill-defined cleavage parallel to (010) and further a striation parallel to (001). This striation, observed even on the next pyroxene, will be treated in that connection. However, this grayish brown pyroxene is not quite unaltered but has been locally replaced by a slightly pleochroic amphibole (γ *faibly green* $<$ β *olive brown*). The amphibole shows rather low double refraction and has a markedly fibrous character, the fibers running parallel to the trace of (010) of the original pyroxene and consequently intersecting the above striation at an angle of 74°—90° depending on the orientation of the section.

2:o. *Compact amphibole* (called so, because it is not fibrous) with a medium double refraction (yellowish brown interference colours) and slightly pleochroic, γ being *faintly green* and α *colourless*. The mineral shows a cleavage probably prismatic, the traces being parallel to (010) of the original pyroxene. Thus the pseudomorph is a homoaxial one. Even here a further alteration may be observed, the same fibrous amphibole as described above developing. In some sections (fig. 19 on page 277) the primary pyroxene on one side changes into grayish brown pyroxene, on the other into compact amphibole; afterward both new-formed minerals alter to fibrous amphibole, the latter forming a rather homogeneous inside area.

Microphoto by the author.

Fig. 18. Primary pyroxene (the light coloured area in the centre of the picture), secondary pyroxene (dark, in the upper part), and secondary amphibole (lightcoloured, in the lower part to the left). Bottorp. Nicols +, magnification 50 diameters.

3:o. *Gray pyroxene.* This kind of pyroxene is very conspicuous because of its low interference colours; moreover its other optical properties are rather peculiar, as is seen from the data below. The following determinations were made:

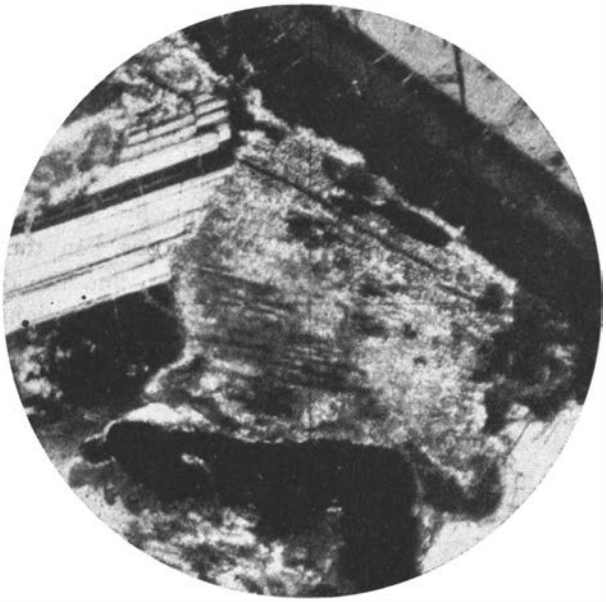
$$2\,V_\gamma \text{ (Fedoroff stage)} = 76^\circ - 84^\circ. \quad c/\gamma \text{ (Fedoroff stage)} = 33^\circ.$$

$$N_\alpha = 1{,}653 \pm 0{,}003 \quad N_\beta = 1{,}658 \pm 0{,}003 \quad N_\beta - N_\alpha = 0{,}005.$$

The double refraction determined is thus in full agreement with the value calculated from the refraction indices. Using 80° as an average value of the optic axial angle the remaining refraction index was calculated from those determined:

$$N_\gamma = 1,666 \qquad N_\gamma - N_\alpha = 0,013.$$

The gray pyroxene shows a striation parallel to the basis quite similar to that of the grayish-brown type, and in some sections this striation is even more marked than in the former one. The mineral is wholly devoid of alteration products. In some sections, however, a secondary amphibole seems to have developed. An intimate intergrowth of the pyroxene with a faintly green amphibole is seen, this arrangement lively reminding of a plagioclase twin. Thus the long axis of the amphibole seems to be parallel to the basis striation of the pyroxene, but a closer investigation



Microphoto by the author.

Fig. 19. Grayish brown pyroxene (to the left), compact amphibole (to the right), and fibrous amphibole (in the central part). Bottorp. Nicols +, magnification 50 diameters.

shows, that the amphibole develops its fibers perpendicularly to the »twinning boundaries» and consequently normally to the striation too. In some parts of the pyroxene, where the amphibole is more irregularly distributed, this combination of striation and fiber orientation leads to the development of an all but typical microcline cross hatching. It has not been possible to ascertain if this amphibole belongs to anyone of the types already described, as, strictly speaking, it exhibits a combination of the two structures characteristic of those types.

The genetic relations of the pyroxenes and the amphiboles of this rock, as understood from the above description, would thus be illustrated by the following scheme:

Compact amphibole → (Fibrous amphibole)
↑ ↑
Primary pyroxene → {Gray pyroxene / Grayish brown pyroxene → Compact amphibole → (Fibrous amphibole)}

The striation parallel to the basis, repeatedly referred to above, is of special interest. In some pyroxene individuals there are irregular patches, showing an extinction different from that of the main mineral, and as the striation does not continue into these patches, the assumption lies near at hand, that the striae are due to a polysynthetic twinning, not developed in the nonstriated parts. Such a twinning would help much to explain the rather peculiar optical properties of the gray pyroxene. Recently T. BARTH (**5** : 143) on the basis of MALLARD's and MICHEL-LÉVY's theories has shown that an orthoclase from the Adirondack Mountains was made up by a polysynthetically twinned microcline (polysymmetry; SCACCHI). In that case a mineral of known optical properties was studied, and the question arose, whether its properties would correspond to the assumption that the mineral was made up by another polysynthetically twinned and with known optical properties. In the present case, however, the problem is the opposite one, *viz.* to find the optical data of an unknown mineral, which by polysynthetic twinning might give those of the gray pyroxene, in order to ascertain whether the data found may really correspond to those of a normal pyroxene. According to BARTH the following formulas may be deduced:

$$\gamma = \frac{\alpha' + \gamma'}{2} - \frac{\alpha' - \gamma'}{2} \cdot \cos 2M \qquad \alpha = \frac{\alpha' + \gamma'}{2} + \frac{\alpha' - \gamma'}{2} \cdot \cos 2M$$

where α and γ are the principal indices of refraction in a section $\perp \beta$ of the »complex» mineral, α' and γ' the corresponding values of the simple one and $2M$ the angle between the corresponding axes of optical symmetry of the two individuals in twin position. If the simple mineral is a normal pyroxene vith $c/\gamma = 45^\circ$, the angle M is 30° and the calculation comes out as follows:

$$\left.\begin{aligned} 2\gamma &= \alpha' + \gamma' - \frac{\alpha'}{2} + \frac{\gamma'}{2} \\ 2\alpha &= \alpha' + \gamma' + \frac{\alpha'}{2} - \frac{\gamma'}{2} \end{aligned}\right\} \begin{aligned} \alpha' &= 1{,}5\,\alpha - 0{,}5\,\gamma \\ \gamma' &= 1{,}5\,\gamma - 0{,}5\,\alpha . \end{aligned}$$

By substituting the observed refraction indices of the gray pyroxene for α and γ, the optical properties of the assumed simple pyroxene may be calculated. The data obtained are:

$$N_\alpha = 1{,}648 \quad N_\beta = 1{,}658 \quad N_\gamma = 1{,}672 \quad 2V_\gamma = 80^\circ{,}5 .$$

The double refraction would thus be somewhat higher than that of the resulting pyroxene, but on the other hand the optic axial angle would also be a larger one. Of course, the proof is of a negative kind, but the following conclusion is, however, allowed: *The peculiar optical properties of the gray pyroxene may not be explained by the assumption, that it is formed by a polysynthetic twinning of a normal pyroxene. This does not, however, exclude the possibility, that such a twinning has really occurred, but then the simple mineral must show optical properties quite as peculiar as those of the complex pyroxene.* For the present it seems rather difficult to decide, whether any twinning has really taken place.

Thus the abnormal optical properties of the gray pyroxene cannot be explained by assuming a polysynthetical twinning only, and consequently the question arises what kind of a pyroxene it is. A study of the data available in the litterature shows that the values obtained correspond only to those of *jadeite*. The closeness of this correspondance is illustrated by the table below (Table VII). The very good agreement of the values in that table would justify the assumption, that the gray pyroxene is really a jadeite. Unfortunately it is quite impossible to check the optical determinations by a chemical analysis, because the occurence of three different pyroxenes and moreover the intimate intergrowth of pyroxenes and amphiboles excludes every possibility of a mineral separation.

Table VII.

Optical properties of jadeites and of the gray pyroxene of the rock 15 at Bottorp.

	1	2	3	4
N_γ	1,666	1,663—1,668	1,665	1,667
N_β	1,658	1,650—1,656	1,657	1,659
N_α	1,653	1,645—1,650	1,650	1,655
$N_\gamma - N_\alpha$	0,013	—	0,015	0,012
c/γ	33°	31°	34°	34°,5
$2V_\gamma$	76°—84°	—	75°	70°

1. Pyroxene, Bottorp. KROKSTRÖM.
2. Jadeite, St. Paul's Rock. H. S. WASHINGTON (**56**).
3. » , Birma. H. E. MERWIN (**32**).
4. » , Tibet. S. L. PENFIELD (**34**).

As to the remaining minerals of this rock there is hardly anything to be added. A remarkable feature is, however, the occurence of *quartz* in proportions not to be neglected. *Serpentine* veinlets of the same kind as those described in rock 123 are frequently observed, and here, too, they seem to converge towards the olivine pseudomorphs. In the vicinity of the amphibolized pyroxenes, on the contrary, they occur very sparingly, and thus it is probable that those represent real paramorphs or transformation products formed without any considerable supply of exogeneous material.

γ. *The fine-grained olivine dolerite.*

The central part of the Bottorp area is occupied by rocks of a type essentially different from those hitherto described. This type of rock is to

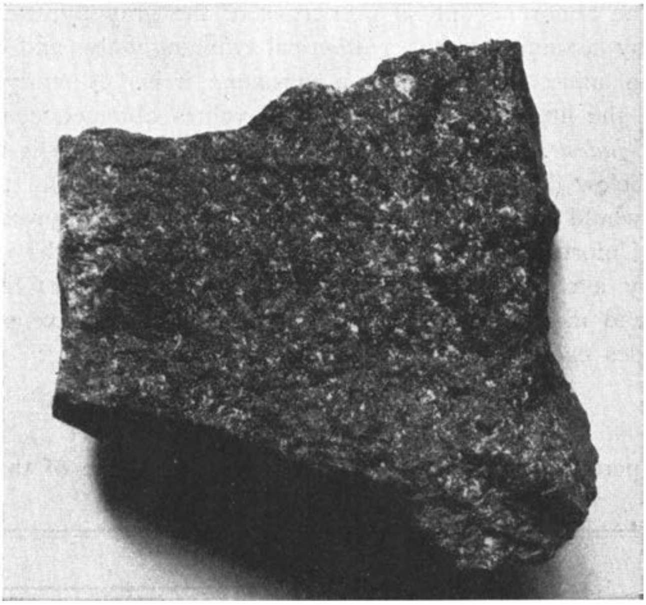


Fig. 20. A hand specimen of the finegrained olivine dolerite at Bottorp. Natural size.

be seen at the exposures 10, 124, 125 and 126 of the sketch-map (fig. 7 on page 263), though at those points, too, rather great differences may be noted. As typical of the normal development, the rocks 126 and 125 may be mentioned. The most conspicuous feature of the rocks in question is their texture. The difference between this dolerite and the coarse-grained one comes off on the microphotographes, figures 8 and 21 on pages 264 and 282 respectively. Already macroscopically the difference is quite obvious as seen by comparison of fig. 6 on page 252 and fig. 20 above. As to the structures they have already been described (page 248—251).

The plagioclase laths do not generally exceed 1 mm. in length, the olivine crystals not 0,5 mm. in diameter. Somewhere, however, larger individuals of both minerals may be observed. Pyroxene occurs quite subordinately and contrary to the pyroxene of the rocks previously described never develops straight outlines caused by the plagioclase laths, but shows well-rounded contours, conveying the impression of a scanty rest solution filtered into the interstices offered. Further it is generally confined to the neighbourhood of the olivine, which is almost constantly surrounded by a thin pyroxene rim. There is no doubt of the late crystallization of the pyroxene.

The plagioclase differs from that of the coarse-grained dolerite in still another respect, zonary structure being only very seldom observed and, when occurring, being of a rather quiet character with a well-developed, conformable banding. Recurrent banding is also often noted. The patchy and irregular aspect of the feldspar has disappeared entirely.

Rock 126 is composed mainly of *plagioclase* and *olivine*. A geometrical analysis gave the following proportions:

Plagioclase 66 vol.-% *Olivine 31 vol.-%.*

The remaining 3 % are made up by *hypersthene*, *augite*, *biotite*, *iddingsite* and *ore*. The plagioclase was determined on the FEDOROFF stage in a pericline twin, the following data being ascertained:

$2\,V_\alpha = 84°$ corresponding to *76 % anorthite* (**13**).
The position of the twin axis indicates *78 % anorthite* (**7**).
The position of the plane of twinning indicates *77 % anorthite* (**7**).
Average 77 % anorthite.

The mode of occurrence of the plagioclase does not deviate from that sketched above.

The *olivine* was determined by measurement of the optic axial angle on the FEDOROFF stage, five measurements giving the following result:

$$2\,V_\alpha = 86°,\ 85°,\ 86°,\ 86°,\ 87°.$$

The average value, 86°, indicates *20 % fayalite* according to BACKLUND (**3**).

Hypersthene is found only very subordinately and all sections observed in one slide show a simultaneous extinction, thus probably belonging to the same large invididual. By measurements on the FEDOROFF stage the following values were obtained:

$$N_\gamma - N_\alpha = 0{,}01 \text{ (approximately)} \qquad 2\,V_\alpha = 71°.$$

According to WINCHELL those values would indicate *30 %* $FeSiO_3$ (**51**: 177).

Clinopyroxene is also subordinate, but more abundant than the hypersthene. As already mentioned it occurs in the vicinity of and surrounding the olivine, but as several different sections of pyroxene show a simultaneous extinction, this mineral must not be understood as forming reaction rims but as a matrix bounding the olivine and independent of the latter. By universal methods the following data were ascertained:

$$c/\gamma = 43^\circ \qquad N_\gamma - N_\alpha = 0{,}017.$$

The rather low double refraction seems to be a characteristic feature of all the pyroxenes of these rocks.

From the geometrical analysis and the compositions optically determined, of the plagioclase and the olivine, the specific weight of the rock was calculated as follows:

The olivine according to BACKLUND (**3**)	$D = 3{,}43$
The plagioclase according to REINHARD and DUPARC (**13**)	$D = 2{,}76$
The rock calculated from the values above	$D = 2{,}99$
The rock determined according to ARCHIMEDES' principle	$D = 2{,}97$

Microphoto by the author.

Fig. 21. Microphotograph of the finegrained olivine dolerite at Bottorp, showing its very fine ophitic texture. Nicols +, magnification 16 diameters.

To the east as well as to the west of the outcrops 125 and 126 the rocks are of a somewhat different type, outcropping at the points 124 and 10 respectively. These types are of such an interest that they are worthy of a detailed description which is given below.

Rock 124 consists of *plagioclase, amphibole, clinopyroxene, serpentine, sericite, talc,* and *carbonates.* The plagioclase predominates and its short-tabular *habitus* gives the rock a peculiar, almost trachytoidal texture (see figure 22 on page 283). It was determined on the FEDOROFF stage, the result being

66 % anorthite.

Next to the plagioclase in quantity are some *aggregates of amphibole,* generally quite identical with the amphibole of the olivine pseudomorphs of rock 123, yet in this case, the talc is almost entirely missing. On the other hand, the amphibole needles are elsewhere scattered in a matrix of *carbonates.* From sections as reproduced in figure 23 on page 284 it is quite clear that *olivine* is the mother mineral of the present pseudomorph, the rounded form of the olivine and the characteristic bounding by a pyroxene being still fairly well recognized. Further the plagioclase

Microphoto by the author.

Fig. 22. Trachytoidal texture of rock 124. Bottorp. Nicols +, magnification 16 diameters.

of this rock is still more dissected by *serpentine veinlets* than in rock 123, and quite as in the latter those veinlets seem to converge and increase in number towards the amphibole aggregates (Fig. 24 on page 285).

In figure 23 another detail is worth noting. The amphibole occurs not only as scattered needles but close to the boundary of the surrounding pyroxene it begins to develop a compact form, leaving only the centre to the disposal of the needle aggregate, sometimes even filling the whole space at disposal. The compact amphibole has been observed only in cases where the pseudomorph is surrounded by pyroxene, this pyroxene itself being monoclinic and apparently identical with the one previously described. The amphibole seems to be of the same kind as that of rock 123, and from the present rock the following determinations have been procured:

$2V_\alpha = 74°40'$ (measurement of two relative retardations by a BEREK's compensator).

$c/\gamma = 15°$ $N_\gamma = 1{,}641 \pm 0{,}002$ $N_\alpha = 1{,}618 \pm 0{,}002$

$N_\gamma - N_\alpha = 0{,}023$ (determined) $N_\gamma - N_\alpha = 0{,}023$ (calculated).

The mineral is quite colourless without pleochroism.

It might be convenient to pay some attention to this amphibolic alteration. Amphibole developing out of olivine has been described early by several authors, among which BECKE (**7**) and KOLENKO (**27**) may be mentioned, and especially the *pilite* formation described and named by BECKE

Microphoto by the author.

Fig. 23. Compact and fibrous amphiboles as transformation products of olivine. Rock 124 at Bottorp. Nicols +, magnification 50 diameters.

seems to show much analogy with the alteration observed in the present rock. BECKE describes an olivine kersantite from Niederösterreichisches Waldviertel in the following terms:

»Viele der hierher gehörigen Gesteine enthalten eigentümliche Gebilde, die man als Pseudomorphosen betrachten muss. Sie bestehen der Hauptsache nach aus einem Filz von Hornblendenadeln; die Hornblende ist im Schliff fast farblos . . .; sie ist zum Strahlstein zu stellen. Diese Hornblendenadeln entspringen am äusseren Rande der Pseudomorphosen und ragen in divergierenden Büscheln in das Innnere hinein. Das Innere ist entweder von einem wirren Filz solcher Nadeln ausgefüllt, oder es tritt ein schwach doppelbrechendes, chlorit- oder serpentinähnliches Mineral ohne deutliche Struktur dazwischen auf. Die Vermutung, dass diese Pseudomorphosen von Olivin abstammen, wurde dadurch zu Gewissheit erhoben, dass in einem der gesammelten Handstücke . . . derartige Gebilde entdeckt wurden, welche noch einen Kern von frischem Olivin enthielten.» (*Loc. cit.* page 163.)

Kolenko describes a similar phenomenon from the Government of Olonetz:

»Sämtliche Olivine sind vollständig, theils in Hornblende, theils in chloritische Substanz pseudomorphosiert . . . Die Hornblende tritt innerhalb der Krystallumrisse einerseits in Form schöner büschelförmiger Aggregate

Microphoto by the author.

Fig. 24. Serpentine veinlets in plagioclase, converging towards the olivine pseudomorphs. Rock 124 at Bottorp. Nicols +, magnification 50 diameters.

auf, die entweder von den Krystallrändern nach der Mitte eindringen oder im Krystall regellos nebeneinander liegen, anderseits erscheint sie in grösseren Krystallen, welche in Querschnitt eine tafelförmige Gestalt besitzen. In beiden Fällen ist die Hornblendesubstanz vollkommen rein und klar durchsichtig und zeigt keinen Pleochroismus, doch heben sich ihre sanften Interferenzfarben ausserordentlich lebhaft von einander ab . . . In den büschelförmigen Aggregaten wurde die Auslöschungsschiefe gegen die Verticalaxe bis zu 18° gemessen, meistens jedoch ist sie bedeutend geringer.» (*Loc. cit.* page 91.)

The two descriptions quoted above are almost entirely in accordance with the observations made in the present rock. The only difference might be that Becke as well as Kolenko mentions the presence of chlorite together with the amphibole. From KOLENKO's description, however, it appears, as if these two minerals did not occur together, everyone, on the contrary, forming its type of a pseudomorph. Further KOLENKO ascribes the formation of chlorite to a chloritization extending all over the rock. BECKE vaguely states that the interstices between the amphibole needles may sometimes be filled by a mineral similar to chlorite or serpentine. It could perhaps be assumed that this mineral really was talc, which because of the insufficiently accurate methods of that time (1883) was misinterpreted, but considering BECKE's eminent skill as microscopist, this assumption seems hardly justified. A fact is, however, that the present author, observing this mineral in the rock, at first interpreted it as chlorite and only after detailed optical investigations the mistake was realized.

Though there are thus some differences, it is the author's opinion that the olivine pseudomorphs described above are equivalent to BECKE's *pilite*. The question then arising is, what kind of an amphibole constitutes the pseudomorphs and how has it been developed. As to the first question the papers cited give no other hint than BECKE's statement, that the mineral ought to belong to the actinolite group, and the value of the extinction angle communicated by KOLENKO. Nor is it quite possible, from the rather detailed optical determinations executed by the present author, to classify the mineral unambiguously, and the only way open seems to be that of a genetical discussion.

The formation of any amphibole out of olivine implies an addition of silica, and the most simple assumption would be, that this silica supply was the only material transport towards the olivine, and that the silica was furnished by the rest solutions during the late-magmatic period. If that is the case the amphibole of the pseudomorphs ought to belong to the *cummingtonite-grünerite*-series. The diagram deduced by SUNDIUS (**47**: 164) for this mineral group, however, gives 1,67 as the lowest value known of N_γ, thus a considerably higher value than those determined in the present rock (cf. page 284). As the determination curves of the diagram quoted are rectilinear and extend only from 40 % to 100 % (Fe, Mn) SiO_3, an attempt was made to check the mutual correspondence of the values obtained by means of extrapolating the curves into the area of lower iron contents. In this way it was found that the refraction indices as well as the double refraction strongly diverge. It must be considered as quite evident, that the amphibole in question does not belong to the lime-free or lime-poor cummingtonite group. This statement is further strengthened by two other facts, *viz.* that the mineral apparently is of the same kind everywhere and that the serpentine veinlets of the feldspars indicate necessarily a rather strong material transport. As far as the transport is concerned, which was directed from the plagioclase, the material must have been taken up by the olivine, as there is no other mineral in the rock that might have played that part. Assuming a primary development of cummingtonite the subsequent material supply would have led to the formation of another type of amphibole. Thus we are compelled to suppose, that this material transport is responsible for the amphibole formation from the very beginning. What substances were then added? In order to get an explanation of the serpentine formation we must assume CaO, Na_2O, SiO_2 and Al_2O_3 to have been brought away, MgO being simultaneously supplied. The latter was of course delivered by the olivine, which must in its turn — as far as is seen from the microscopical study — be made responsible for the taking up of all the oxides first mentioned, thus also Al_2O_3.

A critical examination of most amphibole analyses available shows, however, that in these minerals alumina is never equal to lime, the latter oxide being always in excess (**28**). Thus it would appear that amphibole may not form by means of a reaction between plagioclase and a lime-free silicate like olivine, less there is another mineral, that may account for the excess of alumina. These two facts — the evidence that the amphibole has been formed by means of a reaction between plagioclase and olivine without any mineral to account for the alumina, and the theoretic impossibility of such a process — seem to be obviously contradictory to each other, and the author must admit that he has not been able to find any explanation entirely valid. However, it must be considered most probable, that alumina has been retained in the serpentine veinlets of the plagioclase, entering into some inconspicuous mineral such as chlorite or kaolinite. Another possibility is, of course, that some chlorite occurs among the talc, thus in about the same way as in the pseudomorphs described by BECKE. Yet the latter assumption seems rather improbable, the microscopic investigation indicating no such inhomogeneity of the talcose matrix.

The question about the character of the amphibole, however, still remains unsolved. Considering its optical data, the absence of colour and pleochroism, it seems, however, most probable that this mineral is a member of the *actinolite—tremolite* group. If this assumption as well as the assumption that alumina was retained in the serpentine veinlets, holds good, we may further avoid the supposition of alumina having migrated, which is hardly in accordance with prevailing experience.

Another problem is presented by the ways of transport now filled by serpentine. How did those cracks or veinlets originate? It might be most probable, that the first step of the olivine alteration was a change into metasilicate being effected by the aid of siliceous solutions. This change implied an increase of volume, causing the cracks of the surrounding feldspars. Such a »*Schwellungsmetamorphose*» has been previously suggested by Steinmann (**45**). It is also possible, that the first alteration was a mere transformation without any material supply — a paramorph. This assumption is supported by the fact, that the amphibole development was not at all obstructed even in the case the olivine was surrounded by a pyroxene armour. This armour was also subjected to the »*Schwellungs-metamorphose*», thus breaking up and leaving the way open for the interchange solutions.

Rock 10 is found at one outcrop only, *viz.* at an escarpment close to the railway, and exposes there a direct contact with the coarsegrained dolerite. It appears as a dike or as a filling in a depression in the latter. Already in the field the difference between the two rocks is obvious, rock 10 showing a very strong intimate fracturing, which is entirely missing in the coarsegrained dolerite. Megascopically the rock is black and almost aphanitic, microscopically it is of a rather varying aspect. In some parts it is holocrystalline, consisting mainly of small rounded *olivine* grains, scattered in a matrix of *plagioclase,* the latter mineral being also developed in very small crystalls. *Pyroxene* may occasionally be found, and thus the rock is similar to the normal dolerite as regards the mineral composition. The difference stands out mainly in the extraordinarily fine grain as also in the fact, that olivine predominates quantitatively.

In other parts of the exposure the rock shows microscopically quite another habitus. The olivine has entirely disappeared and is replaced by a colourless *chlorite* of subnormal interference colours. It is quite obvious from the outlines of the chlorite that it was developed as pseudomorphs after olivine, and to judge from the abundance of chlorite the former mineral must have been originally quite as abundant as in the type of rock described close above. Augite occurs in some quantity and is somewhat corroded; apparently this mineral too has suffered from a chloritization. Finally there is some biotite. All these minerals lie embedded in a rather sparse glass matrix, showing signs of a beginning devitrification indicated by the occurence of sphaerulitic structures etc. The glass basis is richly impregnated by ore dust and even some ore particles of a larger size have been observed in the rock.

It may hardly be doubted that this rock belongs to the same series as the rocks 124, 125, and 126, and it is most probably understood as the wedging out of the »stroke» occupied by those rocks. On the sketch-map on page 263 the field relations have also been interpreted in accordance with this view.

b. **The central and eastern part of the dike.**

This part of the dike is occupied by three principal rock types, *viz.* olivinebearing dolerite, olivine-free dolerite, and granophyre. Besides those rocks there are found some local modifications, which are described later on but are not inserted on the map because of their restricted field extension. Two sketch-maps (fig. 25 on page 290 and fig. 26 on page 299) from the vicinity of the farm Högsäter and from the surroundings of the farm Gustafsberg respectively give an idea of the rock distribution, and besides on the latter some interesting details are seen, to whom will be paid attention later on.

1. The olivinebearing dolerite.

The olivinebearing dolerite occurs very sparsely and has been observed only in a few exposures at the northern boundary of the dike. When normally developed this rock is megascopically fine-grained, and of a grayish brown colour, olivine being very conspicuous among the mineral constituents. Microscopically the rock is found to consist of *plagioclase, augite,* and *olivine* besides *chloritic* and *serpentinic* products of alteration. Further there is some *potassium feldspar.* The texture is most conveniently described as subophitic in the sense this term has been used by SUNDIUS (**47**: 50). Thus the augite has not been sufficient for a complete embedding of the plagioclase laths, which here and there emerge from the large, uniform augite individuals. The sequence of crystallization seems to have been as follows: 1:o Olivine and plagioclase most probably crystallizing almost simultaneously; 2:o augite. Most characteristics being thus the same as those of the western olivine dolerite, the conspicuously fine grain, however, constitutes a marked difference. Nor is the rock equal to the fine-grained olivine dolerite of the Bottorp area, the dark minerals of the latter being mainly olivine with only subordinate amounts of pyroxene, whereas in the present rock pyroxene is most abundant.

In one outcrop an olivinebearing dolerite was found of quite as coarse a grain as the western one, but this rock even in other respects differs from the normal type and must strictly be considered as belonging to the olivine-free dolerite, olivine occurring only very sparsely as a few large grains, and the texture being also similar to that of the latter rock. Indeed the mere occurence of the type of rock described clearly indicates that in spite of great and important differences the two dolerites of the area now under discussion are rather closely connected, the olivinebearing type being most probably interpreted as a chilled margin of the olivinefree one. Whether such a margin exists all along the northern boundary of the dike may not be ascertained with certainty, there generally intervening an area without exposures between the dolerite and the wall rock. Along the southern boundary, on the contrary, the author has studied the dolerite at several places close to the wall rock, and chilled types have been observed even here (*cf.* p. 292 below), but no olivinebearing rocks have been found. (A possible exception

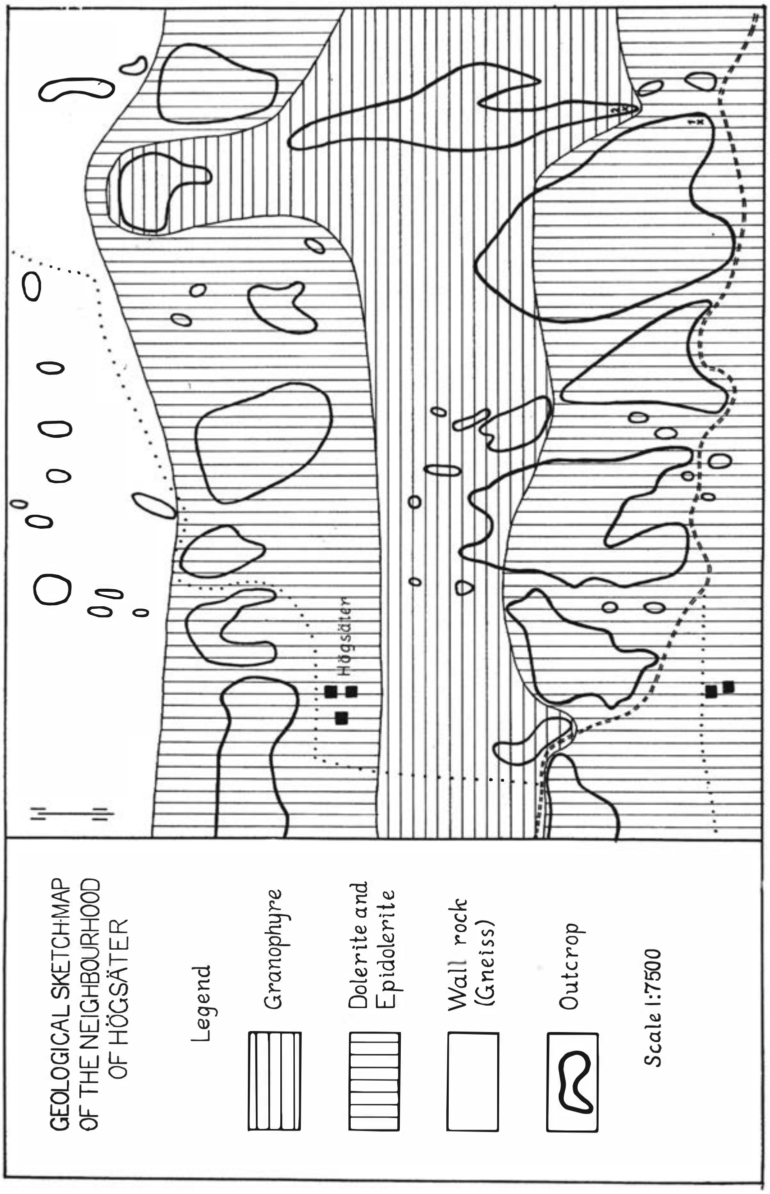


Fig. 25.

from this statement is discussed in the following on page 301.) Thus it seems probable, that the olivine dolerite of this area is confined to the northern contact.

The *plagioclase* of this rock shows an extinction of about $+35^\circ$ $\perp$ M and P, and about $+31^\circ \perp \alpha$. The average composition thus seems to be about *70 % anorthite*. No well-defined zonary banding was observed, but several individuals show extinction angles successively increasing towards the centres, the kernel sometimes having an extinction of 43° corresponding to *91 % anorthite* (**29**: 63).

The *augite* shows the following optical properties:

$$\gamma - \alpha = 0{,}030 \qquad \gamma - \beta = 0{,}026 \qquad \beta - \alpha = 0{,}004 \qquad c/\gamma = 41^\circ.$$

From those values may be calculated:

$$2\,V_\gamma = 44^\circ.$$

The mineral is grayish to colourless and shows a pleochroism hardly perceptible towards a pale reddish.

The *olivine*. It was not possible to make any accurate determinations of the olivine, the approximate values of its optic axial angle and double refraction indicating, however, that it is a rather iron-rich variety.

2. The olivine-free dolerite.

The areas marked on the summary map as belonging to this rock are not quite homogeneous. However, the different rocks are without doubt closely related by origin, they are further connected by a continuous series of transitional types, and there is thus no possibility of separating the different varieties on the map. In the description, however, at least two types must be kept apart, *viz.* a fresh dolerite and a strongly altered one; between them there are, as is already mentioned, all kinds of transitions. For shortness a special name was desirable for the altered types, and because of their alteration *epidolerite* was found most convenient. For further particulars concerning the use of the prefix »*epi-*» the reader is referred to ARTHUR HOLMES (**23**: 91).

α. *The fresh dolerite.*

The fresh dolerite occupies a very restricted area only, being found mainly along the dike boundaries (except at localities, of course, where the outermost zone of contact consists of the olivinebearing dolerite). Megascopically it is of a speckled black-and-white colour and shows a very coarse grain with large, light-coloured feldspar-laths. Microscopically its texture differs essentially from that of the olivinebearing types, the western one as well as the eastern, marginal type. Instead of their ophitic or subophitic texture the present rock has a doleritic one (this term is used in the same sense as the german »*diabaskörnig*»). Thus the *pyroxene* is idiomorphic or subidiomorphic and has obviously crystallized before the feldspars. Often it is developed as laths of a considerable length (sometimes of centimeter length), and those are generally twinned, the plane of twinning bisecting the individuals longitudinally. As the mineral is further striated parallel to the basis, the result is hence a bilaterally symmetrical »herring-bone»-structure, which is very characteristic of these rocks. The pyroxene is monoclinic, optically positive, and faintly brownish, being apparently identical with the pyroxene of the olivinebearing marginal dolerite. The quantitative relations between pyroxene and plagioclase are somewhat varying, but generally the latter shows an excess. The *plagioclase* shows extinction angles ⊥ M and P varying between 27° and 34° and thus indicating a composition of *52—64 % anorthite.*

Besides those main minerals there is subordinate *titaniferous iron ore* surrounded by *leucoxene* and occupying sometimes great areas of the slide, but on the other hand sometimes entirely missing. Some *quartz* and *potassium feldspar* is almost constantly present, yet generally confined to a few micrographic lobes between the plagioclase laths. Some secondary minerals, as *sericite, biotite,* and *amphibole* represent a beginning of the strong alteration, which will be described together with the epidolerite. A somewhat earlier stage of alteration seems to be marked by a few aggregates of *talc, chlorite,* and *serpentine* with needles of *tremolite* scattered all over them. These aggregates show some analogies with those of the Bottorp area (cf. above on page 266), and even here they sometimes appear to be pseudo-morphs of olivine. In other cases, however, an orthopyroxene was perhaps the mother mineral. In the immediate vicinity of the olivinebearing marginal dolerite another rock is found, which, as stated above, though by texture and mineral development belonging to the olivine-free type, contains large crystals of olivine.

Accessory constituents of the fresh dolerite are further *apatite, epidote,* and *titanite* in varying amounts.

At the southern boundary the dolerite sometimes shows a chilled margin, and the rock becomes here rather fine-grained. This zone resembles the one of the northern contact, except that olivine is missing. At the southern boundary, however, the tremolite-chlorite aggregates mentioned above, increase in number towards the contact and, further, the plagioclase individuals are dissected by numerous serpentine veinlets converging towards those aggregates. There are thus fair analogies with the Bot-torp area.

At one locality in the vicinity of the southern boundary another type of development has, however, been observed. Here the rock has as coarse a grain as the normal types, perhaps even coarser, but mineralogically it consists almost entirely of *plagioclase.* The rock, thus, is a coarse *anorthosite,* consisting of about *90 % plagioclase,* the latter being of the same composition as in the main rock. The rest minerals are *pyroxene* with its alteration products and some *ore* with *leucoxene.*

β. *The epidolerite.*

The epidolerite joins the inner areas of the dolerite zones and has a far wider distribution than the dolerite, its beforementioned transitions being observed in the field as well as under the microscope. In the innermost areas — close to the central granophyre — this rock represents a type, chemically as well as mineralogically strongly different from the dolerite. It is perhaps inappropriate to assemble these rocks with a common sign, as has been made on the summary map (Plate XII), but the gradual transitions are rather inopportune for a formal distinction. It must, however, be kept in mind, that the innermost zones of the dolerite diverge rather strongly from the outermost ones. The rocks next to the granophyre are striking already in the field by their rather strong weathering. The outcropping rocks are sometimes so soft throughout, that a blow may bury the hammer to the very handle, and large boulders may be crumbled to granules between the fingers.

The epidolerite is, properly speaking, very inhomogeneous, but the microscope brings out that the development proceeds along the following main lines. The *anorthite percentage* of the plagioclase decreases rather gradually from the very high values (54—62 %) of the dolerite down to *25—30 %*. Simultaneously the rock becomes enriched in *potassium feldspar* — generally showing perthitic, sometimes even »chessboard»-structures — and *quartz* — often with undulose extinction — these two minerals occurring partly independent and partly intergrown micrographically. *Plagioclase* laths surrounded by a rather broad zone of potassium feldspar in parallel crystallographical growth show very distinct idiomorphic outlines, while the orthoclase rim outwardly fades out very irregularly or even enters immediately into a granophyric intergrowth with quartz. The rim of potassium feldspar may be quite homogeneous, but mostly it is perthitic.

The development of the dark minerals is obscured by a number of *amphiboles* and *pyroxenes* together with *biotite* and *chlorite,* the mutual relations of these minerals being very intricate. Somewhere the development seems to proceed quite as at Bottorp (cf. pp. 273—278); no jadeitic mineral, however, has been observed. Yet another development seems to be still more common: the pyroxene becomes surrounded by amphibole and chlorite, these two minerals developing together also in the center of the pyroxene and from there growing outwards. The amphibole shows at least three varieties, the optical data of which are put together in the table below (Table VIII on page 294). The extinction angle of no. 3 is missing because of its development in very small patches only, without distinct cleavage.

Predominant of these amphiboles is undoubtedly no. 1, and it occurs sometimes as quite homogeneous individuals. Generally, however, its centre is made up by no. 2 or in a few cases by irregular small patches of no. 3, embedded in a *matrix* of chlorite, no. 2 forming an intermediate zone between the centre and the fresh and sharp rim of no. 1.

Table VIII.

Optical properties of amphiboles in the epidolerite.

No.	Pleochroismus			c/γ	$2V_\alpha$
	α	β	γ		
1	straw yellow	olive brown	moss green	16°	ca. 80°
2	colourless	yellowish green	grass green	16°	> 80°
3	grass green	dark yellow	bluish green	—	> 80° but < No. 2

That may be the final stage of the pseudomorph, but generally the centre shows a pyroxene relic, and in the types of rock that occur next to the dolerite, only narrow amphibole rims are observed around the pyroxenes, and further small irregular patches of the same mineral developing in the interior indicate a prior stage of alteration. The amphibole no. 1, being generally quite unaltered to the very contours, conveys the impression of a primary origin. Its relation to the pyroxene is thus most probably only a geometrical one, and its independence is further shown by the fact, that it may occur without any connection with the pyroxene. The amphibole no. 3, on the other hand, as well as the chlorite ought to be purely secondary products, and the amphibole no. 2 is most properly interpreted as a reaction product between no. 1 and no. 3.

The chlorite shows a very strong pleochroism, γ of a *dark green* and α *colourless* or of a *faintly reddish* colour. There is also another chlorite present, most probably belonging to a later generation, being non-pleochroic and of a sphaerulitic structure.

Quite exceptionally the relations are as conspicuous as described above. Usually *biotite* enters abundantly and strongly obscures the development. Probably it is formed still later than the amphiboles and the earlier chlorite but earlier than the later chlorite, and sometimes it seems to have been formed out of the amphiboles, as may be concluded from its close association with and penetration of them. It is generally developed as aggregates of small scales.

Elsewhere large masses of amphibole and biotite are felted together as tightly as to be hardly dissolved by the microscope. Small amphibole crystals with traces of idiomorphic development and sharp *epidote* individuals with *b*-axial elongation are discerned, yet their size does not allow of a closer optical determination.

Further these rocks contain plenty of *ore* with *leucoxene* and *biotite* rims, and even *apatite* and *titanite* are fairly abundant. *Epidote* occurs in varying amounts, sometimes developing a considerable size and often showing a kernel of *orthite*. In same sections rather large individuals of *calcite* have been observed.

As stated above there is hardly any possibility to trace a precise boundary line between the epidolerite and the dolerite. Between the epidolerite and the central granophyre, however, an exact boundary may be traced without difficulty. In the field it may appear that there exists a gradual transition here, too, but a closer laboratory investigation everywhere reveals an *hiatus,* though sometimes a very slight one. There are two conspicuous differences between the rocks. In the development of the dolerite towards the granophyre border the amount of plagioclase decreases, the mineral becoming simultaneously more albitic, yet both processes stop at a certain stage. In the last stage observed the plagioclase still contains 25—30 % anorthite and amounts to about 50 % of the total feldspar. In the granophyre, on the other hand, plagioclase is totally absent; thus between those two rocks there exists a real discontinuity. A less protruding discontinuity is shown by the quantitative relations of the dark minerals. The epidolerite, even when strongly altered with all its pyroxene converted into secondary minerals, still contains rather large amounts of amphibole, chlorite and biotite, while the granophyre shows only quite spare flakes of a ragged biotite and some chloritic aggregates of secondary origin. Certainly the epidolerite may sometimes develop a leucocratic *facies,* yet then its whole texture of divergent feldspars as well as its abundance of plagioclase shows a marked distinction from the granophyre. It seems probable, that these types mineralogically behave to the epidolerite in the same manner as the anorthosites described above (cf. page 292) to the dolerite.

Within the main epidolerite area there are found isolated irregular patches and dikes of a granitic composition; it has been considered most convenient to treat them together with the granophyre, although they are located outside its proper area.

3. **The granophyre.**

Megascopically the granophyre is red with sporadic green spots of *epidote,* which may attain a size of about 5 mm. Phenocrysts of *quartz* of about the same size as the epidote patches are prominent. Microscopically the rock turns out to be quite leucocratic, its main constituents being only *potassium feldspar* and *quartz.* They are partly independent, partly micrographically intergrown.

The *quartz* generally shows rather strong undulosity and has never crystal forms of its own.

The *potassium feldspar* is nearly always strongly perthitic, sometimes in such a degree, that it is difficult to decide, if it must be most properly classed as a perthite or as an anthiperthite. In some cases, however, the perthitic intergrowth is wholly wanting and is then generally replaced by a beginning »chessboard»-structure. In a few cases microcline grating was observed, but usually it lacks completely. This mineral often shows crystal forms of its own, or at least strong tendencies of developing them, and this is the case especially when the feldspar constitutes a kernel of a micrographic intergrowth. Those relations will be treated more fully below.

The other minerals of the granophyre are quantitatively very subordinate. They consist of ragged patches of a brownish red *biotite,* further of some *chlorite, apatite, titanite* and *epidote.*

α. *The micrographic structure.*

The texture of this rock is generally micrographic, as indicated by the name, but the extension and distribution of the micrographic intergrowths is somewhat varying, the total texture being, of course, influenced by these variations. Most usually they extend over rather large areas, the granulous, or non-micrographic parts being thus quantitatively very subordinate, but sometimes the latter extend widely at the cost of the former, the rock in extreme cases becoming of a texture, that is most properly designated as granitic or aplitic, in dependence of the coarseness of grain. Those cases are, however, rare, and it has not been possible to find out any rules of the distribution of the almost non-micrographic types.

Originally the author intended to perform a rather detailed investigation of these micrographic intergrowths by means of the FEDOROFF stage in order to contribute to the discussion of the mutual orientation of the micro-pegmatitic minerals, in the course of which especially FERSMAN (**16**), POPOFF (**35**), and ESKOLA (**15**) have published very valuable data. However, owing to the irregular perthitic structure of the feldspar and to the strong undulosity of the quartz, it proved quite impossible to execute such determinations with the necessary precision.

As a matter of fact it will appear as if the micrographic structure met with in this rock were not essentially different from that described by ESKOLA *(loc. cit.).* Generally there is a kernel of orthoclase being fairly well idiomorphic, and from this kernel the micro-pegmatitic fields radiate, the feldspar of the latter being always uniformly orientated and of the same orientation as the central feldspar, whereas the quartz generally represents several different fields of a mutually differing orientation. Sometimes, however, the quartz gathers outside the intergrowth to a single individual of uniform orientation. Thus it appears as if an independent grain of quartz and an independent one of feldspar had in some way hooked into each other, forming a micrographic intergrowth. It is, however, possible that this phenomenon is only an extreme development of a tendency often observed at the quartz *hieroglyphs, viz.* that of increasing in size towards the outer zones of the intergrowths.

On the other hand it may also happen that the feldspar having radiated from the kernel and having partaken in the formation of the micro-pegmatitic field, once more gathers outside the latter into a single large individual, and the micrographic portion thus occurs as an interior zone of a large feldspar. In this case it must, however, be observed, that the part of the feldspar gathered outside the micro-pegmatite never shows crystallographical forms of its own, whereas the boundary between the kernel and the micrographic field clearly indicates the idiomorphic development of the former.

Further there have been observed some other types of development worth noting. Sometimes one finds a micrographic portion without a kernel, a more intimate intergrowth in the central parts, however, apparently indicating the outlines of an idiomorphic feldspar. Thus the impression is gained, that there is really a kernel, though this, too, shows a micrographic structure. In another case a large, idiomorphic feldspar was observed, which was micrographically intergrown with quartz but was not surrounded by any outer irregular micro-pegmatitic field. It is, of course, possible, that at least the first case mentioned may be explained by assuming a somewhat exentric section, but after rather detailed microscopic investigations the author is not inclined to be of that opinion. It seems to the author, that the two phenomena, last mentioned, indicate, that the micrographic structure is developed not only by the crystallization of an eutectic solution, but may also form by a replacement of a preexisting feldspar material. Nor is it easy to explain the other relations just described in accordance with VOGT (**55**: 125) by assuming a simple eutectic crystallization, and further such an assumption is strongly contradicted by BYGDÉNs statement, that the composition of different micro-pegmatites may vary rather widely (**12**). Indeed, it is to be considered most probable, that phenomena of undercooling play an important part in the development of those structures, and surely still more detailed investigations are needed before the problem of the micrographic structures may be satisfactorily solved.

SCHALLER has already previously (**39**, **40**) announced the view, that the micrographic structure may be due to a partial replacement of an earlier mineral by a later one. His point of view was recently, however, criticized by VOGT (**55**: 125—126), who maintains a simultaneous eutectic crystallization of the two components affording the only possible explanation. In support of this opinion he refers to FERSMAN, who was able to show, that there is a special crystallographical orientation between the components, and further VOGT refers to investigations of his own, that the proportion *quartz*:*feldspar* is quite constant in all micrographic intergrowths. By BYGDÉNs analyses, however, the last argument ought to have lost a good deal of its convincing power *(loc. cit.)*, and FERSMANs law seems hardly to be unambiguously bearing upon the solution of this problem. Thus in spite of VOGTs comprehensive research the present author ventures to hold the view, that an eutectic crystallization may not always explain the formation of every micrographic structure.

β. *Distribution and variation of the granophyre.*

The granophyre described above occupies the central part of the area now treated (*cf.* the summary map, plate XII), and its boundary line against the epidolerite is rather irregular. At one place, however, a granophyre exposure has been met with outside this boundary, and this fact is of a rather great importance. The scale of the summary map allows no marking of this exposure, but from the sketch-map, fig. 26 on page 299, the rock distribution may be clearly understood. Within the area represented by that map the granophyre occurs at one locality outside the dolerite, bounding immediately to the wall rock. More important is, however, that this granophyre outcrop is situated even outside the olivinebearing marginal zone of the dolerite; the bearing of this fact upon the genetical relations of the rocks is treated more fully later on in the discussing part of this paper (pp. 309—310). The granophyre of this exposure is practically identical with the one previously described. Megascopically it is, however, a gray rock, thus differing from the main red granophyre. Microscopically the orthoclase of this rock is found to be somewhat less perthitic than in the central granophyre. Besides there occur a few rather large individuals of *plagioclase,* which are strongly sericitized and with a fringe of potassium feldspar. Their composition has not been exactly determined, but, judging from their refraction compared with that of quartz, they are very poor in lime. It is, indeed, hardly surprising, that the granophyre in this position, occupying a narrow zone between the dolerite and the wall rock, differs somewhat in composition from the main rock, and it was even to be expected that it would prove to be a little enriched in lime. The microscopical examination, however, clearly shows that its genetical connection with the central granite admits of no doubt.

Two aplitic dikes cutting the epidolerite to the south and to the east of Lake Hinnersjön must further be counted to the granophyre. The southern one may be traced for a length of about three meters, wedging out at the one end and being covered at the other. It shows a width of about 30 cm. and strikes N 35° W. The boundary against the surrounding epidolerite is straightlined and sharp. The eastern dike strikes N 20° E and has a width of about 1 m. Microscopically those rocks prove to consist almost entirely of *quartz* and *potassium feldspar,* the latter being somewhat perthitic. Besides, a few individuals of *plagioclase* strongly twinned are observed, which were determined as nearly pure *albite.* The mafic minerals

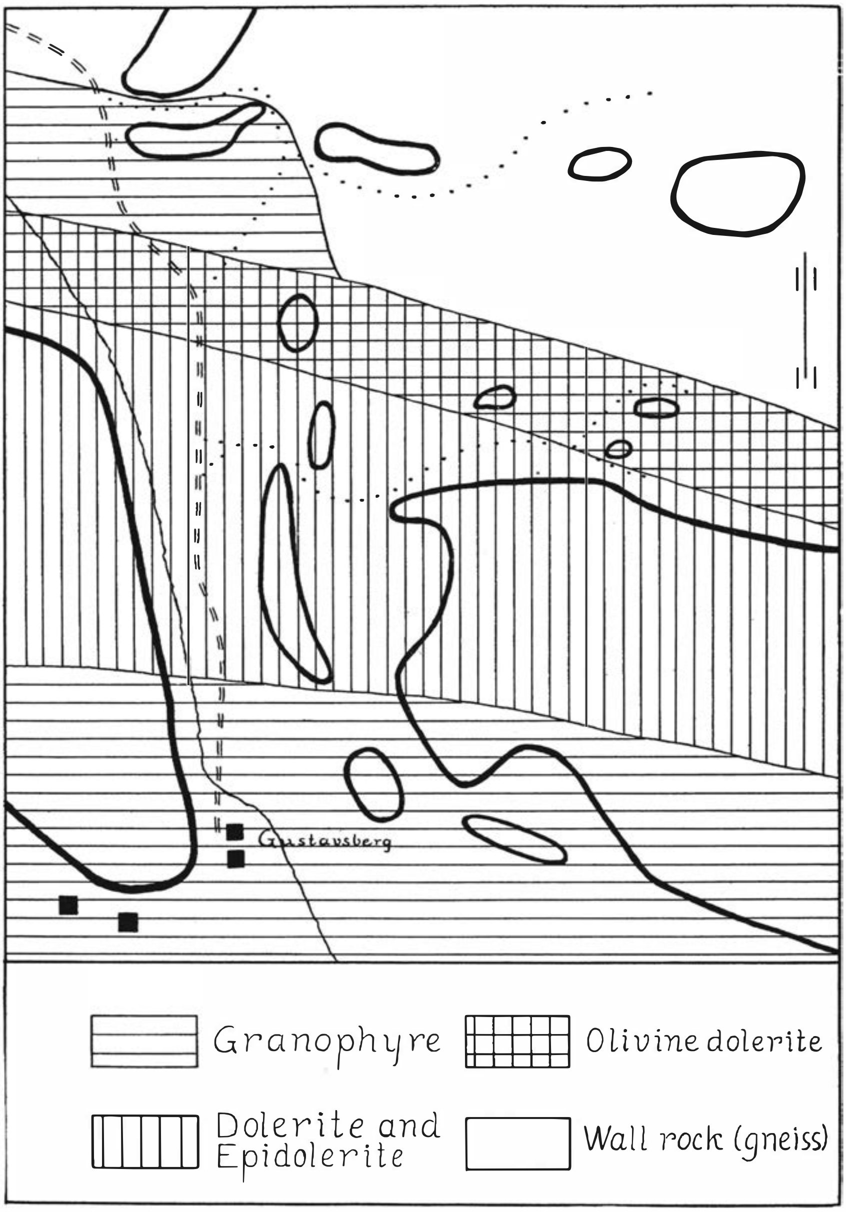


Fig. 26. Geological sketch-map of the neighbourhood of Gustavsberg. Scale 1 : 4000.

are represented mainly by *epidote* and by a few *amphibole* individuals, with a pleochroism of a *green* and *olive brown* colour. It is perhaps venturous to connect those dikes with the granophyre, yet their mineralogical composition agrees very well with the latter, and thus the author considers it quite justified to classify them together with it, furthermore as they occur close to the boundary of the epidolerite against the granophyre.

At two other localities, too, there have been found within the area of the epidolerite rocks which may be considered as intimately connected with the granophyre. These localities are both close to Högsäter and are marked by 1 and 2 on the sketch-map (fig. 25 on page 290). At point 1 there outcrops within the epidolerite area a light-coloured rock of rounded outlines, occupying an area of about two square meters and showing a rather sharp boundary line against the surrounding epidolerite, which at this place still consists of mainly plagioclase and rather abundant pyroxene. At point 2 there is also observed an intimate association of epidolerite and an aplitic rock, but the rocks are not sufficiently well exposed as to allow of a positive settlement of their mutual relations. Microscopically the light-coloured rocks prove to be almost identical at both localities. As to the mineralogical composition they resemble the granophyre and their original texture represents something between micrographic and aplitic. The word »original» is used, because both rocks — yet especially the one from point 2 — show clearly, that they have undergone a mechanical deformation. The quartz is strongly undulose, and all minerals are cracked and crushed. The micrographic structure, too, is rather strongly affected, and finally the rocks show some micro-breccias, who are very well-developed at point 2 but somewhat less at point 1.

4. Local modifications of rock.

Some local rock modifications still may be mentioned. Thus in some portions of the long outcrop between the southern parts of the lakes Hinnersjön and Dunsjön (*cf.* the geological map-sheet Breven, **14**) there is found a rather coarse rock of a grayish green colour in which *epidote,* large *quartz* grains and long *amphibole* needles are visible already to the naked eye. Microscopically the rock is found to consist of about *60 % epidote,* the remaining minerals being *quartz* in large individuals, needles of *amphibole* — probably secondary products of *pyroxene* — and, finally, broad laths of *plagioclase.* The accessory minerals characteristic of the epidolerite are also observed, *apatite* and *titanite* being most conspicuous. The amphibole shows an extinction of $c/\gamma = 14^\circ$ and a slight pleochroism of *green* and *olive brown.* In order to get an idea of the composition of the epidote, the relative optical retardations were measured in three sections, *viz.* normally to the three optical axes of symmetry. The thickness of the slide was in every case measured according to CHAULNES' method. The values of double refraction thus calculated were:

$$N_\gamma - N_\alpha = 0{,}059 \qquad N_\beta - N_\alpha = 0{,}045 \qquad N_\gamma - N_\beta = 0{,}014.$$

From those values the optic axial angle was also calculated:

$$2\,V_\alpha = 60^\circ.$$

The values obtained are rather peculiar. In MALMQVISTs paper on the epidote group (**31**: 257) there is found a compilation of all epidotes optically determined, the highest value of $N_\gamma - N_\alpha$ being 0,0505 and the lowest value of $2 V_\alpha$ being about 69°. It is true, that the values given above are only approximate ones, owing to the inaccuracy of the CHAULNES' method, but the question is whether the deviations are due to such an inaccuracy only. Anyhow, the axial angle may not be much larger than 60° as controlled in sections $\perp \alpha$. The conclusion must then be, that this epidote is very rich in iron, though not necessarily of the high percentage calculated by means of MALMQVISTs formulae from the value of $N_\gamma - N_\alpha$ given above, *viz.* *50 % [*Fe_2O_3*]*.

The epidote rock occurs within the epidolerite area yet close to the boundary between the epidolerite and the granophyre. In quite the same position a rather similar rock is found at the southern shore of Lake Storsjön. It will be shown later on that the occurence of those curious types of rock is not perhaps without consequence for the interpretation of the genetical relations of the dike as a whole.

WINGE mentions (**60**: 190) that an olivinebearing dolerite occurs at the eastern wedge of the dike, viz. WNW of Anstorp, and among his slides there is also one from this locality, showing a finegrained olivine dolerite, quite resembling that described above (pp. 289—291) as a marginal modification of the normal dolerite. The present author has visited all outcrops in the vicinity of Anstorp that may possibly have furnished the specimen in question, yet without success. Either there is some confusion, or this type of rock is of so restricted an occurence, that it may not be encountered even after intensive search. The author thinks there has been some mistake. In a small dolerite exposure immediately to the south of the three-tongued peninsula in Lake Storsjön there is, however, a rather fine-grained rock. It is not olivinebearing, but microscopically some rounded aggregates, surrounded by *pyroxene* and consisting of a *tremolitic amphibole* and *chlorite* are seen. Although uncertain, it is very difficult to resist the supposition of an *olivine* as the mother mineral. The resemblance of these aggregates to those described from Bottorp is surprising (*cf.* page 283 and fig. 23 on page 284). If this assumption holds good, it ought to imply, that the rock belongs to a transitional zone between the normal dolerite and its marginal modification. Olivine had begun to separate, but the cooling was not sufficiently rapid to be able to fix the mineral, that was not really stable in its *milieu* of formation. Most interesting is, however, that this locality is the only one, where we may possibly find an indication of the crystallization of olivine at the southern boundary of the dike.

C. **Chemical analyses.**

The chemical relations of the rather varying types of rock described above are previously illuminated by three analyses, executed by WINGE. The analyses are made of the western olivine dolerite, of the granophyre, and of an »intermediate rock», the character of which is not closer stated. In order to get a more comprehensive idea of the chemical relations, the present author had four new analyses executed. When selecting types o rock for these analyses mainly two requirements were to be satisfied, *viz.* firstly to find out rather constant types, the mineral composition of which was not affected by alteration processes of a later date, and secondly to find types most equally distributed between the silica limits of the two extremes. The latter requisite was set up in order to obtain the most representative variation diagram, but it is easily understood, that it could be met only in a rather small degree.

In the tables IX—XV below the new analyses are given and the old ones from WINGE's paper are also quoted. The analyses are arranged after increasing percentage of silica.

Table IX.

Analysis of olivine dolerite from Krustorp. Analyst: K. WINGE.

Analysis 1.

Weight-%		Mol. Prop.	Norm		Niggli's System	
SiO_2	46,54	0,776	Or	3,34	qz	−29
TiO_2	0,96	0,013	Ab	22,53	si	99
Al_2O_3	16,88	0,166	An	30,58	al	21
Fe_2O_3	3,20	0,020	Ne	1,99	fm	50
FeO	7,41	0,103	Σ sal	58,44	c	22
CaO	9,54	0,170	$CaSiO_3$	6,96	alk	7
MgO	9,77	0,244	$MgSiO_3$	4,70	k	0,11
Na_2O	3,14	0,050	$FeSiO_3$	1,72		
K_2O	0,63	0,006	Mg_2SiO_4	13,79		
P_2O_5	tr.	—	Fe_2SiO_4	5,81		
L. ign.	0,69	—	Mt	4,64		
	98,76		Ilm	1,98		
			Σ fem	39,56		
			H_2O	0,69		
				98,73		

Quantitative System: III : 5 : 4 : 4—5 — *Auvergnose.* Or : Ab : An — 3,8 : 27,1 : 69,1

Table X.

Analysis of the olivinebearing marginal facies of the central dolerite. Johannisberg. Analyst: N. SAHLBOM.

Analysis 2.

Weight-%		Mol. Prop.	Norm		Niggli's System	
SiO_2	48,20	0,803	Or	8,90	qz	−15
TiO_2	1,54	0,019	Ab	19,39	si	113
Al_2O_3	18,07	0,183	An	34,47	al	25
Fe_2O_3	1,76	0,011	Σ sal	62,76	fm	43
FeO	9,16	0,127	$CaSiO_3$	4,99	c	25
MnO	0,15	0,002	$MgSiO_3$	2,50	alk	7
CaO	9,93	0,177	$FeSiO_3$	2,38	k	0,30
MgO	5,94	0,148	$MgSiO_3$	5,00		
Na_2O	2,25	0,037	$FeSiO_3$	4,88		
K_2O	1,46	0,016	Mg_2SiO_4	5,11		
P_2O_5	0,38	0,003	Fe_2SiO_4	5,61		
$H_2O^{+105°}$	0,94		Ap	1,01		
	99,78		Mt	2,55		
$H_2O^{-105°}$	0,28		Ilm	2,89		
			Σ fem	36,92		
			H_2O	0,94		
				100,62		

Quantitative System: III : 5 : 2 : 4 — *Kilauose.* Or : Ab : An — 9,0 : 20,9 : 70,1.

Table XI.

Analysis of olivinefree dolerite from WNW. of Högsäter. Analyst: N. SAHLBOM.

Analysis 3.

Weight-%		Mol. Prop.	Norm		Niggli's System	
SiO_2	52,89	0,882	Qu	8,40	qz	−8
TiO_2	2,20	0,028	Or	10,01	si	132
Al_2O_3	14,07	0,138	Ab	22,01	al	23
Fe_2O_3	2,83	0,018	An	21,68	fm	43
FeO	9,37	0,131	Σ sal	62,10	c	24
MnO	0,15	0,002	$CaSiO_3$	5,57	alk	10
CaO	8,18	0,146	$MgSiO_3$	2,40	k	0,30
MgO	3,59	0,090	$FeSiO_3$	3,17		
Na_2O	2,63	0,042	$MgSiO_3$	6,60		
K_2O	1,67	0,018	$FeSiO_3$	8,45		
P_2O_5	0,76	0,006	Ap	2,02		
$H_2O^{+105°}$	1,44	—	Mt	4,26		
	99,78		Ilm	4,18		
$H_2O^{-105°}$	0,20		Σ fem	36,65		
			H_2O	1,44		
				100,19		

Quantitative System: III : 4 : 3 : 4 — *Vaalose.* Or : Ab : An — 13,0 : 30,4 : 56,6.

Table XII.

Analysis of a basic epidolerite from WNW. of Högsäter.
Analyst: N. SAHLBOM.

Analysis 4.

Weight-%		Mol. Prop.	Norm		Niggli's System	
SiO_2	40,76	0,679	Qu	10,32	qz	−19
TiO_2	2,20	0,028	Or	6,12	si	93
Al_2O_3	10,27	0,101	Ab	5,24	al	14
Fe_2O_3	12,28	0,077	An	22,24	fm	62
FeO	14,57	0,203	Σ sal	43,92	c	21
MnO	0,55	0,008	$CaSiO_3$	3,71	alk	3
CaO	8,47	0,152	$MgSiO_3$	1,40	k	0,52
MgO	3,30	0,083	$FeSiO_3$	2,38		
Na_2O	0,61	0,010	$MgSiO_3$	6,90		
K_2O	0,97	0,011	$FeSiO_3$	11,62		
P_2O_5	1,68	0,012	Ap	4,03		
$H_2O^{+105°}$	4,06	—	Mt	17,86		
	99,72		Ilm	4,26		
$H_2O^{-105°}$	1,15		Σ fem	52,16		
			H_2O	4,06		
				100,14		

Quantitative System: III : 4 : 4 : 3. Or : Ab : An — 18,2 : 15,6 : 66,2.

Table XIII.

Analysis of an acid epidolerite from SW. of Lake Dunsjön.
Analyst: N. SAHLBOM.

Analysis 5.

Weight-%		Mol. Prop.	Norm		Niggli's System	
SiO_2	53,98	0,899	Qu	10,20	qz	+4
TiO_2	5,50	0,069	Or	21,13	si	160
Al_2O_3	10,95	0,108	Ab	18,34	al	19
Fe_2O_3	1,79	0,011	An	9,73	fm	51
FeO	10,26	0,143	Σ sal	59,40	c	16
MnO	0,40	0,006	$CaSiO_3$	4,29	alk	14
CaO	5,03	0,089	$MgSiO_3$	2,30	k	0,52
MgO	4,64	0,116	$FeSiO_3$	1,85		
Na_2O	2,24	0,035	$MgSiO_3$	9,30		
K_2O	3,64	0,038	$FeSiO_3$	7,26		
P_2O_5	0,72	0,005	Ap	1,68		
$H_2O^{+105°}$	1,16	—	Mt	2,55		
	100,31		Ilm	10,49		
$H_2O^{-105°}$	0,25		Σ fem	39,72		
			H_2O	1,16		
				100,28		

Quantitative System: III : 4 : 2 : 3. Or : Ab : An — 35,2 : 32,4 : 32,4.

Table XIV.

Analysis of »intermediate rock» from S. of Svärdfallet.
Analyst: K. WINGE.

Analysis 6.

Weight-%		Mol. Prop.	Norm		Niggli's System	
SiO_2	60,16	1,003	Qu	19,14	qz	+35
TiO_2	0,20	0,003	Or	20,57	si	211
Al_2O_3	13,18	0,129	Ab	28,82	al	27
Fe_2O_3	8,88	0,056	An	10,29	fm	39
FeO	3,15	0,044	Σ sal	78,84	c	15
MnO	0,22	0,003	$CaSiO_3$	2,90	alk	19
CaO	3,89	0,070	$MgSiO_3$	2,50	k	0,40
MgO	1,03	0,026	Woll	0,93		
Na_2O	3,42	0,055	Mt	10,21		
K_2O	3,53	0,037	Häm	1,76		
P_2O_5	tr.	—	Ilm	0,46		
L. ign.	1,90	—	Σ fem	18,76		
	99,56		H_2O	1,90		
				99,50		

Quantitative System: II : 4 : 2 : 3 — *Adamellose.* Or : Ab : An — 23,7 : 42,6 : 23,7.

Table XV.

Analysis of granophyre from S. of Säterstugan.
Analyst: K. WINGE.

Analysis 7.

Weight-%		Mol. Prop.	Norm		Niggli's System	
SiO_2	71,51	1,019	Qu	27,48	qz	+130
TiO_2	0,10	0,001	Or	26,69	si	382
Al_2O_3	12,82	0,125	Ab	35,63	al	40
Fe_2O_3	2,09	0,013	An	2,50	fm	16
FeO	1,40	0,019	Σ sal	92,30	c	6
MnO	—	—	$CaSiO_3$	1,04	alk	38
CaO	1,09	0,020	$MgSiO_3$	0,40	k	0,41
MgO	0,17	0,004	$FeSiO_3$	0,66		
Na_2O	4,24	0,068	Woll	0,23		
K_2O	4,52	0,048	Mt	3,02		
P_2O_5	tr.	—	Ilm	0,15		
L. ign.	1,23	—	Σ fem	5,50		
	99,17		H_2O	1,23		
				99,03		

Quantitative System: I : 4 : 1 : 3 — *Liparose.* Or : Ab : An — 38,4 : 54,4 : 7,2.

It might be necessary to discuss in a few words some of the figures given by the analyses above. First of all, of course, some reservation is needed when comparing the analyses of 1896 by WINGE with those made by SAHLBOM in 1931. It must be borne in mind, that the analytical methods have been largely improved during this period of 35 years, and especially the older evaluations of Na_2O and K_2O as also the distribution of iron between the ferrous and the ferric stages deserve some cautiousness. In WINGE's analysis of the olivine dolerite, there is also a rather large deficiency in the total sum, which is, according to WINGE (**60**: 195), due to an incomplete precipitation of TiO_2.

Considering the analyses of 1931 there are also some facts worth of attention. Thus the analyses 2 and 3 fall very close to the boundary between two classes of the quantitative CIPW system (**57**). Properly they both belong to class II, the proportion $\frac{100 \text{ sal}}{\text{sal} + \text{fem}}$ being $63{,}_3$ and $62{,}_8$ respectively, whereas the upper limit of class III lies at $62{,}_5$. Referring those rocks to class II, however, we find no. 3 being co-ordinated as *Tonalose* with granites, tonalites and andesites, whereas no. 2 enters together with monzonitic and syenitic rocks under the name of *Akerose*. The two rocks are, however, true dolerites, and thus it might be justificable in this case to adjust the limits of classification as to introduce the rocks into the class III where they will find »natural companions». Thus the rock 3 is brought into the subrang *Vaalose*, where is also found a dolerite from the Euganées (**43**: 331), the analysis of which is almost identical with the former one.

Another fact worth noting is that the analyses 4 and 5 fall within subrangs, who are without any representation among the rocks of WASHINGTON's tables (*loc. cit.*). No. 4 shows an abnormally high percentage of iron, whereas in no. 5 the high percentage of titanium is most conspicuous. In spite of its $26{,}_{85}$ % of iron oxides rock 4 shows no extraordinary accumulation of ore minerals, the mafic minerals being, however, rather abundant. Indeed, it was the microscopical investigation of this rock, that led to the conception given on pp. 293—294 of the succession of pyroxenes and of secondary amphiboles.

Beside the high percentage of titanium the analysis no. 5 shows another interesting feature. Its silica percentage exceeds that of the true dolerite no. 3 with $1{,}_{09}$ % only. Certainly the former rock develops a fairly characteristic doleritic texture with divergent feldspars, but the dark minerals are quantitatively very restricted, being substituted by abundant quartz and orthoclase micrographically intergrown. Indeed the rock makes the impression of belonging to the more acid members of the sequence, and its low percentage of silica is thus quite surprising.

It has been considered convenient to point out some peculiarities presented by the analyses already in this connection, and in the following discussing part of this paper they will be more fully treated. In course of that part an explanation of some apparently abnormal relations will also be attempted.

II. Genetical discussion.

It has already been pointed out above (page 245) that the only attempt to explain the formation of the Breven dike was made by WINGE (**60**), who assumed »an eruption of an already previously heterogeneous magma, differentiated in the magma reservoir». From WINGE's paper it is not clear what he thinks of the mode of the original differentiation, nor does he state clearly, whether he supposes the eruption to have proceeded in one or several casts. Comparing his statements concerning other theories of the formation of composite dikes, however, one gets the impression that he assumed that the dike was formed by a single eruption.

In course of the investigation carried out by the present author, however, a lot of facts have presented themselves, that may hardly be brought into accordance with WINGE's opinion. In the following pages some data are put together that — according to the author's apinion — especially bear upon the genetical interpretation of the dike.

A. Petrological data.

The most striking feature brought out by a close study of the Breven dike, is the marked difference between the western part, the olivine dolerite of which is fairly uniform all over its extension area, and the central and eastern parts of the dike, which show a veritable confusion of several rock-modifications. Between those two areas there are no petrological transitions at all, the olivine dolerite that is sometimes met with even within the eastern part of the dike being, as already stated, of quite another type than the western one. It is simply a fine-grained marginal modification of the olivinefree dolerite, whereas the western olivine dolerite itself already through its coarse texture rejects the assumption that even here a chilled facies might be represented. Between the easternmost outcrops of the western olivine dolerite and the westernmost outcrops of the central part of the dike there is — it is true — an area of a length of about 800 m. which is wholly devoid of exposures, but it seems hardly probable that this area should conceal a transition between the types of rock at either side. On the contrary, one gets the positive impression that there is really a discontinuity in the development of the rocks. If this opinion holds good, it becomes necessary to keep at least two problems apart, *viz.* firstly the relations between the western olivine dolerite and the rock sequence of the eastern and central parts of the dike; and secondly the mutual relations of the components of the rock sequence last mentioned. It is true, that even within the area of the western olivine dolerite there is at one locality found a rock of a rather diverging character — as stated already on page 280 foll. — but to this rock and to the consequences probably implied by its occurrence we shall find opportunity to return later on.

If we now turn to the central and eastern parts of the dike, a study of the summary map (Plate XII) as well as of the sketch-maps on pages 290 and 299 reveals two most conspicuous facts. Firstly one may observe the rather regular bilateral symmetry of the distribution of the rocks, there being a central granophyre portion and two marginal zones of dolerite and epidolerite. Betwen Lake Hinnersjön and Lake Storsjön as well as to the south of the latter the marginal zones disappear, the granophyre joining directly the wall rock, but still more to the east they are developed again. The other conspicuous fact is represented by the rather large area occupied by the granophyre as compared with the total area of the dike.

As to the bilateral symmetrical structure it seems to the author, as if it could hardly be brought into accordance with the assumption of a single eruption of an heterogeneous magna. Such a process would most probably give rise to a very irregular distribution of the rocks and the occurrence of numerous inclusions and xenolithes etc. or to a banded structure showing alternating acid and basic bands. It is true, that the magma is supposed to be originally entirely differentiated into, say, two distinct portions, but the power involved in an eruption would most probably be sufficient to stir rather thoroughly the material forced up. The author does not attach too great importance to that admission, but wishes to point out, that the very structure of the dike seems to contradict WINGE's opinion, such as it has been understood above.

As is further seen on the summary map, the granophyre rocks occupy a rather important part of the total area of the dike. A planimetric calculation is, of course, of no special importance, as the present surface represents only one single section through the dike, but perhaps, nevertheless, it would be of some interest. It may be stated that about 40 % of the total area is occupied by purely granitic rocks, though only the all but leucocratic types were included into that group. Quantitatively next to the granophyre follow the western olivine dolerite and the epidolerite, whereas the olivine-free dolerite is of a very restricted extension. This quantitative distribution — even when admitting the difficulty of drawing general conclusions from this measurement in a single section — was hardly to be expected when assuming either a differentiation *in situ* or a single intrusion of a previously heterogeneous magma.

Finally, when considering the mutual relations of the different components of the central and eastern part of the dike one may observe — as already mentioned — that the transition between the dolerite and the granophyre is by no means so continuous as was stated by WINGE. From the dolerite one may follow a rather quiet evolution towards the innermost portions of the epidolerite, an evolution appearing mainly in an increasing acidity and an enrichment of hydrous minerals. All the time, however, the doleritic texture is fairly well preserved and the quantity of the dark constituents does not decrease under a certain limit, which is not all too low. Then there is a sudden change — the granophyre shows no trace of relic doleritic textures and is all but devoid of dark minerals. It is quite impossible to find any continuous transition here.

Summing up the data mentioned above, it seems to the author as if they were all in better accordance with another interpretation than that suggested by WINGE, *viz.* that this composite dike was formed as a result of not one but several intrusions. One intrusion must be made responsible for the western olivine dolerite, another for the granophyre, and still another for the olivinefree dolerite. According to this conception the epidolerite ought to be interpreted as a hybrid rock between the two types last mentioned.

In what order, then, have the intrusions taken place and how is the formation of the hybrid rocks to be understood? Concerning the chronological order of the granophyre and the olivinefree dolerite there are above all the following facts to be considered:

1:o. The granophyre is of an almost constant composition all over its extension area. It shows no transition to the epidolerite and no contact phenomena produced by the dolerite.

2:o. The dolerite changes continuously into epidolerite, the transition characterized mainly by a decreasing percentage of anorthite of the plagioclase, an enrichment of minerals with volatile compounds and an increasing acidity and alkalinity, the latter being conspicuous by an increase of the percentage of K_2O, absolutely as well as relatively.

3:o. Aplitic dikes are observed, which cut the epidolerite along sharp boundary lines. The microscopic investigation seems to bring out, that the rock of those dikes is intimately connected with the granophyre (pp. 298 and 299).

4:o. At one locality the granophyre occurs outside the chilled margin of the dolerite (p. 298).

5:o. Within the epidolerite area, but close to the boundary against the granophyre, two curious types of rock have been observed, one (pp. 300 and 301) consisting of mainly epidote, the other (p. 306) showing a rather surprisingly high percentage of iron.

6:o. At two localities small irregular portions of rock are found within the epidolerite area, which show partly an aplitic, partly a micrographic texture and a composition quite similar to that of the granophyre (p. 300).

The first five observations strongly favour the opinion, that the granophyre was intruded later than the dolerite, whereas the observation no. 6 apparently contradicts such an opinion. However, it might be impossible to neglect the first five proofs, and it seems thus necessary to find another explanation of the granophyre portions in the epidolerite, than that they should be fragments of a rock earlier congealed. Indeed, it seems by no means impossible that the dolerite, when forcing its way upwards, might have carried with it portions of granitic composition which had already separated from the main magma. Or, the »inclusions» may represent parts of the preexisting roof which were recrystallized by the heat of the ascending doleritic magma. The lack of any indications of a resorbtion might be explained by the very probable assumption that the granophyre portions now observed are only remnants of larger ones which were partly resorbed. As the epidolerite shows rather wide variations of composition even within fairly small areas it is hardly possible to ascertain, whether it shows any traces of assimilation in the immediate neighbourhood of the granophyre portions.

The remaining facts numbered above hardly need any further explanation as to their bearing upon the problem, but the observations 4 and 5 might perhaps conveniently be treated somewhat more in detail. Beginning with no. 4 it seems hardly probable that the dolerite if intruded later than the granophyre should show a chilled margin against the latter, for even if a *hiatus* between the two intrusions must be assumed, it ought not to have been of so long a duration, that the granophyre might have cooled down completely before the dolerite was intruded. Thus it seems most probable, that the chilled marginal zone was produced by the cool wall rock, and that a portion of granophyre was then squeezed in between the epidolerite and the wall rock. The lack of contact phenomena in the dolerite at this locality is easily explained by the small quantity of granophyre and by the more rapid cooling effected in the immediate neighbourhood of the wall rock.

As to the curious rock varieties mentioned under no. 5 above, they are not easily explained. It must be considered quite impossible, however, that the enrichment of epidote and iron respectively, might be due to a direct migration from the extremely salic granophyre magma. On the other hand, the extreme concentration of iron and lime might hardly be explained without assuming a pneumatolytic action. 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 rather easy to remove, which then at some places might be deposited in the way already described. On the other hand, if assuming the dolerite to have been intruded later than the granophyre, those rocks may hardly be explained without assuming a more or less mysterious differentiation, which would really be no explanation at all. Thus the mere occurrence of these abnormal rocks, too, strongly favours the same opinion as gathered from the first four points above.

Consequently, it seems to be reliably proved that the granophyre portion of the magma was intruded later than the doleritic one. Such a succession is commonly found in large massives built up by several successive eruptions, whereas dikes and other minor intrusives most usually show a development in the opposite direction, *viz.* towards an increasing basicity (**21**: 117). In a dike of such dimensions as the one treated in this paper, however, it seems by no means impossible that the evolution might have proceeded in the direction generally found in large massives. HARKER has, indeed, stated (**22**: chapters XII and XIII) that in the Skye area, there is a great number of dikes that show early marginal zones of a basic composition and a central granophyre area, thus exhibiting relations quite analogous to those of the Breven dike.

The chronological order of the granophyre and the olivinefree dolerite being thus satisfactorily ascertained, there still remains the question where to place the western dolerite in the scheme of time and it has not been possible for the author to find any facts that might reliably solve that problem. However, one might be entitled on purely petrological reasons to consider it as the result of a still earlier eruption and thus we are forced to assume the following succession of the intrusions:

1:o. Olivine dolerite.
2:o. Olivinefree dolerite.
3:o. Granophyre.

As to the formation of the hybrid rock — the epidolerite — it ought to be sufficient to refer to the statements already given about its main line of evolution. Here we must consider a rich supply of volatile compounds (amphibolization of the pyroxenes), potassium (formation of biotite) and silica (quartz developing both independently and in micrographic intergrowths with the feldspars) and the whole process must be interpreted as a very strong pneumatolytic action effected by the intruding granophyre magma. The fact that the granophyre itself shows no changes in the neighbourhood of the epidolerite is a matter of course; as the latter is an earlier member of the series of differentiation, it might hardly be assimilated by the granophyre.

Still there remain the questions about the mechanics of the repeated intrusions and about the origin of the different magmas. It is of course very difficult if not even impossible to propose a decisive solution of the last question, yet it seems most probable that the successive intrusions emanated from the same magma reservoir and were brought to action at different stages of the differentiation of the magma. How this differentiation is to be understood must, however, be an open question. Recently HOLMES (**24**) has announced a somewhat different view on the origin of those inhomogenities of magmas leading to the very frequent association of acid and basic rocks, e.g. granite — gabbro, granophyre — dolerite. From a study of the central complexes of North-western Scotland, the so-called cone-sheets and ring dikes, he concludes that they have emanated from a cupola-shaped magma reservoir 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 those magma cupolas may always maintain a temperature sufficiently high to permit of an assimilation of the roof and this assimilation would lead to a gradually changing composition of the fluid magma. It seems to be rather difficult to find any decisive proofs for or against this very fascinating hypothesis. In this connection it should be pointed out that the Breven dike in many cases shows rather great analogies to the minor intrusions described from Scotland (*cf.* for instance **36**) and it would be very interesting to make an attempt to trace those analogies still farther. Perhaps some of the dolerite dikes of middle Sweden might be associated to central complexes of the same type as those of Scotland. It is the author's intention to take this problem under consideration more fully in a following paper.

As to the mechanics of intrusion, there are also several ways open for an explanation. Taking up an old hypothesis, HÖGBOM (**25**: 224) assumed when studying composite dikes of quartz-porphyry at Rödön, that the fissure was first laterally coated by basic rocks, after which the remaining open fissure in the centre was filled up by acid magma. It seems, however, hardly probable that a fissure of the length and the width of the Breven dike might have remained open during any longer time. It is thus perhaps more appropriate to assume that it was first filled completely by a basic rock and then broken up again by a more acid magma. The western olivine dolerite may very well be held apart from the other rocks — it might have intruded separately in a more or less latent fissure and was then not affected by later intrusions. This assumption is strengthened by the fact that within the central and eastern part of the dike there is nowhere found any olivine dolerite of the same type as the western one.

A summing up of the view about the formation of the Breven dike gained on petrological grounds may thus be formulated as follows:

Several successive intrusions operated, emanating from a common magma reservoir. Because of the differentiation gradually proceeding (or because of assimilation) the material in this reservoir changed its composition at every intrusion. Firstly an olivine dolerite was intruded into one part of a more or less latent fissure. The next magmatic manifestation led to an intrusion of a normal dolerite into another part of the same fissure. A third intrusion of granitic material strongly enriched in volatile compounds broke through the dolerite already congealed, effected upon it a strong pneumatolytic action, the dolerite being simultaneously cut by aplitic dikes associated with the granite and finally it congealed as a central granophyre portion.

B. **Chemical data.**

In order to picture perspicuously the chemical relations of a series of cognate rocks so-called variation diagrams were used rather early. Such a diagram is a rectangular coordinate system in which the weight percentages of SiO_2 are plotted against the weight percentages of the other oxides. Especially HARKER has pointed out (**21**: 118) that the curves obtained by connecting the different projective points of the same oxide of a rock suite do not produce a casual shape if the rocks are genetically connected, but tend to assume ideal forms which are upon the whole common for every rock suite. HARKER (**21**: 123) has further shown that by using such variation diagrams it may be settled, whether all members of a rock sequence are coordinated or whether some of them are subordinate in relation to the others or not even belong to the proper line of differentiation. An especially elucidating application of this method is quoted by HARKER concerning some rocks of the Oslo field. BRÖGGER first considered the lardalite and the åkerite as coordinated with the essexite, the larvikite, and the other rocks, but later on he found that the lardalite is only a derivative from the larvikite magma and the åkerite a derivative from the essexite magma. If a variation diagram including all these rocks is erected, the lardalite and the åkerite cause two very strange bends of the curves which, on the other hand, assume a very smooth shape if the projective points of those two rocks are left aside. Of course, such a treatise of the Breven Rocks would be very elucidating. In fig. 27 on page 314 a variation diagram is given which is based upon all analyses available. Its curves are all of a very irregular shape, and, furthermore, they do not at all argree with the general curves deduced from a very comprehensive empiric material. If, however, the projective points of the analyses 2, 4 and 5 are left aside and the remaining points connected by curves, the latter assume almost exactly the shape and the curvature that is generally met with in diagrams of coordinate members of a sequence of differentiation. Such a diagram is given in fig. 28 on page 315. The three analyses that do not fit into the diagram represent the olivinebearing marginal facies of the eastern dolerite (analysis 2) and the type of rock that has been previously interpreted as a product of pneumatolytic alteration

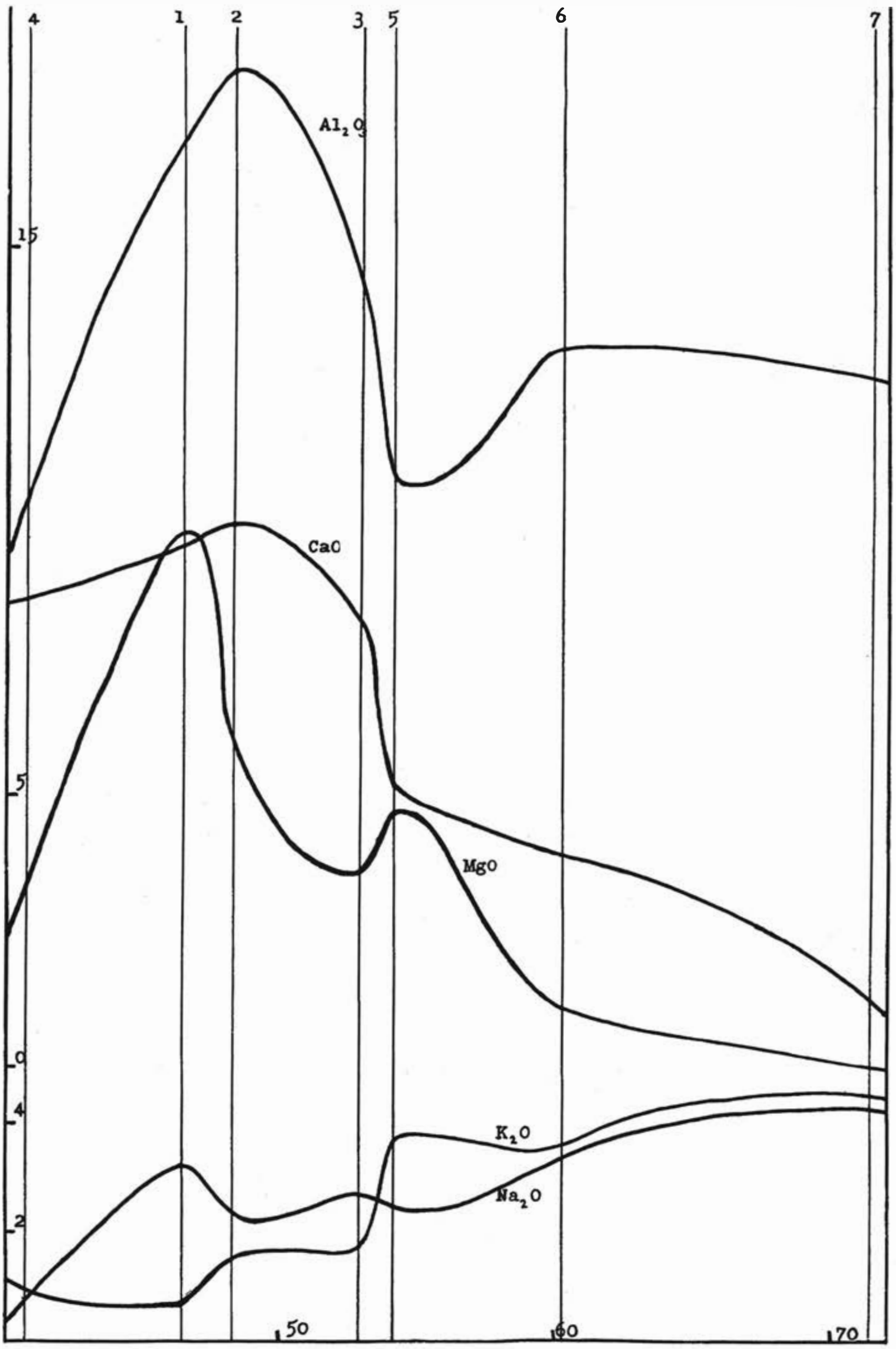


Fig. 27. Variation diagram of the Breven rocks including all analyses available.

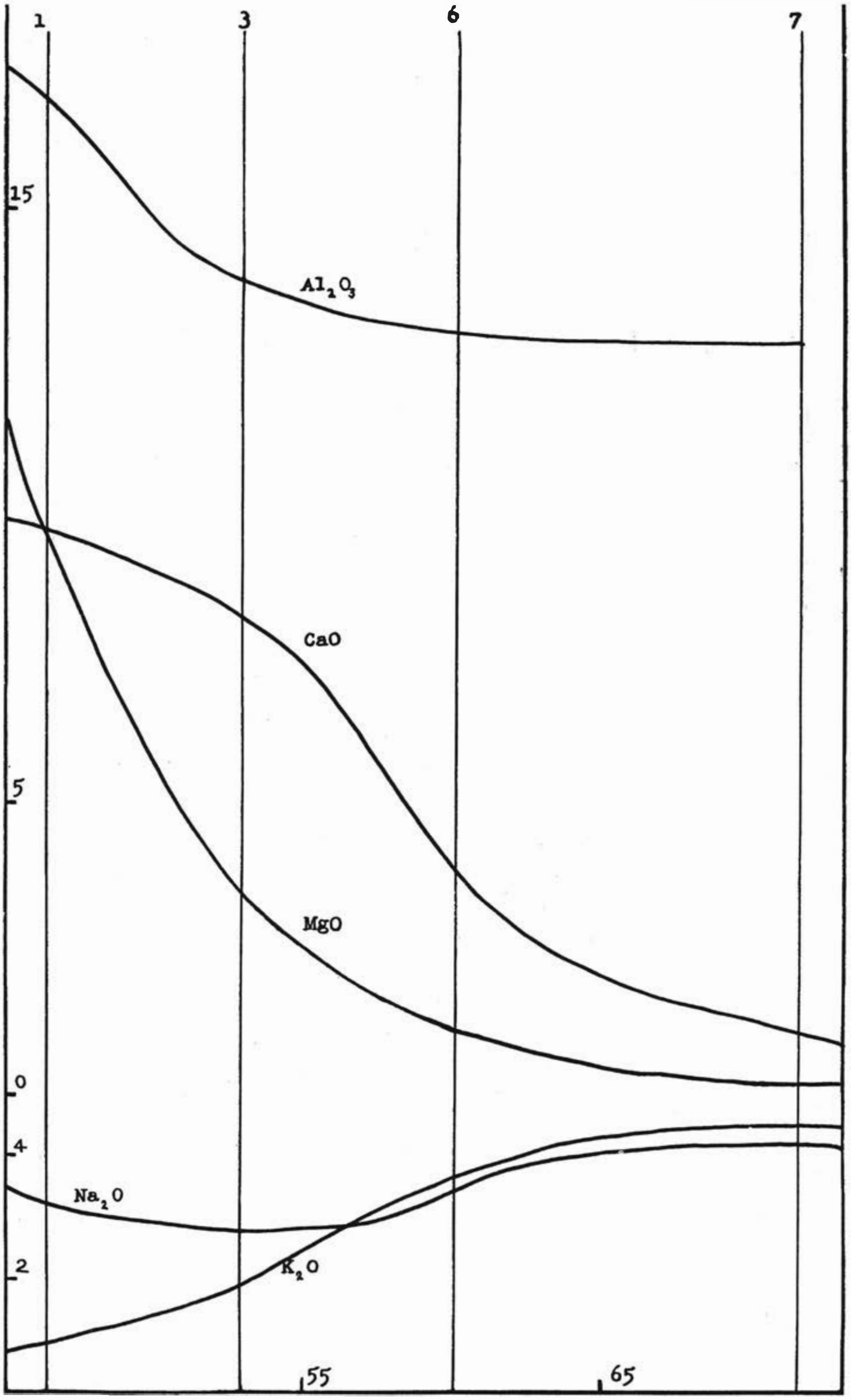


Fig. 28. The same diagram as in fig. 27 the analyses 2, 4 and 5 being excluded.

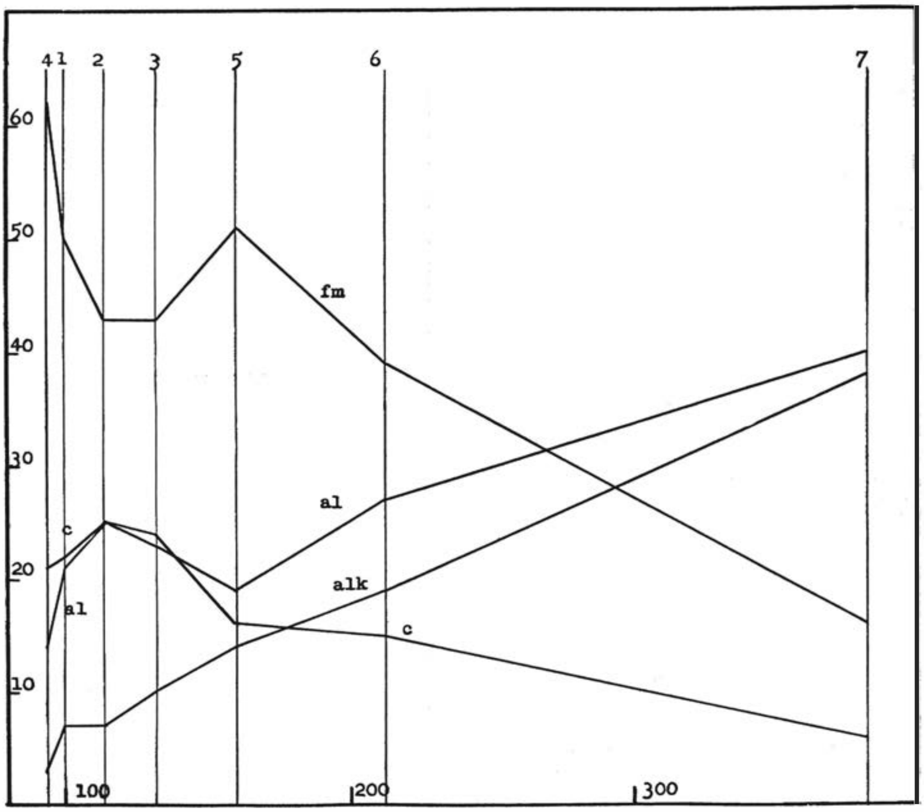


Fig. 29. Diagram of the NIGGLI reference values of the Breven rocks including all analyses available.

(analyses 4 and 5). In the first case there is most probably a perfect analogy to the relations of the Oslo rocks quoted above, *viz.* the rock in question does not belong to the main line of differentiation but to a subordinate one proceeding from the olivinefree dolerite. In the second case, however, that explanation may hardly be valid as is understood from the fact that an attempt to put the dolerite (analysis 3 above) together with the analyses 4 and 5 in a variation diagram resulted in curves of a quite irregular shape. It seems, thus, that there is no other explanation left, than that the rocks 4 and 5 do not at all belong to the sequence of differentiation but represent types formed by an irregular supply of material to an original member of this sequence, probably the dolerite. Of course, also some material might have been carried away.

It may be objected that in a diagram based on seven analyses only — as in the present case — the elimination of any analysis must imply an increasing smoothness of the curves, but several attempts have shown that only the elimination of the analyses 2, 4 and 5 leads to curves of a satisfying shape.

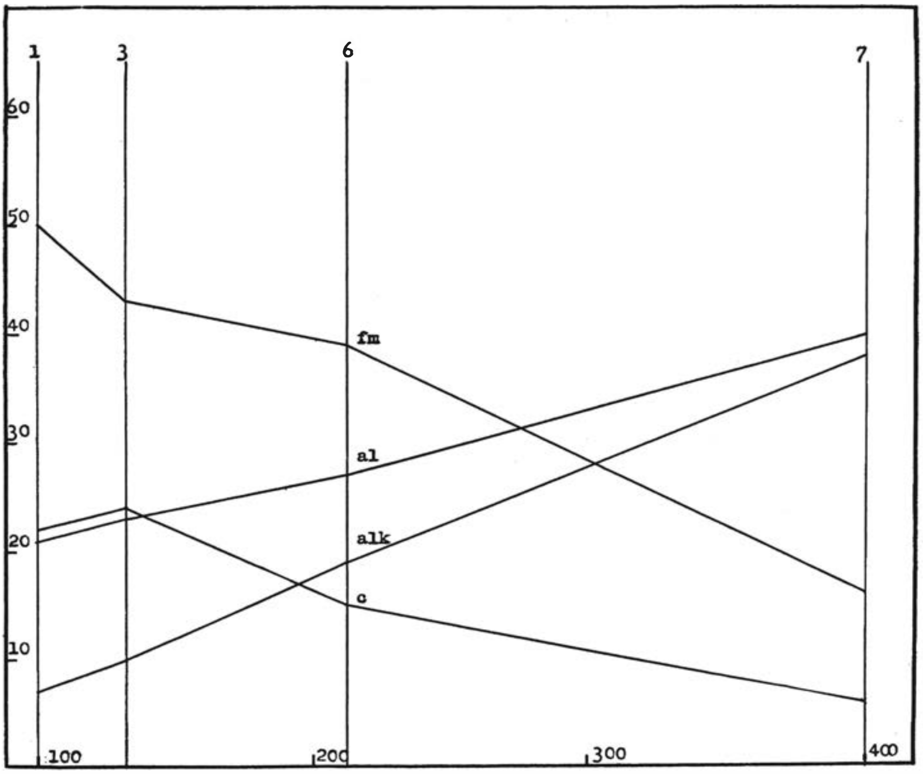


Fig. 30. The same diagram as in fig. 29 the analyses 2, 4 and 5 being excluded.

As to the rocks that give the satisfying variation diagram of fig. 28, they consist of the western olivine dolerite, the olivinefree dolerite, the granophyre and a rock that was named »intermediate rock» by WINGE (**60**: 195). It is not quite in accordance with the interpretation just suggested that this »intermediate rock» fits into the diagram. But the author has had the opportunity of examining the slides prepared for WINGE's investigation and thereby it was found that not less than three of the four slides of »intermediate rock» from the locality in question must be classified — in the present author's opinion — as belonging to the granophyre. The only difference between them and the typical granophyre is a slightly higher percentage of *biotite,* but it is quite clear, that such accidental variations must exist in a rock of so wide an extension as the granophyre. Thus it might be considered as very possible that the analysis given by WINGE refers to such a granophyre rich in biotite and then the apparent controversy disappears.

In the diagrams the iron oxides are not plotted, as they occur mainly as ore. It is the author's opinion that in such a case it is not convenient to base variation curves upon the values of these oxides, as it cannot be reliably stated, whether the ore really formed primarily in the place where it is now observed or not. This uncertainty is, of course, especially pronounced as regards such a rock as no. 4 with its rather exceptionally high content of $FeO + Fe_2O_3$.

In this connection it should be pointed out that such rock sequences, as might most possibly be considered as formed by simultaneos eruptions of several different magma portions, have been found to give variation diagrams showing a tendency of a rectilinear development of the curves. Such diagrams were found by GEIKIE and TEALL to be valid for the gabbro of the Skye area (**19**) and by HARKER for the ultrabasic rocks of the Isle of Rum (**20**). At the locality first mentioned there was also observed a well-developed banded structure such as would be expected in the case of an eruption of a heterogeneous magma (cf. page 308 above). The absence of every indication of a rectilinear development of the diagrams given above (pp. 314—315) thus ought to be still another proof of the impossibility of assuming a simultaneous eruption of different magma portions.

In order to give still another illustration of the petrological and chemical variations within the area treated, two diagrams were furthermore constructed on the basis of the NIGGLI reference values (**33**). The first diagram shows that the curves through the projective points of all analyses have a rather irregular shape (fig. 29 on page 316), whereas the curves obtained after exclusion of the analyses 2, 4 and 5 are of an all but rectilinear development (fig. 30 on page 317). Even though it must be admitted that we are not quite well-informed as to the significance of those different types of curves, it ought to be ascertained by the diagrams that the rocks 1, 3, 6 and 7 may be put together as belonging to the same line of differentiation, while the rocks 2, 4, and 5 fall outside it. It is true, that there is a rather wide interval along the silica line between the analyses 6 and 7, and thus a slight change of the projective points of no. 7 would imply but a small disturbance of the curves. Thus perhaps a rather great number of granites would fit into the diagram as well as the Breven granophyre, but this hardly reduces the validity of the conclusion arrived at above.

Finally in fig. 31 on page 319 all analyses available are projected into the c-alk-fem-triangle. From this figure the same fact may be gathered as was already found on petrological grounds, *viz.* that the rocks 1—6 are closely related, whereas no. 7, the granophyre, falls at a considerable distance from the rest and is separated from them by a rather wide field of discontinuity containing no transitional rocks.

A summing up of the conclusions gained from the chemical data may thus be formulated as follows:

The olivine dolerite, the dolerite and the granophyre belong to the same main line of differentiation. The olivinebearing dolerite of the central and eastern parts of the dike belongs to

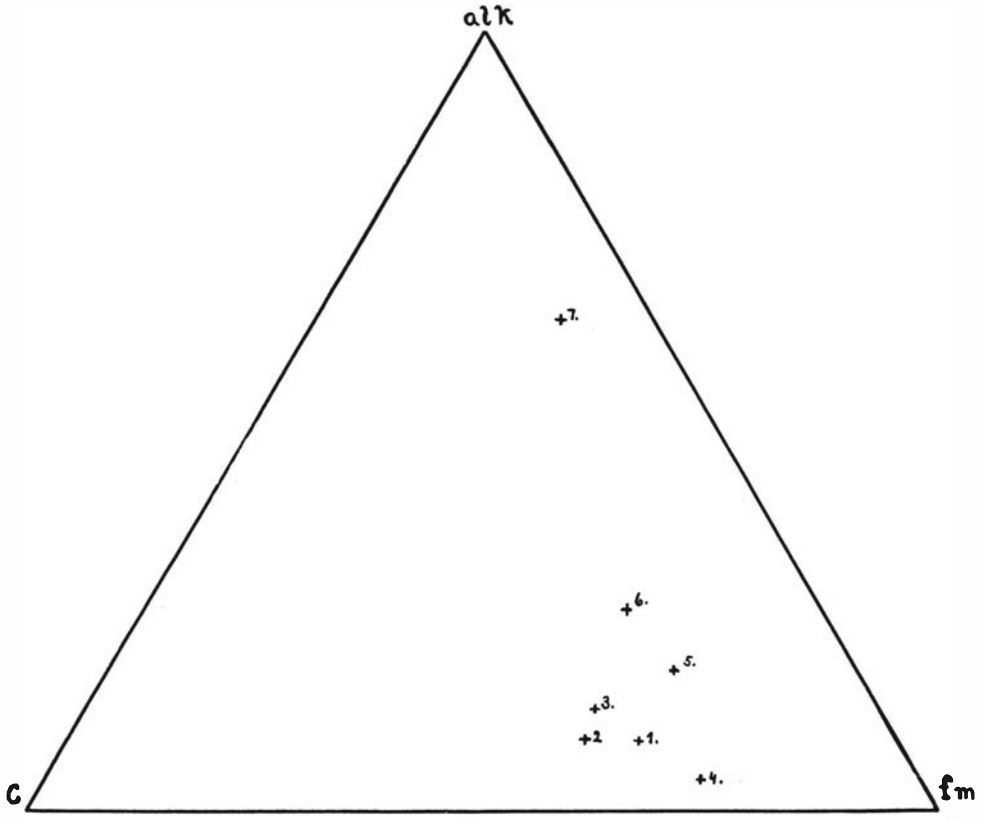


Fig. 31. The analyses of the Breven rocks projected into the c-alk-fem-triangle.

1. Olivine dolerite. Krustorp.
2. Olivinebearing marginal *facies* of the dolerite. Johannisberg.
3. Olivinefree dolerite. WNW. of Högsäter.
4. Basic epidolerite. WNW. of Högsäter.
5. Acid epidolerite. SW of Lake Dunsjön.
6. »Intermediate rock.» N. of Svärdfallet.
7. Granophyre. S. of Säterstugan.

a side line of differentiation beginning at the olivinefree dolerite. The epidolerite may hardly find any place in the series of differentiation but was most probably formed by a later alteration of the dolerite. The diagrams seem to indicate that a single eruption of a heterogeneous magma cannot be assumed.

Comparing this summing up with the one given on page 312—313 one finds that they agree in every respect. Before forming a decisive conclusion from this convergence of several data it ought, however, to be considered whether the geological relations may give any reasons for or against the interpretation that has hitherto proved most natural.

C. Geological data.

The only geological observation that — in the author's opinion — may be bearing upon the genetical interpretation, is the one mentioned on pp. 248—251 about the stroke of outcrops at Bottorp showing a *habitus* of surface congealing. There ought to be no doubt as to their character of real superficial phenomena, and from that fact some very important conclusions may be drawn. Those surface rocks occur close by and in contact with the normal western olivine dolerite, which shows every sign of having congealed at an intermediate depth at least. The logical conclusion must be that two different eruptions have taken place here. Most probably the normal olivine dolerite was first erupted and later on the effusive rock. Between those two eruptions there must have been a *hiatus* sufficiently long to allow denudation to carry away all the rock material which once covered the section now visible and which has produced the *habitus* of congealing at an intermediate depth displayed by the rocks of this section.

Those relations thus seem to indicate that at this locality several — at least two — eruptions took place and that a considerable *hiatus* of time passed away between them, but it would perhaps be rather hasty to conclude from this fact only that the other types of rock of the dike, too, must be due to several different epochs of eruption. There is, however, another fact that, strictly considered, seems to favour the same opinion, and that will now be treated.

The dike is, as has already been mentioned, of rather considerable dimensions attaining at some places a width of 1200 m. If we assume that such a dike was formed by an eruption following a fissure and reaching the surface, the walls would run roughly parallel. On the other hand, if the eruption follows a zone of weakness in the earth's crust and does not reach the surface, the eruptive force must decrease the more the magma approaches the surface and the result would be a dike of a slightly lenticular cross-section. A necessary condition for the development of a section now at surface of the width mentioned above would then be that denudation might carry away firstly the covering rock material and secondly the upper parts of the lens down to a depth where the width in question is attained. It is, however, easily understood that this would imply an amount of denudation of a rather improbable if not even impossible measure within the time at disposition.

Assuming that the magma really reached the surface, the problem comes out much simpler. In that case it must only be supposed that the denudation was of such an amount, that the section now visible has laid bare the more deap-seated equivalents of the originally existing effusive rocks, a condition that may be satisfied without any improbable assumptions.

Neither of the data mentioned above may be considered as a decisive proof, but their convergence ought to allow of the statement that the geological facts, too, favour the assumption of several eruptions, the material of which most probably reached the surface, where it formed effusive rocks which are now obliterated almost entirely. It should also be pointed out that recent eruptions *e.g.* in Iceland show that a fissure that has been filled by ascending lava thus forming a dike, may often once more serve as a channel, through which lava is brought up to the surface.

Even if we accept this interpretation there remains, however, still some ambiguity as to the significance of the geological data. How is the effusive rock previously mentioned to be understood? It has been made probable above that it is younger than the western olivine dolerite, but its relations to the other rocks of the dike are still obscure. It may be associated genetically with the olivinefree dolerite or it may be quite independent of it but for the common magma reservoir. The first assumption is contradicted by the opinion gained on chemical grounds, *viz.* that the granophyre is younger than the olivinefree dolerite, for experience seems to show that granophyres and related rocks generally congealed at a rather shallow depth (cf. **4**: 165—167), whereas the dolerite in question seems to have congealed at an intermediate depth. Thus we are compelled to assume a *hiatus* even between the formation of these two rocks, a *hiatus* that ought to have been sufficiently long to allow of an obliteration even of the small effusive remnants now observed if they wery directly equivalent to the dolerite, all the more as there are no signs indicating that they were in any way protected from denudation. From this reason it seems most likely that the fine-grained olivine dolerite must be considered as the result of a special phase in the formation of the dike probably representing the last magmatic manifestation. However, no rock is observed that might be considered as a deeper equivalent of this effusive facies, and thus we must assume, either that this small effusive relic covers its own channel of supply or that the latter is not exposed. Anyhow, this channel must be of a much smaller extension than that of the other rocks, and the first explanation suggested is in full accordance with the possibility mentioned on page 312, *viz.* that the western olivine dolerite (including the effusive rock) might be entirely separated from the rest of the dike. Of course, it was forced up in one part of the same fissure as was used by the other rocks, but not a single fact has been met with that would compel us to the assumption that — except for the common magma reservoir — the rocks of the western part of the dike are in any way associated with or affected by those of the central and eastern parts. It must, however, be admitted that there is also no fact observed that makes the assumption of such a distinction between the two parts of the dike necessary. The author only wishes to emphasize that all possibilities of this distinction seem to exist.

According to the above statements we must assume the following order of differentiation (extrusion):

1:o. Coarsegrained olivine dolerite.
2:o. Olivinefree dolerite.
3:o. Granophyre.
4:o. Finegrained olivine dolerite.

Still there remains the question whether such a series is in accordance with the experiences gathered from other localities. As far as the author has been able to find, it was v. RICHTHOFEN who first pointed out that there might be traced a certain regular succession of the different eruptions within the same area. On the basis of investigations in western America he found the following series (**37**):

1:o. Propylite, 2:o. Andesite, 3:o. Trachyte, 4:o. Rhyolite, 5:o. Basalt.

Later on it was found that this scheme is of a rather vide application. Thus BRÖGGER (*cf.* **11**: 163) found the following series to be valid for the eruptives of the Oslo field:

1:o. Melaphyre, augite porphyry, gabbro-diabase.
2:o. Rhombporphyry.
3:o. Quartzsyenite.
4:o. Granite.
5:o. Proterobase, diabase.

Studying the volcanics of the Velay area of Central France BOULE (**9**) found the following succession:

1:o. Basalt, 2:o. Trachyte, 3:o. Labradorite, 4:o. Andesite, 5:o. Phonolite, 6:o. Basalt.

Those examples might easily be multiplied. Almost at every place where the different types of rock of a volcanic cycle have been studied, it has been stated that the action began with magmas of an intermediate or basic composition, which were followed by more acid magma and finally the volcanic manifestation was finished by a renewed eruption of basic material. Thus it is clear that the hypothesis suggested above concerning the Breven dike is highly favoured by experience.

A summing up of the conclusions gained from the geological data may thus be formulated as follows:

The fissure now occupied by the Breven dike most probably on several occasions served as a channel of supply for lava, which reached the surface where it congealed. The volcanic cycle is represented by the following successive extrusions: 1:o. olivine dolerite, 2:o. olivinefree dolerite, 3:o. granophyre, 4:o. olivine dolerite. (The names of the rocks refer to the results now visible of the magmatic manifestations, no matter which was the orignal superficial rock.) Between 2 and 3 above all but also between 3 and 4 there was a hiatus during which denudation began to work thus uncovering the more deep-seated equivalents of the effusive rocks resulting from the phases 1, 2 and 3. The rocks of the phase 3 probably represent a somewhat higher section than those of the phases 1 and 2. Finally the last phase of the cycle began, representing a rather restricted extrusion of 4, the results of which are still to be seen as a few effusive remnants.

D. **Summary.**

Comparing the last summing up with those given on pp. 312—313 and 318—319 one finds that they all agree in every essential respect. In the last one only one statement is new, *viz.* the opinion that the whole dike is the result of a superficial volcanic activity. This opinion is favoured by a great many geological data and must be considered sufficiently proved although neither petrological nor chemical observations speak in favour of it. In all other respects, however, the conclusions gained on widely different grounds show such a convergence, that there ought to be no doubt as to the validity of the interpretation suggested. On risk of being charged with reiteration the author ventures to recapitulate the essential points of this interpretation:

The parts of the Breven dike now visible represent a section of intermediate depth through a fissure that has served as a channel for a series of extrusions belonging to the same volcanic cycle. The material brought up by the different eruptions most probably emanated from a common magma reservoir and the different types of lava were exponents of the normal line of differentiation within that reservoir. Those lavas in chronological order had a composition corresponding to the following rocks:

1:o. Olivine dolerite.
2:o. Olivinefree dolerite.
3:o. Granophyre.
4:o. Olivine dolerite.

The granophyre when ascending effected a strong pneumatolytic action upon the olivinefree dolerite, which thus to a large extent was altered into an amphibole-rich, biotite-bearing and somewhat alkalic intermediate rock, for which the name epidolerite is suggested. The latest olivine-dolerite was extruded only in a rather restricted amount and after the epoch of denudation that uncovered the more deep-seated equivalents of the rocks.

Concluding remarks.

The investigation of the petrology and the genesis of the Breven dike given above is so far incomplete as there have been given no hints of the geological age of the dike. The author believes, however, that this problem cannot be solved on the basis of this special investigation alone but that the solution must be sought for by a close comparative study of the geological and petrological relations of the dolerite dikes of middle and southern Sweden (and perhaps of Finland) in general.

Hithertoo the ages of our dolerites — when not immediately clear from their field relations to other eruptives or sediments of a known age — have been determined mainly by two different methods. Partly a pronounced petrological similarity has been considered as a proof of a common age, partly one has tried to ascertain the age of the fissures filled with the eruptives thus determining simultaneously the age of the latter, as the fissuring and the eruptions generally ought to be due to the same force. The first method was used extensively by TÖRNEBOHM (**49**, **50**), while the second one has been recently applied to Swedish dolerite dikes by ASKLUND (**2**).

On the basis of a comprehensive study of the fissures of south-eastern Sweden, ASKLUND has divided the dolerite dikes of that area into two main groups. The first includes dikes occupying fissures of a north-westerly to northerly direction, and its rocks are petrologically characterized as olivine-free bronzite-dolerites often showing transitions to uralite-bearing types. ASKLUND considers the dikes to be of subjotnian age. This view is supported mainly by the rather perspicuous resemblance of these rocks to the subjotnian dolerites of southern Finland, which, quite as the Swedish rocks in question, are olivinefree, often hypersthene-augite-bearing and sometimes show transitions to porphyritic or uralite-bearing types. Furthermore, in Småland the dolerites of this group are often associated with quartz-porphyries of quite the same type as those connected with the dolerites of *rapakivi* age in southern Finland and in Åland.

The second large group includes firstly a number of dikes of a north-north-easterly to northerly direction (Karlshamn dolerite, Almesåkra dolerite and the olivine dolerites of eastern Småland) and secondly the large Hällefors and Breven dikes with their associates running in an east-westerly direction. On petrological grounds the olivine dolerite of the dikes last mentioned is generally considered to be equivalent to the rather similar Åsby dolerite and thus they have been classed as jotnian or postjotnian. This opinion is supported by ASKLUND, who remarks that the Hällefors dike *probably* often cuts the north-westerly system of fissures[1] (*loc. cit.* page 278; italics by the present author) and further according to STOLPE (**46**: 16) there is observed at St. Sidus in the neighbourhood of Norrköping a typical Hällefors dolerite cutting some dikes that belong to the north-north-westerly system. On these grounds ASKLUND considers the whole second group of dikes to be of jotnian or postjotnian age.

This division is thus based upon petrological dates as well as upon tectonic ones. The petrological method, however, already *à priori* must be considered as rather uncertain as it postulates that dolerites of the same petrological character may not belong to different periods of eruption. LJUNGNER (**30**: 108) has recently pointed out that in western Sweden its application leads to uncomfortable controverses. That seems to be the case in south-eastern Sweden, too. Thus the Breven dike according to its westerly strike must be connected with the Hällefors dike which on petrological analogies is considered of postjotnian age. The petrological relations of the Breven dike proper seem, however, to indicate that it is more closely related to the subjotnian dikes. Thus FROSTERUS has described (**17**) two subjotnian dikes situated immediately to the south of the Mäntyharju-Jaala area of southern Finland, which, to judge from the description, are rather analogous to the Breven dike. Furthermore there may be traced fairly good analogies between the latter and the doleritequartz-porphyry dikes of Småland, *e.g.* the Påskallavik dike. Although the author has not yet had the opportunity to study the so-called dike porphyries of Småland he is fairly convinced that their rocks are not essentially different from some parts of the Breven granophyre and the epidolerite and even part of the olivinefree dolerite of the Breven dike may very well be classed as uralite diabase, thus still more emphasizing the analogies just mentioned.

As to the method used by ASKLUND it seems to the present author as if great difficulties were met with here, too. It is well known that in several successive epochs of tectonic movements the resulting fissures may prefer developing in the same direction. Their direction ought to depend to a large extent on the relations of stability of the ground that is affected. And, moreover, a latent fissure may develop during one epoch of movement but get filled during another. Thus it ought not to be quite justificable to judge the relations of age from the directions of the dikes.

It is the author's intention to take up the problems suggested above

[1] ASKLUND does not mention how this *probability* is to be understood. The present author has visited the Hällefors dike for a few days and is inclined to think that ASKLUND's assumption is not quite well-founded. Yet the possibility of its correctness will not be denied as in order to give a decisive answer to the question a closer investigation seems to be necessary.

to a closer investigation. For this purpose it seems necessary to study rather intimately the field relations as well as the petrology of a number of dolerite dikes and further to find out their relations to the great tectonic lines of Fennoscandia. Perhaps a comparison with the Finnish dikes would give the clue to some of the problems as we have there the advantage of rather vast sedimentary terranes, the rocks of which are to a great extent known as to their geological age.

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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 (Geological Society of Stockholm).
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 (Geological Survey of Sweden).
T. M. P. M. = TSCHERMAKS mineralogische und petrographische Mitteilungen.

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Addendum.

Some words may conveniently be added concerning the nomenclature used in this paper, *viz.* about the use of the term *dolerite* for rocks that in Swedish are generally named »*diabas*». According to HOLMES (**23**: 78) the term *diabase* »originally denoted rocks, that were later recognized as diorites. For a time the term was applied to pre-Tertiary dolerites and since, especially in Britain, such rocks are frequently altered, the term has come to mean an altered dolerite in which the feldspars are saussuritised or albitised, or the pyroxenes more or less replaced by hornblende or chlorite. German and most american authors, however, (following ROSENBUSCH) use *diabase* in a sense synonymous with the British usage of *dolerite*». About the term *dolerite* HOLMES writes (**23**: 83): »An igneous rock occurring as minor intrusions, consisting essentially of plagioclase and pyroxene . . . in Britain only altered dolerites are denoted by the term *diabase*».

It is quite evident that this question of nomenclature has given rise to some confusion. In Britain two different terms are used to denote two different stages of alteration of the same rock, whereas in Sweden (and other countries) only one term has been found necessary. The author thinks it is most appropriate to follow the *praxis* of the language that is used. Thus, when writing in Swedish we ought to use the term »*diabas*» while when writing in English this name ought to be replaced by *dolerite* except when the rock in question has undergone a sensible alteration. In accordance with this view it must be considered justified to speak of the Åsby dolerite, the Breven olivine dolerite *etc.*, whereas the Swedish »*uralit-diabas*» conforms with *uralite-diabase* in English.

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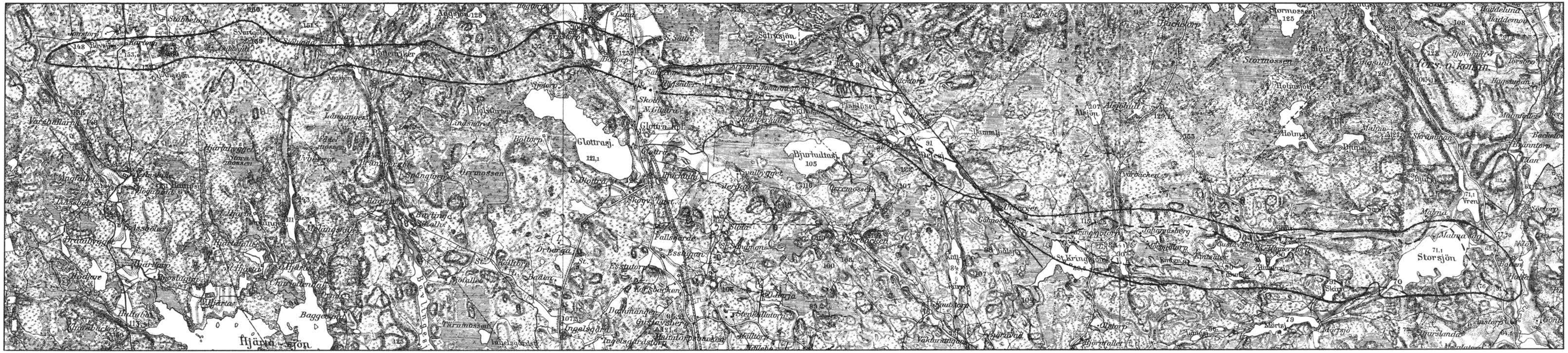
SUMMARY MAP

Scale 1:50 000



EXPLANATION.

Because of the oblong shape of the area treated in this paper it prooved rather difficult to represent it on a map. In order to avoid an inconvenient length of the map-sheet the scale must necessarily be held fairly small. This, on the other hand, implies that the names of the map become very difficult to read if marks are inserted in order to show the distribution of the different rocks. The author has tried to avoid those difficulties by tracing on the map only the boundary lines of the main rocks, and for further particulars the reader is referred to the following explanations.

The unbroken lines represent the boundaries of the dike against its wall rock.

The broken lines represent the outer boundaries of the central granophyre areas.

The dotted lines represent the supposed boundaries of a part of the dike which is devoid of any exposures. Thus it has not been possible to ascertain by what types of rock this area is occupied.

The areas outside the granophyre portions are occupied by olivine dolerite to the west of the dotted lines and by olivinefree dolerite and epidolerite to the east of them.

The unbroken straight line represents a fault.