GRØNLANDS GEOLOGISKE UNDERSØGELSE
BULLETIN No. 24

ON THE FIELD OCCURRENCE AND PETROGRAPHY OF SOME BASIC DYKES OF SUPPOSED PRE-CAMBRIAN AGE

FROM THE SOUTHERN SUKKERTOPPEN DISTRICT WESTERN GREENLAND

BY

ASGER BERTHELSEN AND DAVID BRIDGWATER

WITH 15 FIGURES IN THE TEXT
AND 3 PLATES

Reprinted from
Meddelelser om Grønland, Bd. 123, Nr. 3

KØBENHAVN
BIANCO LUNOS BOGTRYKKERI A/S
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CONTENTS

Abstract.

Within the southern Sukkertoppen district the highly metamorphosed basement rocks are traversed by several systems of basic dykes which on field evidence may be divided into an older and a younger group. The two periods of dyke intrusion are separated by the formation of an important system of NE-striking wrench faults, the Fiskefjord faults. The older dykes are displaced dextrally by these faults. Both groups of dykes include several sets, each with its definite and persistent trend.

Petrographically the dykes may be divided into the same two main groups, an older generally orthopyroxene and olivine-bearing group and a younger pigeonitic, olivine-free group. These criteria are, however, not absolute. The older group shows, when all dykes are considered, a gradation from a very mafic rock to a more normal tholeiite, with considerable interstitial quartz, development of pigeonite instead of orthopyroxene, and an ophitic texture. These latter features are all characteristic of dykes belonging to the younger group.

Within the older group, variation in mineral composition and texture seems to have been controlled by two interdependant factors, a) the order of crystallisation and b) sorting, probably under gravity.

These have lead to the following, seemingly anomalous relationships; 1) dykes with a high content of early, euhedral, magnesium-rich mafic minerals show interstitial anorthite-poor feldspars; while 2) dykes with a late, iron-rich, ophitic pyroxene show more euhedral feldspars with a greater anorthite content.

It is suggested that this is due to movement and sorting of crystals during the consolidation of the magma. The mafic rocks may thus have been formed by a concentration of early crystals set in a late feldspar residium; while the lighter, early feldspars solidified in a residium containing iron-rich pyroxene and a concentration of quartz and alkali feldspar. This differentiation took place prior to injection of the dykes.

1. INTRODUCTION

This paper is a part of a forthcoming description of the regional geology of the Tovqussaq-Fiskefjord-region as well as being the first of a series dealing with the post-orogenic basic dykes of western Greenland. Quite apart from the petrogenetic aspects, these dykes call for particular attention as they may serve as a very important tool to clarify the pre-Cambrian chronology of the long but narrow ice-free coast.

The field relations of the dykes are described by the senior author (A. B.) who headed the field work within the area shown in fig. 1, assisted by Messrs. HARRY MICHEELSEN, mag. scient., STIG BAK JENSEN, cand. mag., and ERLING BONDESEN, mag. scient.

The section on the petrography is prepared by D. BRIDGWATER who carried out the study of the samples in the laboratories of the Geological Survey of Greenland and The University Museum, Copenhagen.

The conclusions were discussed by both authors.

A few comments should be given on the extent of the field work. Systematic mapping has only been carried out within a small part of the area in 1954, '56 and '57. For the rest, our geological knowledge is based on reconnaissance mapping mainly performed from boats in 1949 and 1953. Although most of the work within the actual Fiskefjord area was carried out in three weeks of 1953 and was mainly restricted to inspections of the coast and shores, the highly branched shape of the fjord and the large lake systems made this type of mapping reasonable. As both dykes and faults stand well out on aerial photographs, interpretation of these have been useful in completing the field results.

The dyke map covering the area from Alángua to Sukkertoppen is based on reconnaissance mapping performed by Dr. HANS RAMBERG in 1949.

The preparation of the maps has been made possible through the courtesy of the Geodetic Institute, Copenhagen.

Finally we want to thank all who helped us to perform this study in the field as well as in the laboratories. Special thanks are due to the skippers Mr. SANDERS NIELSEN and MAURENTIUS POULSEN for their never-failing interest and skilful navigation during the operations in the

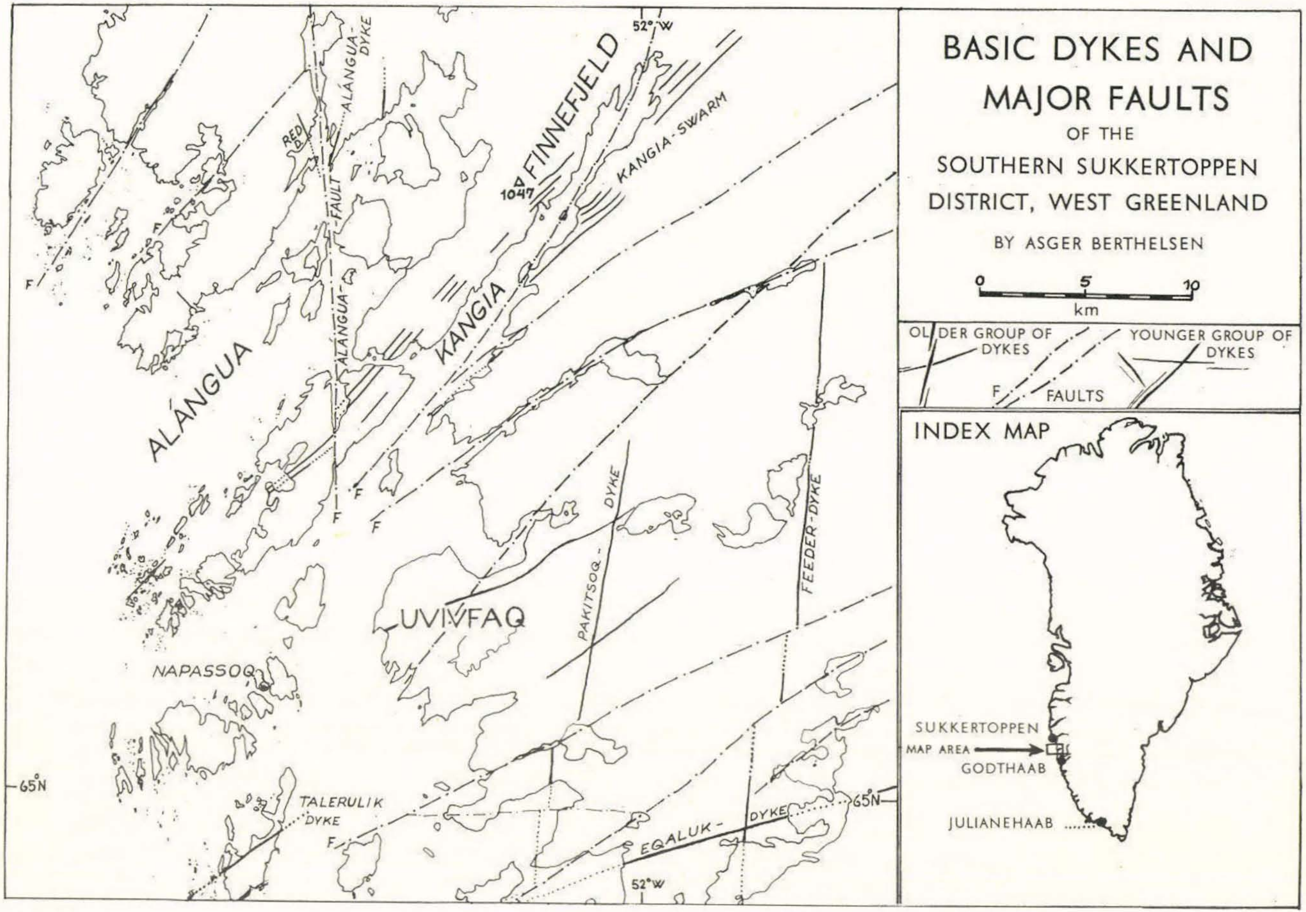
BASIC DYKES AND
MAJOR FAULTS
OF THE
SOUTHERN SUKKERTOPPEN
DISTRICT, WEST GREENLAND
BY ASGER BERTHELSEN
0 5 10
km
OLDER GROUP OF DYKES
YOUNGER GROUP OF DYKES
F FAULTS
INDEX MAP
SUKKERTOPPEN
MAP AREA
GODTHAAB
JULIANEHAAB
ALÁNGUA
KANGIA
FINNEFJELD
KANGIA-SWARM
1047
ALÁNGUA-DYKE
FAULT
RED D.
UVIVFAQ
PAKITSOQ-DYKE
FEEDER-DYKE
NAPASSOQ
TALERULIK DYKE
EQALUK-DYKE
52° W
65° N

Fig. 1a.

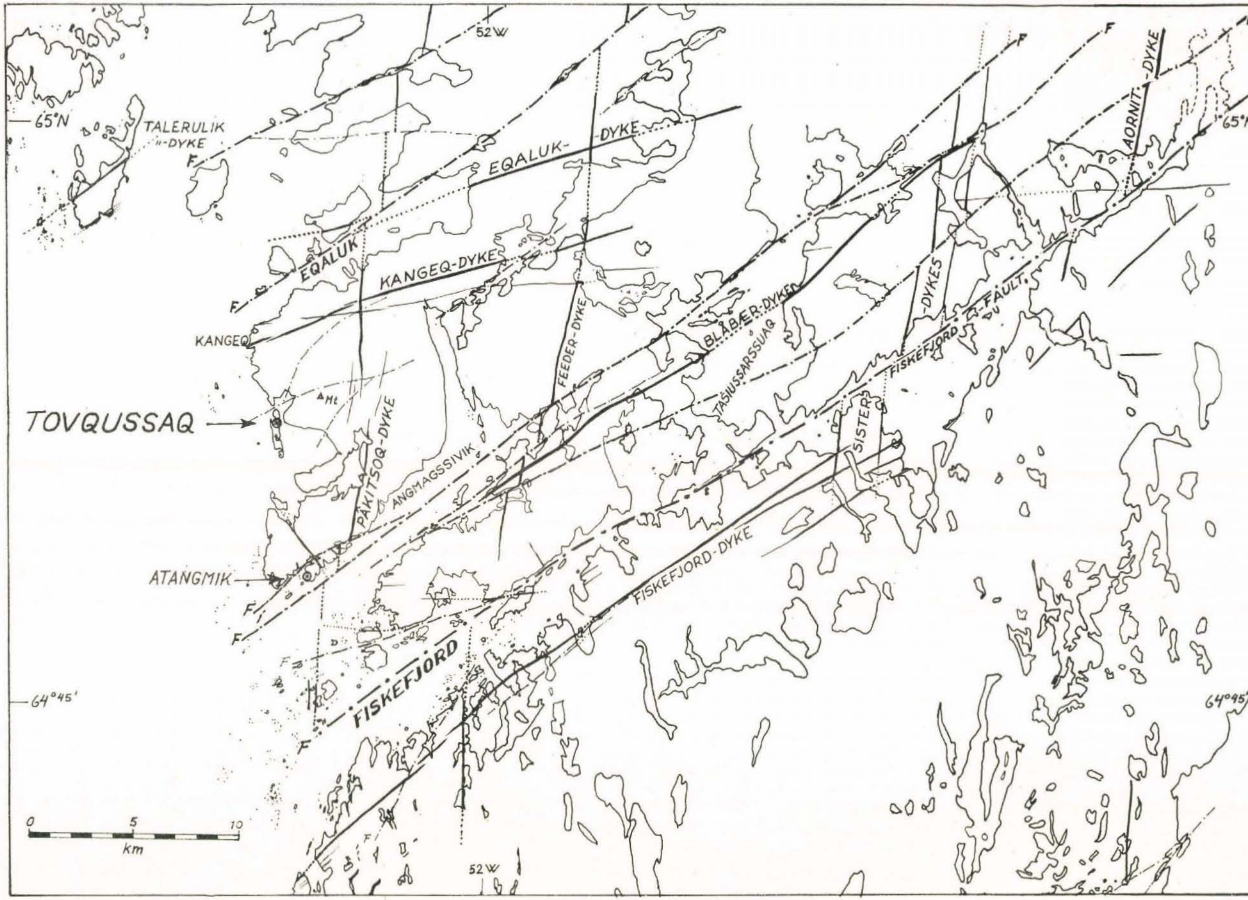
52 W
65°N
TALERULIK
-DYKE
EQALUK-
-DYKE
EQALUK
KANGEQ-DYKE
KANGEQ
FEEDER-DYKE
BLÅBÆR-DYKE
TASIUSSARSSUAQ
-DYKES
FISKEFJORD
FAULT
AORNIT
-DYKE
TOVQUSSAQ
PÅKITSOQ-DYKE
ANGMAGSSIVIK
SISTER
ATANGMIK
FISKEFJORD-DYKE
FISKEFJORD
64°45'
0
5
10
km
F

Fig. 1b.

strong currents of the skerry-filled fjords. We are, moreover, particularly indebted to Mr. T. C. R. PULVERTAFT for correcting the manuscript and making many helpful suggestions. Since the drafting of this report Mr. STIG BAK JENSEN rendered invaluable service by collecting new material.

ASGER BERTHELSEN

Geological Institute of the University, Copenhagen.

DAVID BRIDGWATER

Geological Survey of Greenland, Copenhagen.

2. ON THE DIVISION OF THE DYKES

The general geology of the region discussed here (viz. fig. 1a and b) has been reviewed in a recent paper which also contains full references to previous work (A. BERTHELSEN, 1957).[1]

The southern Sukkertoppen district is characterised by highly metamorphosed gneisses and schists which recrystallised under PT conditions corresponding to granulite and amphibolite facies. The structural evolution of these metamorphic rocks has been highly complicated.

This basement is traversed by several systems of post-orogenetic basic dykes and is dissected by a system of cratogenic faults, named the Fiskefjord faults.

After these introductory remarks, we may immediately turn to the main subject of this paper, the dykes. Our present knowledge only allows us to establish a rough classification of these dykes into:

1. THE OLDER GROUP of dykes which are older than the formation of the Fiskefjord faults,
2. THE YOUNGER GROUP of dykes which intrude the said faults but which may have suffered from posthumous movements of the faults.

Both groups embrace several sets, each with its definite and persistent trend. An attempt has been made to prepare a statistical diagram of the directions and persistence of the dykes, fig. 2. A 5 km grid was placed over the map of fig. 1a, which area is the best fitted for such an analysis. Then the average directions of the particular dykes within each square were drawn. Following this, the lines from all squares were compiled into a compass rose in such a way that the dykes with similar directions were drawn in extension of each other.

[1]) Se also A. BERTHEHSEN: Structural Studies in the Pre-Cambrian of Western Greenland, part II, Geology of Tovqussap nunâ. Medd. om Grønland, Bd. 123, Nr. 1, 1960; and part III: Southern Sukkertoppen district, Medd. om Grønland, Bd. 123, Nr. 2 (in print).

By this procedure, an impression of the preferred directions and their persistence is obtained — disregarding the width of the dykes.

The diagram brings out that there is a clear distinction between 5 main directions (sets). There is one varying from NS to 20° (here called the 10° set), another prominent maximum is found around 50°, a less prominent one occurs about 70°, an important direction is almost EW (85° set) and a small maximum is seen at 140°.

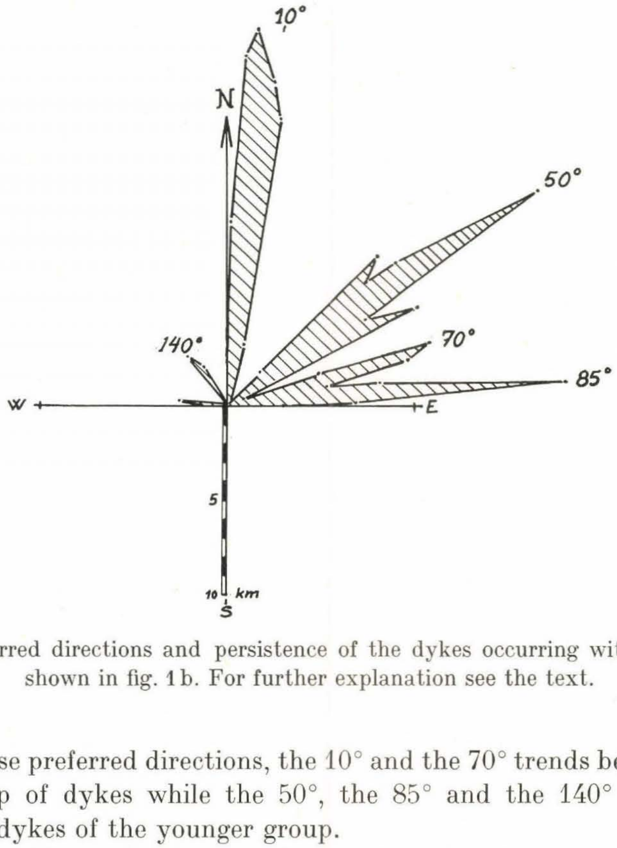

Fig. 2. Preferred directions and persistence of the dykes occurring within the area shown in fig. 1b. For further explanation see the text.

Of these preferred directions, the 10° and the 70° trends belong to the older group of dykes while the 50°, the 85° and the 140° trends are caused by dykes of the younger group.

It is highly probable that these dyke-sets all represent different generations but so far only a single intersection between dykes from different sets of the same group has been found.

Finally, a particular group of dykes here called the Red Dykes should be mentioned. These dykes occur abundantly to the south of our region, in the Godthåb Complex, but only a single representative has been observed within the area covered by the maps of fig. 1a and 1b. It is found in the long narrow branch on the north side of the Alángua fjord. The age relation of the red dykes to the younger and older groups described here is unknown.

Fig. 3. View of the Kangeq dyke east of the intersection with the Pâkitsoq dyke, Tovqussaq peninsula. The person in the foreground is standing on the covered intersection (Photo: GGU, A.B.).

3. ON THE FIELD OCCURRENCE OF THE DYKES

The older group.

This group may be divided into two sets, which trend 70° and 10° (on average). Only two dykes represent the first named trend while the latter is represented by 7 dykes, two of which form a pair, the Sister dykes. One intersection, on the Tovqussaq peninsula, between the Kangeq dyke and the Pâkitsoq dyke showed the latter (trending 10°) to be the youngest as it cut an apophysis given off by the Kangeq dyke. The actual intersection between the main dykes is covered at this locality (fig. 3).

The dykes of this group have been named in such a way that the continuation of several individual dykes has been regarded as a single dyke. For example, what has been called the Pâkitsoq dyke in reality is a suite of dyke-filled fissures which may be traced as a more or less continuous line. This system is useful when the dykes are used to evaluate the movements within the younger Fiskefjord faults.

The discontinuity of the dykes are caused by *en echelon* structures which where mapped in detail (as on the Tovqussaq peninsula) showed up

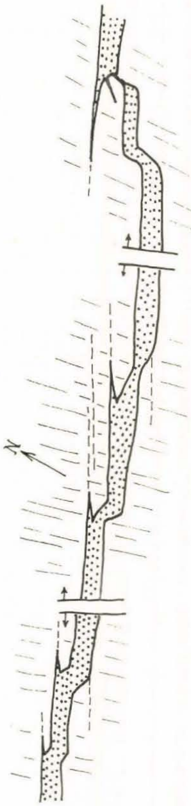

Fig. 4. Apophysis from the Kangeq dyke showing combined *en echelon* and *en bayonet* structures. Note how pre-existing joints in the gneiss seem to have controlled the "*relais*" of the dykelet. The width of the apophysis is about 25 cm. The sketch is compiled from three actually more separate localities.

to be very complex. This is seen in the Kangeq-dyke where the *en echelon* "jumps" occur irregularly. Similarly, the Påkitsoq dyke exhibits complicated structural "*relais*" with both eastward and westward "jumps".

En bayonet structure and combined *en bayonet* and *en echelon* structures have been observed in an apophysis from the Kangeq dyke, fig. 4. All these observations are of some interest as they seem to indicate that regional tension may have played a major role during the opening of the dyke fissures.

When the thinning out in relation to the known structural "*relais*" is considered, the width of the dykes have been recorded as:

70° set: 7—10 m for the Eqaluk dyke
20—25 m for the Kangeq dyke

20° set: 9 m for the Alángua dyke
10—20 m for the Påkitsoq dyke
4—10 m for the Feeder dyke
8—9 m for the western Sister dyke
2—10 m for the eastern Sister dyke
20 m for the Aornit dyke.

The Feeder dyke and the Påkitsoq dyke have been traced over 50 and 45 km respectively, the northern part of the courses being drawn from study of aerial photographs.

The dykes are usually vertical but may show dips as low as 60°. There is, however, no constancy in the direction of the dip.

In the field, the 10° and the 70° sets appear very similar. The dykes usually stand well out with a red-brown or rusty brown colour on the weathered surface. Jointing is not prominent but a weakly developed box-jointing which leads to spherical shapes when weathered is present. The columnar jointing so often met with in basic dykes seems absent even in the thinner dykes and the apophyses.

The texture of the dykes is usually medium grained and granular. At a certain composition, as found in the Feeder and Påkitsoq dykes, the felspars develop poikilitically around euhedral orthopyroxenes.

The contacts are well chilled and dense to almost glassy. Short thin apophyses are common along the contact of the Kangeq dyke. Small irregular xenoliths, occasionally showing signs of assimilation, have been noticed near the contacts of the Eqaluk and the Kangeq dykes.

The Feeder dyke forms an exception to the other dykes of this group, as in places it shows very different contact relations to the surrounding gneisses (fig. 5). Where this dyke has been observed around the eastern branches of the Angmagssivik fjord (fig. 1b) the contacts were found to be hybrid. The gneissic wall rock is not only veined by narrow apophyses sent out by the main dyke but has undergone palingenetic mobilisation and mixing with the basic material.

The width of the Feeder dyke is here only about 4 m so the melting of the wall rock can hardly be ascribed to the heat given off during the crystallisation of the present dyke filling. A prolonged flow of magma through this latter and a correspondingly long maintained temperature gradient must be assumed to explain the melting of the adjacent gneisses. Such conditions would have been fulfilled if the dyke had functioned as a feeder for surface volcanism, hence the name.

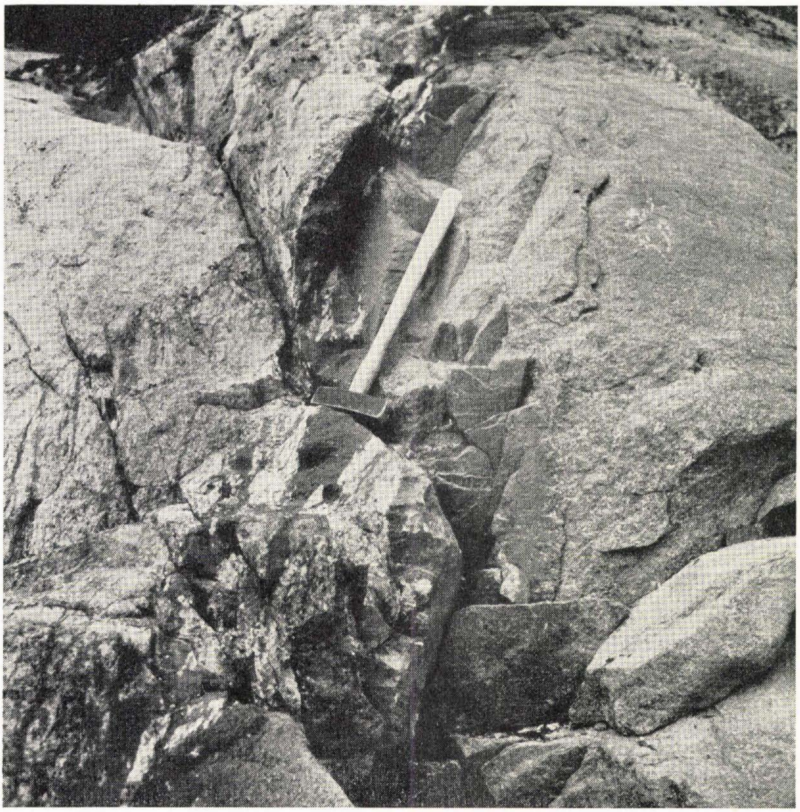

Fig. 5. Hybrid contact of the Feeder dyke, east coast of Angmagssivik (Photo: GGU, A.B.).

In thin section the centres of the Feeder and Påkitsoq dykes are indistinguishable although the contact relations of the two dykes are so different. The Påkitsoq dyke shows normal chilled margins although it is between two to five times as broad as the Feeder dyke.

The dykes of the older group are usually not much altered. Only close to the younger faults is a strong retrograde metamorphism and deformation seen to have affected the dykes. This has led in places to the formation of genuine greenschists. Thin epidote-bearing quartz veins have also been observed within the sheared dykes.

The younger Fiskefjord faults wherever observed have displaced the older dykes dextrally. The total observed displacement of the Sister dykes amounts to 4—5 km of which the Fiskefjord fault proper accounts for about 3.5 km.

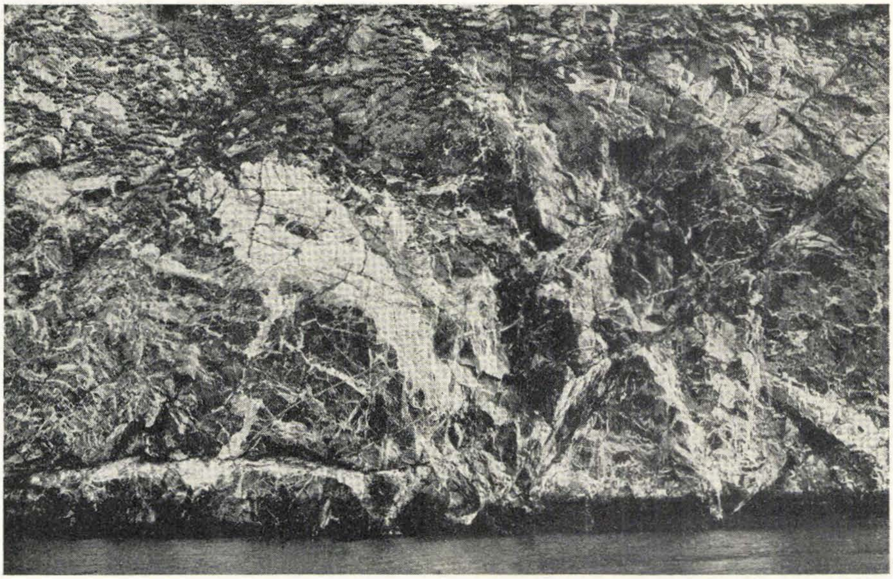

Fig. 6. Fault breccia (agmatitic), south coast of central Fiskefjord (Photo: GGU, A. B.).

The Fiskefjord faults.

This name has been given to a system of NE-striking wrench faults which all show dextral displacement. The name is taken from the most prominent of the faults which runs as an almost straight line through the narrow, natural sluices of the Fiskefjord which is famous for its strong tidal currents.

The low but steep mountain walls of the fault-determined fjord show in several places excellent exposures of fault breccia (fig. 6). Here fault agmatites, fault breccias veined or healed by pegmatites, and epidote rich schists approaching helsinkite in composition may be seen. The present erosional section of the fault evidently represents what once was a deep-seated portion where strong recrystallisation and retrograde metamorphism were predominant over simple mechanical crushing.

The mineral association of the recrystallised rocks within the fault-zone also indicates that PT conditions corresponding to the uppermost epidote-amphibolite or even greenschist facies obtained when the formation of the faults took place.

The retrograde metamorphism has in many places reached deep into the fault blocks where formation of epidote and sericitisation of the feldspar everywhere indicate such changes.

The formation of the Fiskefjord faults also caused a rejuvenation of several late-orogenic mylonites, thrusts, and shear zones in the basement rocks. The renewed movements are shown by the fact that the dykes of the older group, which otherwise cut such thrusts and mylonites, show dextral displacement where traced into rejuvenated fractures. The dextral displacement of the Pâkitsoq dyke north of the Tovqussaq mountain may be mentioned as an example of rejuvenation of an older, i.e. late-orogenic, mylonite.

Within the region discussed here, the Fiskefjord faults all seem to form vertical zones of dislocation. Further to the south, on the Nordlandet, a moderate northerly dip has been observed in equivalent faults.

The faults have been classified as wrench faults, as evidence of any important vertical movements has not been found so far from the gneiss structures.

The younger group.

This group embraces the dykes with the 50°, 85° and 140° directions. All these dykes seem to have been intruded after the formation of the Fiskefjord faults. The following observations favour this conclusion.

1. Apophyses from the Blåbær dyke (50°) intrude the fault-zone on the south coast of Angmagssivik and the main dyke as a whole is only slightly influenced by alteration even where it runs almost parallel to the fault direction.

2. Apophyses from a dyke belonging to the 85° set of dykes intrude the fault breccia on the south coast of the round island north of the Eqaluk fjord. Another 85° dyke has been traced across the major fault in the entrance of the Fiskefjord without any displacement, although it is somewhat altered. In the inner parts of the same fjord, a third dyke (at 85°) actually cuts two faults.

3. One of the 140° dykes has been traced undisturbed across the fault which displaces the older Pâkitsoq dyke, to the north-east of Atangmik on the Tovqussaq peninsula.

The relation between the older and the younger groups is based on the following observations. The Blåbær dyke and the Fiskefjord dyke both cut the Feeder dyke. The intersection between the Feeder dyke and the Fiskefjord dyke is under the sea, but the dilatation relation clearly indicates that the latter is the youngest. The 85° dykes cut both the Kangeq and the Feeder dykes.

It could be argued that if the Blåbær dyke is younger than the faults, it should contain inclusions of fault breccia, which is often seen to be the case where dykes have been intruded later than severe faulting (Wegmann, 1938). Such xenoliths, however, have not been observed in the

Blåbær dyke, and their absence can easily be explained when the nature of the fault breccia described above is kept in mind.

The Blåbær dyke and the Fiskefjord dyke have both suffered somewhat from tectonic disturbances and alterations, but not to the extent that should be expected if they really are older than the faulting. It seems more probable that these features are due to posthumous movements of the faults.

The 50° set.

The Blåbær dyke is the thickest dyke in the region discussed here. The width varies from 30—40 m. The dyke is usually vertical but may dip to either side at as low as 60° and in one locality even down to 45°. The dyke is easily recognised all along its course because of its distinct porphyritic texture (fig. 7). Ice-transported boulders undoubtedly originating from this dyke have been found in several places within the region. The plagioclase phenocrysts are found especially near to the chilled contacts. At some localities a peculiar variation in colour has been noticed within the phenocrysts. Irregular patches show a brown colour contrasting to the normal white. The dark colour is seemingly caused by a patchy strong alteration of the felspar. The size of the phenocrysts is generally from 1 to 5 cm.

In one place, on the western shores of Tasiussarssuaq, the dyke was seen to be traversed by thin epidote veins, and gash joints are developed. This is explained as being caused by posthumous movements of the nearby fault.

The Fiskefjord dyke is about 30 m broad. At several localities it is seen to be accompanied by thinner satellite dykes. The main dyke exhibits on aerial photographs a clear en echelon structure to the south of the entrance of the Fiskefjord. The arrangement of these "*relais*" is interesting, as it seems consistent with the dextral movements in the Fiskefjord faults. Possibly the forces which caused faults were still in action when the 50° trending dyke fissures were opened.

The Talerulik dyke (fig. 1a) is about 25 m broad. Towards the southwest it may be traced to the outermost skerries. Towards north-east a possible continuation is seen on the aerial photographs east of the Uvifaq peninsula on the mainland. Three thin dykes with a similar trend were noticed on the southern coast of Talerulik.

Around the Kangia fjord (fig. 1a) several dykes with a trend from 40° to 50° are met with. These dykes have been grouped in *the Kangia swarm*. The thickness of the individual dykes varies from half a meter up to 10 m. The Kangia fjord itself seems controlled by a fault, as crush and shear zones occur parallel to the coast. On a small island which is made

Fig. 7. Close up of the Blåbær-dyke. Note the multicoloured plagioclase phenocrysts to the left of the hammer (Photo: GGU, A. B.).

up entirely of sheared gneisses, apophyses trending 50° were seen to intrude the sheared gneiss, but they are also faulted locally (fig. 8a and b). These details seem in complete agreement with the conclusions drawn above about the age relations between the younger dykes and the Fiskefjord faults.

The Alángua fault is only exposed for short distances north and south of the Alángua fjord, the remaining parts of its course being sea-covered. At the southern locality partly recrystallised pseudotachylitic rocks were seen in the actual fault, and signs of potash metasomatism were observed in the surroundings. In this respect, the fault is similar to some of the late-orogenic faults and mylonites of the Tovqussaq-peninsula.

On the west coast of the narrow branch on the north side of Alángua, signs of bleaching have been observed close to the fault, which here runs under the sea. The basic dyke on the east coast of the same fjord-branch seems affected by crushing close to the coast.

On the islands close to the fault line drawn across Alángua thin veins of pseudotachylite have been observed in the gneisses. The veins are very irregular, but have undoubtedly originated in connection with the faulting.

The age relation between the Alángua fault and the Kangia swarm is so far unknown. A dextral displacement along the fault may be postulated from basement structures on the north coast of Alángua, but the swarm has not been mapped in enough detail to prove or disprove a similar displacement of the dykes.

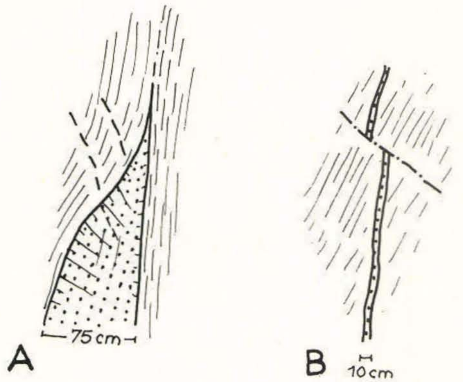

Fig. 8. Apophyses from the Kangia swarm. A and B are both intrusive into the sheared gneiss, but B has been displaced later by a local fault.

It may be mentioned however that small almost NS-striking dextral faults on the east coast of Angmagssivik were found to be older than the Blåbær-dyke which belongs to the same set as the Kangia swarm.

The 85° and the 140° sets.

The set of dykes with a trend about 85° comprises only thin dykes with a width from less than half a meter to maximum of 10 m. They can only be traced for 10 to 20 km.

The dykes trending 140° are also thin dykes. The dyke close to Atangmik (fig. 1b) is 3,5 m thick on the south coast and about 2 m to the north. The dyke shown in fig. 1a on the north-west coast of Alángua is only 0,2 m broad.

All the younger dykes stand out as black dykes in the field. The contacts are well chilled, dense to glassy. The texture of the larger dykes is medium grained and ophitic. The Blåbær dyke is the only porphyritic dyke found. Jointing seems sparsely developed and decay due to weathering is negligible. They are thus, in most cases, easily distinguished from the older group.

The red dykes.

The so called red dyke from the head of the Alángua fjord really consists of two closely spaced, parallel intrusions, each about 1 m thick, emplaced in a NNW-striking joint zone. The dyke weathers to a distinct red-brown colour and crumbles into small cubes. The texture is fine grained and the rock is highly vesicular.

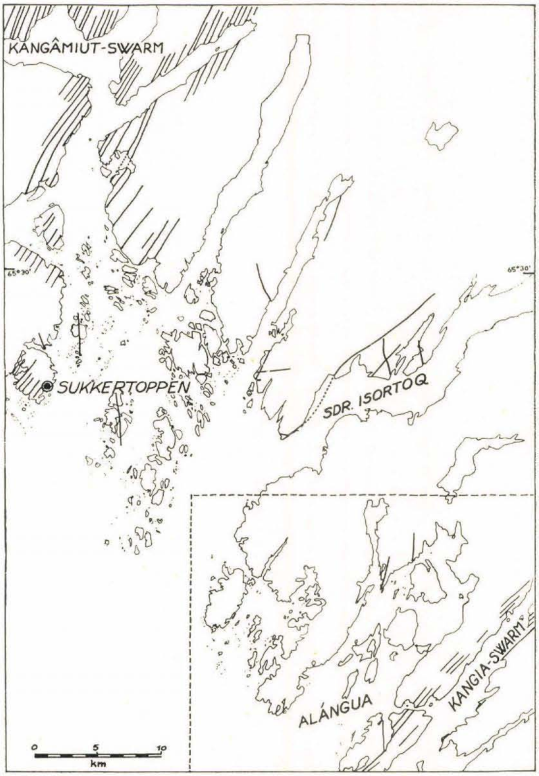

Fig. 9.

4. TENTATIVE CORRELATION WITH THE KANGÂMIUT SWARM

Our knowledge about the northward continuation of the dyke systems just described is rather fragmentary.

Only a few dykes are recorded from the area between the Alángua fjord and Sukkertoppen island, which latter is reached by the southermost extension of the Kangâmiut swarm, fig. 9. It might be profitable to concentrate future work on the dyke rocks within this "gap", because a direct correlation on field evidence could possibly be established here.

So far we have to content ourselves with the knowledge that olivine-hypersthene-dolerites clearly belonging to the older group have been found north of Sukkertoppen, where they strike 20° W. We also know that similar dykes at various places further to the north have been found to be older than the Kangâmiut swarm.

Some samples of the Kangâmiut dykes have been sectioned in connection with the present investigation and it showed up that in thin sections they correspond closely to the 50° set of the younger dykes from the southern area.

The petrographic resemblance is naturally not decisive, but at least it does not invalidate the tentative correlation between the Kangâmiut swarm and the NE-striking younger dykes, which has been suggested previously by one of the authors (A. BERTHELSEN, 1957). The two sets, the 10° and the 50° sets, seem in this case however to change their directions (anticlockwise) north of the region investigated by us.

If this correlation holds good, all the dykes of the older and younger groups, as well as the formation of the Fiskefjord faults, can be dated as pre-Nagssugtôqidian (for the relation between the Kangâmiut swarm and the Nagssugtôqides see RAMBERG, 1948).

This means also that the basic dykes described here could safely be called pre-Cambrian.

5. PETROGRAPHIC AND MINERALOGICAL METHODS

The detailed mineralogy was carried out in the following ways:

Plagioclase determination: In the presence of numerous Carlsbad/Albite twins and strong zoning, the writer finds the curves published by CHUBODA (1932) are the most convenient to use for comparative work, although they are probably in need of revision for more absolute composition measurements. As a check to the above, the full orientation methods of VAN DE KAADEN (1951) and KÖHLER (1952) (see TRÖGER 1956) were carried out on at least four individuals per slide. The results suggest that the felspars are low temperature forms although they rarely correspond exactly to either curve. The anorthite content as estimated by the last two methods is some 5 $^0/_0$ lower than that estimated by extinction angle measurements from twin planes in the central areas of crystals. In heavily zoned crystals this may well be due to the difficulty in orientating X : Y : Z : exactly, the actual readings are probably more of an average of several zones near the twin plane.

Mafic minerals were determined by a combination of optic axis and refractive index measurements (see HESS 1949, and KENNEDY 1947 in TRÖGER 1956). 2V was measured on a five axis stage (EMMONDS 1943) the errors due to the difference between the refractive indices of the mineral and the hemispheres being corrected on a nomogram devised by KLEEMAN (1952). As all the minerals were zoned the accuracy was probably within 2° in the centres 4°, at the edges.

Refractive index measurements were used as a more accurate guide to composition; the most convenient way to obtain the various zones was to pick out fragments from an uncovered slide with a pin. The actual measurements were carried out with the aid of a monochromator and a series of glass powders of known dispersion and R.I. This enabled the immersion liquid to be determined at the same time as the mineral, thus eliminating the normal inaccuracies of the immersion method. This fine quick modification was developed by H. MICHEELSEN (1957) and gives results to .001 for the novice and with considerable more accuracy for the expert.

Immersion methods are very suitable for the measurement of orthopyroxene, as cleavage fragments will give Z in one direction. In the material used the olivine was not so suited to this method as it was full of inclusions, which made the Becke line indeterminate. The refractive index of Y in the clinopyroxenes was determined from grains giving centred axis figures, and by the measurement of Z′ X′ in many grains.

Refractive index work was generally in good agreement with the results obtained by the 2V measurements, which could be used to get a more general picture of the whole rock.

The mineralogical composition was determined for each dyke by means of point counting, but the results are of very little use since the majority of the specimens are not from the margins, and the original magma is unknown. The older group of dykes have undergone considerable sorting, while the younger have suffered considerable alteration in places.

6. PETROGRAPHY OF THE OLDER GROUP

The 70° set.

The Eqaluk and Kangeq dykes which represent this set are very similar mineralogically if not texturally, they are therefore described together with notes on their differences.

In the coarse grained central parts there is a considerable disparity of composition between the two dykes, which is the dominant reason for the textural differences. Unfortunately only the Kangeq dyke is fresh enough for point counting. It contains the following percentages of minerals.

1. Centre: Plagioclase 45 %. Clinopyroxene 36 %. Olivine 10 %. Ore 4 %. Secondary minerals 5 %.
2. Contact: Plagioclase 19,5 %. Clinopyroxene 60 %. Olivine 8 %. Biotite 8 %. Ore 4.5 %.

The central part of the Kangeq dyke consists of a mass of anhedral mutually interfering grains with the felspars averaging 2 mm in diameter and the mafic minerals about half this size. Olivine is often enclosed by felspar, in which case it may show some euhedral faces. Less often smaller crystals of olivine are enclosed by pyroxene. In the contact specimens olivine is far more euhedral than from the centre, it appears to be in the process of being redissolved in places, and is commonly surrounded by augite grains and a thin rim of biotite and ore. The average diameter of the olivine phenocrysts is that of the normal mafic grain size from the central areas of the dyke .5—1 mm but there are smaller rather irregular individuals down to .05 mm that is to say the same size as the ground mass formed by rapid solidification. These small crystals are not part of the chilled ground mass but relics of larger olivines.

The augite phenocrysts are rarely euhedral, they are generally aggregates of several grains probably with a central olivine, or zoned subhedral crystals with very irregular twinning.

The ground mass is an interlocking structureless mass of felspar, augite, biotite, and ore all of which appear to have been solidified at the same time. The composition of the margin is far closer to the composition of the Eqaluk dyke, as far as can be estimated, than the centre of the dyke, the reason for this is not apparent from the present specimens.

Both the centre and the contact specimens suggest that the order of crystallisation is as follows: Olivine-Augite-Plagioclase. The chilled margin gives the best evidence, showing the following sequence.

Olivine — Augite.	as phenocrysts.
Augite. Plagioclase. Biotite. Ore.	as ground mass.

The Eqaluk texture is dominated by the greater percentage of mafic minerals, which are generally better shaped than those from the centre of the Kangeq dyke. The felspars are interstitial laths, generally later that the mafic minerals. In the Sister dyke from the 10° set, where this texture is seen again, it is suggested that it is due to accumulation of mafic minerals with the plagioclase forming late.

The Mineralogy of the 70° set.

Plagioclases from the Kangeq dyke are fresh, roughly equidimensional irregular crystals, showing distorted lamellæ in places which suggest intergranular movement during crystallisation. In the Eqaluk dyke the plagioclases are long thin laths, the central zones of which are stained with dust, while the outer are clear and fresh. In spite of the change in form in the felspars from the two dykes, twinning on Albite, Carlsbad, Ala-albite, and Pericline laws is common to both. The composition of the plagioclase from both is also similar, with central zones at about An. 45 %, regular smooth normal zoning about An. 20 %, and a slight break before the small albitic rim. There is a little quartz intergrown with this rim in the Kangeq dyke.

Clinopyroxene: All the clinopyroxene present belongs to the augite range of composition. It forms simply twinned, subhedral to irregular grains, sometimes occuring in aggregates; which are irregularly distributed in the rock. Variation in the pyroxene takes place in three ways:

a) Simple zoning, with the cores of the crystals ranging from a 2V of 55° to 50°, the rims 46° to 42°.

b) "Patch" crystals, in which single individuals are split into areas with slightly different 2Vs, the whole crystal being in optical continuity.

c) Granular aggregates, in which there are groups of pyroxene grains with no physical connection between them, which show a decrease in 2V towards the edges of the aggregate.

Naturally the last two are not so regular as the first, although they show a similar range of composition.

The refractive index averages 1. 69. while the angle Z/c averages 42°.

Olivine: In the Eqaluk dyke this mineral occurs in some well-shaped phenocrysts, while in Kangeq dyke it is less well formed, and often enclosed by augite or plagioclase. It has the characteristic purple brown colour, very high relief, and slight pleochroism seen from the olivine throughout its occurrence in the older dykes, and is probably the most diagnostic mineral present.

The composition was determined by both R. I. and 2V measurements. The former was hampered by the presence of numerous inclusions of spinel (?) and by zoning (TOMKEIEFF 1939). The results showed a R. I. varying from 1.700—1.760 for Y while the 2V varied from 90° to 74° — ve. These indicated a large range in composition from Fa. 12 % to Fa. 50 %. Some of this variation may well be due to loss of some of the iron as secondary minerals. There was no apparent correlation between size and composition.

Inclusions in the Olivine: The olivine contains a large number of inclusions of opaque iron minerals in the form of dendritic plates and rods arranged in definite crystallographic planes. The plates lie in the plane 100 (containing the optical directions X and Y), while the rods are parallel to the b direction (= X) or more rarely to c (= Y). The plates are made up of dendritic fibres which form hexagonal stars in the same pattern as skeletal snow flakes. The fibres themselves are symmetrically arranged, parallel to b and c, or running at 37° to b; these are shown in figure 10. The composition is unknown but they are thought to be magnetite. The olivines are very strongly magnetic probably on account of these inclusions. The slight pleochroism may indicate the presence of manganese in the mineral.

Accessory Minerals: Orthopyroxene is a rare accessory mineral found in the Eqaluk dyke; it has not been seen from the Kangeq dyke. It occurs as irregular crystals with a composition of 10 % Fs., as shown by the 2V of 84° — ve. No definite relationship with the other minerals present could be seen.

Biotite occurs in minor amounts in both the dykes, it appears to be mainly late as it surrounds the iron ore formed from the break down of olivine. It is normally brown with strong pleochroism but there is a little of the green variety present.

Iron ores are present both as secondary products after olivine and as primary skeletal octohedra of magnetite.

As with the other members of the older group no apatite has been seen in any of the slides.

Secondary Minerals: Apart from the iron ore the main secondary mineral is a pale tremolitic amphibole formed from the pyroxene. This mineral is seen in large amounts in the Eqaluk dyke where this has been cut by small fissures. It both replaces the pyroxene in situ, and also recrystallises in the cracks as crystals up to 1 mm long and about .5 mm in width. When it replaces pyroxene directly it is often made up of small fibres arranged in a whorl, resembling a fingerprint, in such cases there is often some carbonate present. The amphibole pleochroism is from colourless to very pale green.

The 10° set.

The five dykes comprising this set appear to the author to form a logical sequence; and the following divisions are for descriptive convenience and are not based on fundamental differences.

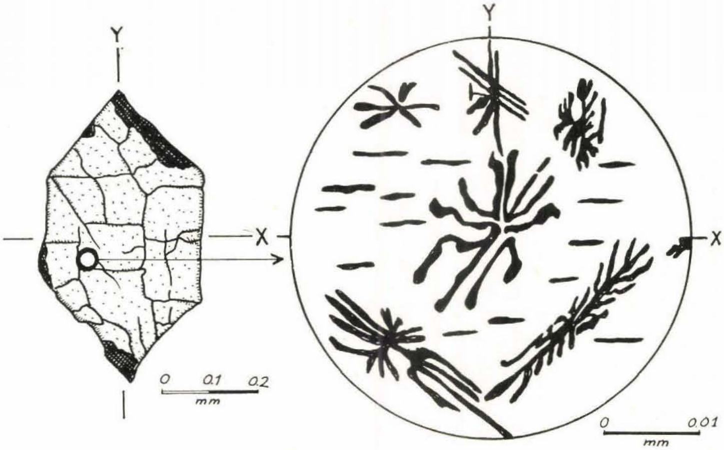

Fig. 10. Olivine showing oriented inclusions of magnetite. The Eqaluk dyke, slide G.G.U. 19288.

a. The Sister dykes.

Minerals: Plagioclase, Clinopyroxene, Orthopyroxene, Olivine, Ore, Biotite, and secondary products.

The main feature apparent on examining sections from these dykes, was the large percentage of mafic minerals present. This seemed to be a general rule and not due to a fortuitous selection of material, but owing to the majority of specimens being badly sheared, it is not absolutely certain. The freshest rock contains 90 % mafic minerals, with the result that the felspar occupies a very insignificant area, and occurs as interstitial laths in the same fashion as the plagioclase from the Eqaluk dyke. The mafic minerals form a mass of mutually interfering crystals, of which the olivine is the most euhedral, the clinopyroxene the least. Occasional large crystals of clinopyroxene enclose both olivine and orthopyroxene.

The rock is relatively coarse grained; with the orthopyroxenes generally the largest crystals present, averaging between 1 and 2 mm long and with cross sections between .3 and .7 mm in diameter. The average dimension of the augite is about .5 mm, but there are larger phenocrysts reaching 4×1.5 mm. Olivine varies between .25 mm and 1 mm. The felspar laths are small, a typical example being $.5 \times .05$ mm in section. Pl. 1a.

Mineralogy.

Plagioclase occurs as thin laths, often arranged in a radiating pattern in the interstices of the mafic mass, it may be stained brown by dusty inclusions, especially in the centre, but shows no sign of breakdown. It is sometimes surrounded ophitically by small patches of augite, thus showing that although the felspar crystallised late, after the main mafic minerals had been formed, there was still some pyroxene being formed at the end of crystallisation.

The plagioclase composition varies from central zones of An. 45 to approximately An. 20 at the edge; there are no breaks in the zones.

Clinopyroxene: Approximately 20 % of the rock, that is to say 30 % of the pyroxene present is augite. It is irregularly distributed and the form varies from subhedral phenocrysts to ophitic patches, the latter on a very minor scale.

It is almost always twinned and shows zoning. The composition indicated by the 2V of 48° to 46° with a refractive index of 1.685 to 1.700 (Y) is that of a normal augite, approximately: Wo. 40 % Fs. 15—25 %, En. 45 %—35 %.

Orthopyroxene forms 50 % of the rock, as 1 mm large subhedral grains with no signs of pleochroism even at the rims. There are no signs of exsolution lamellae, although the crystals do show a slightly patchy extinction in places.

Composition ranges from 12 to 22 % Fs. iron increasing regularly outwards. The majority of crystals show a composition of 15 % Fs. The results were obtained from the variation of 2V between +ve 85° to —ve 78°. R. I. (Z) varies from 1.679 to 1.682.

Olivine forms 20 % of the rock, it shows the same high relief, slight pleochroism, and inclusions as mentioned from the previous set of dykes. The two methods of determining composition gave a small but consistent discrepancy between them, the R. I. of grains giving centered axis figures being between 1.700—1.705 which should mean a composition of 20—25 % Fa., while the 2V measurements are remarkably constant, 15 grains measured all gave a 2V of 82° +ve which suggests a composition of 32 % Fa. No reason has been found for this discrepancy.

Accessory Minerals. Biotite is present in small amounts interstitially, it appears to be late. It is strongly pleochroic from colourless to red-brown.

Iron ores are not common and are mostly the alteration products of olivine, there is also a little serpentine from this mineral.

Secondary Minerals: In those parts of the dykes that have been sheared the main mineral formed is a pale tremolitic amphibole, similar to that formed in the Eqaluk dyke. The following properties are recorded from the amphibole.

Pleochroism: X Colourless. Y Pale green or honey. Z Very pale green or honey.

$$2V\ 80° + \text{ve}.\ Z/c\ 15°.$$

The mineral must have continued growing well after the movement, for the minor shear zones are filled with well shaped crystals. Accompanying the amphibole which is mainly formed from the pyroxene there is a copious amount of iron minerals from the olivine.

b. The Feeder and Pâkitsoq dykes.

These dykes in spite of their different field relations, are indistinguishable in thin slice. Their mineralogy, although not their texture or composition is seen to be very similar to that of the Sister dyke just described.

In hand specimens from the dyke centres plagioclase phenocrysts are seen up to $20 \times 10 \times 5$ mm, but the average size is about half this. Mafic minerals average $1.5 \times .5 \times .5$ mm and may reach twice this size, they are generally enclosed by the plagioclase. The mafic minerals are seen in thin sections to be euhedral orthopyroxene, and less well shaped augite and olivine set in sheets of heavily twinned plagioclase (Plate 1 b). The augite is generally later than the orthopyroxene, and occasionally forms similar ophitic intergrowths with the plagioclase as seen from the Sister dyke.

Plagioclase forms 50 % of the rock, mostly as the large poikolitic crystals mentioned above. There are, however, some patches where the mafic minerals have accumulated so that the same texture is seen in these dykes as is seen from the Sister Dyke. There are a large variety of twin laws present, the most noticeable being Albite, Carlsbad and Pericline, all of which are almost ubiquitous.

The centres of the crystals show a very constant composition between An. 55 and An. 60 %. Zoning is smooth and gradual and the rims rarely fall below An. 40 %. There are one or two examples of zoning down to An. 15 % where the crystals are bounded by interstitial quartz.

The limited occurrence of the laths as seen from the Sister dykes is worth noting since they have a composition of An. 40 % and appear to be late formed.

Clinopyroxene forms approximately 10 % of the rock in four different modes of occurrence: a) as rims to orthopyroxene, b) as small subhedral grains, c) as granular aggregates or single patchy crystals, often mixed with orthopyroxene, d) rarely as ophitic grains enclosing plagioclase.

There is commonly zoning or grouping of patches so that the less calcic and more ferriferous are on the outside. The boundary between orthopyroxene and clinopyroxene is sharp and sometimes appears similar to a twin plane. This intimate relation makes it impossible to separate the two minerals during point counting.

The composition was a little more variable than that seen in the Sister dyke, 2V varies from 52° to 42°, the refractive index averages 1.695. This indicates a normal range in the augite series.

The clinopyroxene and more rarely the orthopyroxene show a symplectic intergrowth with the plagioclase on a very small scale along the crystal boundaries.

Orthopyroxene forms 35 % of the rock, as the most euhedral mineral present. It takes the form of stubby rectangles, with square cross sections. There is a slight pleochroism, especially in the thicker sections, where the edges of the crystals often show rims with pink and green colours.

The composition of the centres of the crystals is fairly constant at about 5 % Fs. There is a sharp increase of iron at the edges with extreme compositions of 23 % Fs. Average compositions as shown by the majority of 2V measurements indicate a composition of 12 % Fs. The sudden increase of iron is seen by both the presence of pleochroism and the increase in birefringence; it may be measured by the change in optic angle and refractive index. The orthopyroxene crystals are sometimes cracked and warped suggesting that they were transported after they had crystallised.

Optical Data: R. I. 1.676—1.695 (Z).

2V centre +ve 74°. edge —ve 76°. average 90°.

Olivine is very sporadically distributed, occuring in both dykes but only half the slides. It has the same characters as described from the 70° group and from the Sister dyke, and shows a similar variability in composition. Generally the range is from 20—30 % Fa.

Ore minerals. Apart from the secondary iron minerals formed after olivine there are a few cubes and octohedra of (?) magnetite, with minute inclusions of sphene. Where primary the ore is rimmed by biotite.

There are occasional interstitial quartz grains which may be secondary.

No apatite has been found in these dykes.

The Contacts of the Feeder and Pâkitsoq Dykes.

Since the original drafting of this report specimens of the margins of the Feeder and Pâkitsoq dykes have become available.

As mentioned above the contact relations of the two dykes differ markedly and the following brief notes illustrate this.

In hand specimen the Påkitsoq dyke shows a fine grained chilled rock, set with unoriented mafic phenocrysts up to 3 mm in length but usually slightly smaller than the phenocrysts from the centre of the dyke. They are almost all euhedral orthopyroxene, a few augite crystals occur. The general texture can be seen in Pl. 3b. The ground mass is dominated by needle shaped clinopyroxenes some nearly 1 mm long but only .04 mm in cross section. No sign of flow texture could be seen.

The plagioclase is also needle shaped and appears to be later than all other minerals. Needles of plagioclase assume a roughly parallel position in patches, and the texture could be called "trachytic" but it seems doubtful whether this is due to flow but rather to some phenomenon of crystallisation. In places the small crystals coalesce and it would appear that the chilled margin shows the first stages in the formation of the texture described from the dyke centres.

The ground mass also contains biotite and ore minerals and a few fragments of olivine. The orthopyroxene sometimes contains small brown isotropic grains of high relief believed to be chromite.

Samples from the Feeder dyke are highly variable, some show a complete mixture of country rock and dyke, giving a fine grained indeterminate mass consisting mainly of sodic plagioclase, quartz and hornblende. Other specimens show the same texture as the centre of the dyke, with no sign of chilling or mixing.

c. The Aornit Dyke.

This dyke differs considerably from those dykes described so far, but the mineralogical characters are such that there would appear to be a logical sequence. In the composition of the dyke the mafic minerals are no longer the dominant constituent, forming only 30 $^0/_0$ of the rock by volume, while quartz (7 $^0/_0$), and microcline (4 $^0/_0$), make their appearance. Plagioclase forms 50 $^0/_0$ of the rock and the iron ore is slightly increased to 4 $^0/_0$.

Olivine has disappeared completely.

Both in texture and composition there are several significant changes in mineralogy, the most interesting of which is found in the pyroxenes. There are now three pyroxenes present, pigeonite making its appearance as a late mineral, either rimming augite or forming the commonest member of the ophitic pyroxene, which is itself more common than previously. Augite usually rims orthopyroxene.

The plagioclase has become far more euhedral as the mafic minerals have diminished in importance.

The more detailed mineralogical differences are considered below.

Plagioclase is more markedly zoned both in the individual crystal and in the total range of those present. The total range of composition is from 65 $^0/_0$ An.—15 $^0/_0$ An., one crystal often covering the greater part of the range. (The majority have a difference of some 30 $^0/_0$ An. between centre and rim). Although the zones show more breaks than those seen from the dykes described previously, there is no sign of reverse or true oscillatory zoning. As the plagioclase becomes more euhedral so there is greater space for the interstitial minerals; and the development of over 10 $^0/_0$ of these

Fig. 11. The Quartz-Plagioclase-Microcline intergrowth, slightly simplified from the Aornit dyke. Slide no. 19391 G.G.U. Q = quartz, Pl = plagioclase, CP = clinopyroxene, M = microcline. There are only two quartz crystals visible in this field, the one is left plain, the other black. The plagioclase within the intergrowth is seen to be in optical continuity with the main crystals.

minerals is probably a reflection of this. The fact that the plagioclase forms distinct crystals probably means that they were able to move in the half solidified magma in contrast to those of the Feeder, Pâkitsoq, and Sister dykes: this seems a possible explanation for the presence of more distinct zones.

The Quartz-Microline-Plagioclase intergrowth. These three minerals form a very complex intergrowth between the normal plagioclase crystals.

At the sodic edge of the felspar crystals there is often a rim of clear quartz, which may be a complete crystal surrounding the plagioclase. Outside this rim the plagioclase appears again and is usually in optical continuity with the more sodic part of the main felspar. The intergrowth between quartz and plagioclase is controlled by the latter's crystallography, the boundaries being a series of straight lines. To further complicate the relationship, microcline showing the fine cross lamellae of this mineral and a 2V of 80°—82°—ve, also intergrows with the quartz in the centre of the interstitial spaces. A slightly simplified drawing of this relationship is shown in figure 11 while Plate 2a shows a photograph of a typical intergrowth.

In places the above relationship is not found; the plagioclase may be sharply separated from the intergrowth, or even its own albitic rim, the break occuring at about An. 30, often with a brown staining of the felspar.

The Pyroxenes. Figure twelve shows one of the simplest examples of the three pyroxenes together, often the relationship is too complex for the Lietz U. M. 3. to resolve. Generally the sequence appears to be:

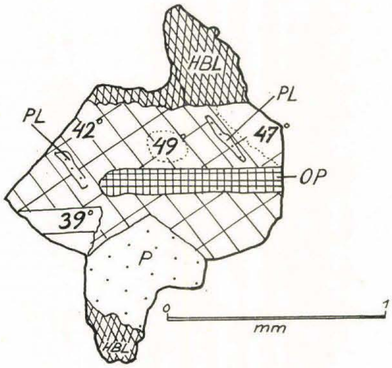

Fig. 12. Complex relationship between the pyroxenes in the Aornit dyke. G.G.U. no. 19391. OP. = orthopyroxene. PL. = pigeonite lamellæ. P = pigeonite. HBL. = Hornblende. The figures refer to the 2V measurements in the augite.

subhedral orthopyroxene, granular augite, ophitic pigeonite. The last two minerals may be in optical continuity.

The clinopyroxenes from this dyke show considerable variation in their composition. This is seen both by the formation of pigeonite and the variable optical properties of the augite. The 2V of the latter varies from 52°—38°, the common range being from 48°—42°. This variation is seen both in individuals, and in measurements from separate crystals, fig. 12.

The orthopyroxene is more iron rich than that described from other dykes of this suite: zoning from 16 $^0/_0$ Fs in the centre to highly pleochroic rims of about 35 $^0/_0$ Fs. The refractive index of these iron-rich edges is 1.708 (Z). The average composition of the crystals as taken from 2V measurements is about 20 $^0/_0$ Fs.

Accessory and secondary minerals: The amphibole which rims the pyroxene, may have been formed at the same time as the intergrowth between quartz and felspar. It is distinctly more hornblendic than that from the dykes described earlier from this suite. It has a pleochroic scheme with X grass green, Y and Z blue green. This is far darker than the tremolite of the Sister dykes.

There is a slight increase in the amount of iron minerals present, mostly associated with the late stage products. Magnetite as small subhedral grains is usually surrounded by biotite.

Contact specimens from the Aornit dyke have not been found fresh enough for detailed work. However, they show one very important feature in that they possess plagioclase not mafic minerals as the main phenocrysts. They also show the relatively high percentage of plagioclase seen in the specimens from the centre of the dyke. No orthopyroxene crystals have been preserved in the specimens examined but there are several patches of hornblendic fibres which would appear to have replaced this mineral.

d. The Alángua Dyke.

This dyke is some 25 kilometres north of the main group described here, and has many important differences. It approaches a normal dolerite more closely and is far less distinctive than the orthopyroxene-rich rocks described above. The hand specimen shows a fine grained, semi-ophitic rock, with no distinctive features. The texture varies from granular to ophitic within one slide, the proportion of ophitic pyroxene is higher than from any of the dykes described so far.

Plagioclase forms 51 % of the rock; it is highly zoned, moderately sized (1 × .5 × .1 mm) and shows some bending and breaking, which suggests that the crystals may have been transported in their solid form. The interstices are full of ophitic pyroxene and quartz/plagioclase intergrowth.

The plagioclase composition ranges from 65 % An. to 30 % An., with the average being about 50 % An. There are occasional crystals with composition of 70 to 80 % An. in the centre. This is probably another indication that the plagioclases were not formed in place.

The intergrowth is similar to that described from the Aornit dyke except that there is no microcline present. A greater percentage of the intergrowth is not in continuity with the main felspar crystals in this dyke.

Clinopyroxene forms 39 % of the rock, it is formless, fresh, and generally twinned. The distribution of the two types present show that the pigeonite was usually the later of the two, it forms rims to the augite and is the commonest constituent of the ophitic pyroxenes. There is a little formed by exsolution from the augite. Detailed study of the boundary between the two minerals shows this to be very complex; this is probably due to simultaneous exsolution and crystallisation from the magma. There are fine examples of "herring bone structure" where the pigeonite has exsolved on either side of the 100 twin plane in augite.

The composition of the augite is less calcic than the dykes containing large amounts of orthopyroxene. 2V varies from 48° to 33°; while that of the pigeonite varies between 8° and 0°. The composition of the augite varies both by zoning and patches.

Orthopyroxene is very sporadically distributed, and the exact proportion is difficult to judge, as the point count of 1 % is probably an underestimate.

Those crystals proved to be orthopyroxene are moderately large for this dyke, averaging 1 × .5 × .5 mm. They have a refractive index of 1.686—1.694, and an average 2V of 80°, indicating a Fs. content between 16—24 %.

As in the Aornit dyke, there is a slight increase in the content of iron minerals, accompanying the late stage minerals such as quartz and albite. They are all poorly shaped interstitial grains appearing to be mainly magnetite. They are accompanied by a little hornblendic amphibole and some biotite in the areas of the quartz-felspar intergrowth.

Summary of the older dykes.

The mineralogy and field relations of these dykes suggest that they were formed at approximately the same time from magmas of similar ultimate origin.

The 10° set illustrates stages in a logical sequence between widely different end members. What can be seen of the 70° set suggests that they may also be in a similar sequence beginning with a slightly less magnesium rich magma.

The 10° set.

Two interdependent factors which cause the variation in mineralogical composition and texture may be illustrated from these rocks. They are: 1) Order of crystallisation; and 2) Sorting, probably under gravity.

Order of crystallisation. By considering all the specimens from the five dykes the following sequence can be established:

Olivine
(Fa 10 %. . . . . Fa 50 %)
Orthopyroxene
(Fs 5 %. . . . . Fs 35 %)
Augite. . . . . ?
Pigeonite
Late iron ore, Hornblende
Biotite
Quartz Albite Microcline
An. 10 %
Plagioclase
An. 70 %

No single dyke shows the whole sequence, although there is enough overlap to suggest that it may be correct. The two series, Mafic and Felsic, are not directly comparable as will be shown later.

All the mafic minerals show an increase of iron towards the end of their crystallisation. It is interesting to note that the orthopyroxenes from the Alángua and Aornit dykes start with a much more iron-rich composition than that of the other dykes. Plagioclases show the normal sodic enrichment towards the end of their crystallisation.

The occurrence of three pyroxenes in a rock is unusual, according to the literature (HESS 1941). The presence of orthopyroxene and pigeonite in the same slide must be due to a change in conditions during the crystallisation of the dyke. This may be either the crossing of the orthopyroxene/pigeonite boundary, or it may be caused by the influence of other constituents accumulated in the magma during late crystallisation. POLDERVAART (1947) has suggested that the presence of water as a volatile during the crystallisation of pyroxenes may cause pigeonite to be the stable member of the pair. Conditions for the concentration of such volatiles seem to be present in the Alángua and Aornit dykes, both have large intergranular spaces, now full of late products such as quartz and microcline. (See EDWARDS 1942 p. 579).

One of the most interesting features of the dykes is the relation between the mafic and felsic minerals. In general in the dykes where there is a high percentage of mafic minerals present the plagioclase is poor in anorthite; this is the opposite to what might be expected, and seems to be connected with the time at which the felspar started to crystallise relative to the mafic minerals. This is shown in the table below, correlating texture, percentage of mafic minerals and plagioclase composition.

Dyke	Texture and Mafic $^0/_0$	Plagioclase
Sister	90 $^0/_0$ Mafic minerals Interstitial laths of felspar	An. 45 $^0/_0$ and lower
Feeder & Pâkitsoq	45 $^0/_0$ Mafic minerals. Poikilitic felspar enclosing early mafic minerals	An. 55 $^0/_0$ and lower
Aornit & Alángua	Average 35 $^0/_0$ Mafic minerals Subhedral felspar and late ophitic pyroxene	An. 75 $^0/_0$ and lower

The most acceptable explanation would seem to be that each rock is made up of two parts: 1) partially sorted early minerals, 2) whatever crystallised from the remains of the magma on final consolidation. Thus the Sister dykes show one extreme, with the early mafic minerals accumulating to such an extent that there is only interstitial felspar. The Aornit and Alángua dykes show the other extreme with the concentration of early felspar and late ophitic pigeonite. The idea that this is due to movement and sorting of crystals is supported by the breaking and bending of the first formed minerals in several specimens.

These observations have been carried out on a handful of specimens from dykes that cover quite an appreciable area. Further work when specimens are available might well prove some of the conclusions erroneous, but the writer hopes that the problem is interesting enough to pursue further.

7. PETROGRAPHY OF THE YOUNGER DYKES

As described in the first section in this paper, these dykes may be divided into three sets on field evidence, but attempts to carry these divisions into the petrography have so far met with little success. It is therefore unnecessary to separate them in the petrographical descriptions below.

These dykes differ considerably from the normal development of the older group as shown by the Feeder or Pâkitsoq dyke. They are less rich in mafic minerals with a total absence of orthopyroxene; and the olivine, where it occurs, is not the characteristic form seen from both sets of the older dykes. Texturally the felspars are better shaped in these rocks, and exhibit better zoning, while the pyroxenes are often ophitic. Among minor differences the presence of apatite as an accessory may be mentioned.

In hand specimen the most striking feature seen in any of these dykes is the presence of large felspars in the Blåbær dyke. These are up to $6 \times 3 \times 4$ cm and show a curious mottled appearance in the hand specimen. This is seen to be due to clinozoisite almost completely replacing the felspar in the centre of the crystals. One dyke (14954) shows a micro-layered structure with bands of pyroxene at 1 cm intervals. This only shows up in thin section so no field relations are known.

The rocks are more subject to alteration than the older group, especially the north east set, which runs parallel with the main fault direction in the area.

Apart from the large phenocrysts from the Blåbær dyke, grain size is fairly uniform throughout these dykes and is smaller than seen from the older group. Plagioclases average $1 \times .5 \times .2$ mm while the pyroxenes when forming compact crystals average $.5 \times .4 \times .4$ mm.

The texture appears to be controlled by both the relative proportions of the two main minerals and the order of crystallisation. Where pyroxene forms a relatively high proportion of the rock as in the north-west set (14956 and 14964) its form is subhedral, while in the pyroxene poor rocks, such as the Talerulik dyke (6289), the late pyroxene, usually pigeonite, fills in the spaces between the felspar laths ophitically. Pl. 2b (See Krokström 1932),

The felspars show considerable reverse zoning and signs of mechanical damage suggesting that they were moving while they were solidifying.

Mineralogy.

Plagioclase forms moderately euhedral crystals, showing very strong zoning. Twinning is usually complex, with Albite, Carlsbad and Pericline types predominating. The phenocrysts from the Blåbær dyke are exceptions, as they are simply twinned on the Albite law.

The composition ranges between An. 70 % at the centre to ca. An. 10 % at the rims. Most of the crystals range between An. 60 and An. 35 %, the central part of the crystal often showing oscillatory zoning, while the outer part shows an even change in composition. This suggests that the crystals were free to move in the first part of their crystallisation and that their zones reflect slight variations in the magma, while the even outer zones suggest that the crystals had come to rest and that the conditions changed gradually and regularly. Oscillatory zones from one crystal do not agree with the next in the same slide, thus it appears that the crystals were independent units. Strangely enough the phenocrysts from the Blåbær dyke do not show the same range of composition as the smaller crystals and they are generally less calcic. As these plagioclases differ both in their composition and zoning from the normal type seen in these rocks it seems quite probable that they are inclusions from another source.

Some of the oscillatory zoning found in these dykes is illustrated in the accompanying drawings including one of a remarkable crystal with a centre of 93 % An. This is thought to be due to contamination by country rock (Slide 14964) fig. 14.

Pyroxenes are represented by both augite and pigeonite in all three sets, although in the 140° the pigeonite is only a minor constituent exsolved from the augite. In the other two sets the pigeonite is mainly late magmatic, the amount present as exsolution lamellae being negligible.

The augite is in general less calcic than that found in the older group, although the same forms of variation are repeated here. Crystals are generally less calcic and more iron-rich towards the edge, this is accomplished either by normal zoning or by a patchy break up of the crystal into areas of slightly different composition (fig. 13a). Pigeonite forms a complex intergrowth with augite as may be seen in figure 13b from slide 6289. It normally occurs at the edge of augite crystals but may sometimes be seen at the centre. Optical measurements show there is some difference between the pyroxenes from the 3 sets of dykes.

The 50° set shows a distinct break between pigeonite and augite, with the augite zoning between 2V 48° to 32° and the pigeonite between 10° and 0°. The 85° set shows a far less distinct break between the two pyroxenes, the augite is subcalcic, with a 2V under 40° while the pigeonite varies from 0°–20°. Unfortunately it was not found possible to measure the crystallographic orientation of the pigeonite. One of the 140° set has calcic augite, with 2V over 50° but as this is the same dyke that shows probable contamination of the felspar with anorthitic country rock the results are probably misleading. Refractive index measurements were hampered by impurities and the results do not seem reliable enough to publish.

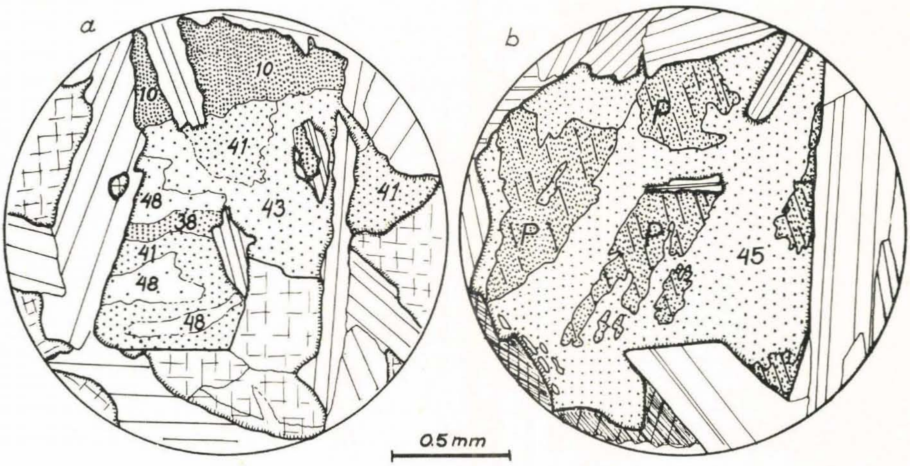

Fig. 13. Two examples from the Talerulik dyke, (G.G.U. 6289) illustrating the variation in the optical properties within individual pyroxenes.

a. Shows the "patch" form of variation, with discrete areas within a single crystal possessing different 2V's. Note the pigeonite (10°) at the edge of the crystal. All the pyroxene in the drawing belongs to one individual, divided by a twin plane. The directions X.Y.Z. are constant in each twin, although the optic axial angle varies.

b. Shows the distribution of pigeonite of a second type, where it appears to penetrate into the centre of the pyroxene crystal. The small window of plagioclase may indicate that the section passes close to the edge of the crystal.

Olivine. This mineral only occurs in the Talerulik dyke (6289). It is only seen as unstable relics, almost completely replaced by secondary minerals. It shows none of the character of the olivine seen from the older dykes, unfortunately it has decomposed too far to measure the com-

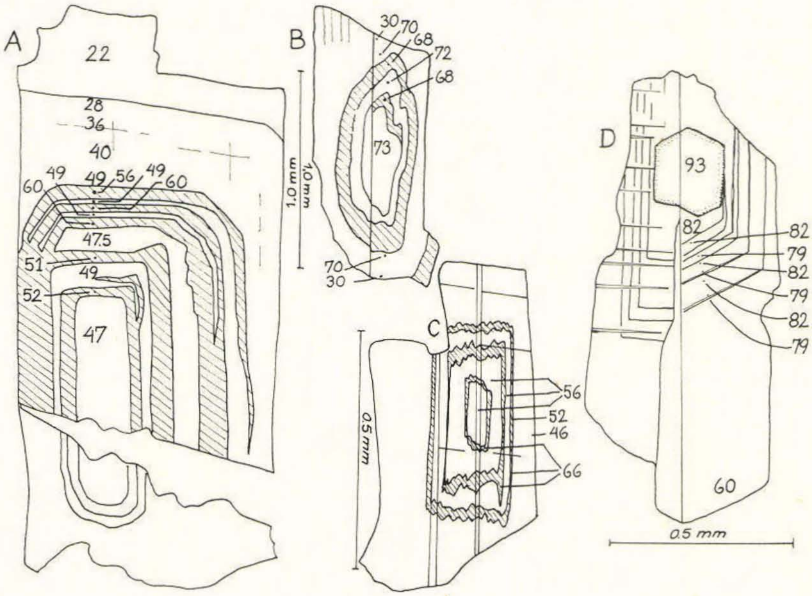

Fig. 14. The oscillatory zoning of plagioclases from the younger dykes. In general there is a strongly zoned, highly variable central area, followed by smooth zoning towards the edge of each crystal.
Examples are from the following dykes. A. G.G.U. 14805 Kangia swarm (50° set). B and C. G.G.U. 6289 Talerulik (50° set). D. G.G.U. 14964 Atangmik (140° set).

position. Inclusions are not present on the same scale or in the same form as seen from the older dykes and the characteristic pleochroism is missing.

Quartz. With the exception of the Blåbær dyke the interstitial quartz, although present to some degree throughout, does not form intergrowths with the plagioclase, but forms irregular grains, often associated with the secondary minerals in the slides. The Blåbær dyke shows very fine intergrowth between the quartz and plagioclase, in the same way as seen in the Alángua dyke from the older group.

Secondary minerals. The alteration of plagioclase in many of the slides leads to the formation of plentiful sericite and clinozoisite. The central part of the large felspars from the Blåbær dykes is often replaced almost completely by these minerals arranged in bands suggesting zones although zoning is not so apparent in the fresh mineral. Sericite is formed along the albite twin plane or along sets of cleavages, giving a very ordered appearance.

As might be expected the clinozoite from the felspar is iron-poor, with a +ve 2V of 85°, X/c 8°, and low interference colours, while the clinozoisite from the surrounding mafic minerals has a far higher birefringence, and is more iron-rich.

Amphibole replaces pyroxene to a variable extent throughout these slides, from an indeterminate rim, to a stage where there is no pyroxene left. There is often more than one amphibole present in a slide, most of them appear to be in the hornblendic group of these minerals, with a general pleochroic scheme of: X = colourless. Y = green, X = blue green.

The commonest mode of occurrence of the replacing amphibole is a grain with a formless centre of thin fibres with no preferred orientation and pale colours, surrounded by a more distinct crystalline rim, with darker greens and the typical amphibole cleavage developed.

The optical measurements from these amphiboles show Z/c 15°—17°. 2V varies between 60° and 70°.

Olivine is replaced by a pale fibrous magnesium amphibole and by (?) bowlingite.

Ore minerals form an appreciable part of several of the younger dykes, reaching their maximum in 35835 as 10 % of the rock. They appear to be mainly magnetite, probably with some ilmenite and a little pyrite. The ilmenite is seen as skeletons of iron ore crystals with neat equilateral triangles formed by their ribs.

8. THE PETROGRAPHY OF THE RED DYKE

This dyke is treated as a separate unit on both field evidence and mineralogical grounds. It is a 2 metre broad dyke, fine grained and containing many vesicles and phenocrysts. The rock when fresh is dark grey, but the surface weathers to the colour that gives the dyke its name.

In section the rock is seen to consist of phenocrysts of clinopyroxene; unstable olivine, now replaced by antigorite and chlorite; and calcite-filled vesicles; all set in a fine grained ground mass of plagioclase, clinopyroxene, biotite, spinel, and an amorphous almost isotropic glass. One large corroded phenocryst of amphibole has been found.

The rock texture is remarkable for the fact that the primary minerals are all euhedral, the intercrystalline spaces being filled with amorphous glass, which appears to be variable in composition. This makes the accurate estimation of the composition of the rock impossible. The grain size varies from 10 × 10 mm in the largest pyroxene phenocryst, to the submicroscopic inclusions in the glass. The ground mass felspars average .5 × .1 mm, while the ground mass pyroxenes are slightly smaller, Pl. 3a.

Pyroxene. There is a tendency for the pyroxene to be divided into two groups on size; the one, large phenocrysts; the other ground mass.

There is, however, no complete break between them, and all appear to be of the same generation. All the pyroxenes are intensely zoned, often show hour glass structure, and sometimes show a distinct pleochroism at the edge. Twinning is rare; sometimes there is a very irregular boundary between two individuals, presumably as they interfere with each other. The zoning reflects the large variation between the composition of the centres and margins; the centres of the crystals are very diopsidic, with a 2V of 58° and Z/c of 39° while the rims are far more ferriferous, with a 2V of 44° and a Z/c of 46°. These are the average measurements of 16 crystals. The centres of the pyroxenes often show carbonate inclusions; this may account for the high calcium content of the central zones.

Olivine. Before alteration the olivine formed euhedral phenocrysts up to 5 × 3 mm in the sections but there is little left of the original mineral. Many of the vesicles are the shape of olivine phenocrysts, and seem to have been formed when this mineral decomposed. The optical properties of the olivine still remaining show it to be an exceptionally magnesium-rich form. A 2V of 84°—86° +ve suggests a very high forsterite content. The alteration products from this olivine show no iron-rich products, as might be expected.

Plagioclase. Fresh plates of plagioclase averaging .2 × .25 × .03 mm, are seen in thin section as laths with complex Albite and Carlsbad twins. They show a strong relief, indicating their high anorthite content. Because of their small size and strong zoning, it is almost impossible to obtain satisfactory results using full orientation techniques for composition determination. The Carlsbad/Albite curves show the plagioclase to have a central composition of 90—95 $^0/_0$ anorthite, which zones down to 40—50 $^0/_0$ anorthite at the rims.

Biotite. In spite of the small size of the crystals this mineral forms an appreciable constituent of the rock, in region of 10—15 $^0/_0$. It occurs as perfectly euhedral plates, .03 mm in diameter, and also as rims to the ore minerals. Pleochroism is very strong from straw to a dark reddish brown.

Ore Minerals. Spinels occur as small octohedra, which are sometimes non-opaque, and dark brown in colour. These are thought to be chromite while the slightly smaller opaque octohedra present are probably magnetite.

Amphibole. Only one crystal has been seen of this mineral, 4 sq mm in section. It has a generally rounded form, and a slight discolouration at the edges, suggesting that it has been corroded by the magma. The optic angle of 86° +ve suggests an unusual composition. Z/c measures 22.5°, the pleochroism varies from X very pale brown, to Y and Z deep reddish brown.

Ground Mass. The interstitial ground mass is irregularly distributed between the euhedral minerals. It contains minute rods of felspar, and small poorly shaped pyroxenes set in a glass, the refractive index of which does not seem to be constant.

Alteration Products. These were formed mainly from the olivine, and consist of: carbonate, antigorite, and a colourless amphibole, probably anthophylite.

The carbonate is often arranged parallel to the original c axis of the olivine, or occurs filling cavities in the altered mass. The composition of the carbonate could not be determined optically, but microchemical tests suggest that it is either dolomite or magnesite. This would agree with the large amount of magnesium present in other minerals.

9. CONCLUSIONS

The number of specimens is too small to ensure that the collection studied is representative. Moreover fresh specimens from the contacts are only available in a few cases. Our conclusions are therefore drawn with some reservations.

The main petrographic division of the dykes follows the two main groups that the field work suggested, an older generally olivine and orthopyroxene bearing group and a younger olivine-free pigeonitic group.

The gradation described in the older group, from a very mafic rich rock to a normal tholeiite prevents the use of absolute criteria to distinguish the dykes. The more tholeiitic members of the older group show features such as abundant interstitial quartz, the development of pigeonite instead of orthopyroxene and an ophitic texture, which are all characteristic of the younger group.

This makes it impossible on mineralogical evidence alone to ascribe an individual specimen to either of the main groups. We have even no definite proof that the olivine-orthopyroxene association thought to be typical of the older group does not occur within the younger group. A careful study of a larger, representative collection could confirm or eliminate this reservation.

However, as the present petrographic evidence is in agreement with the field work there seem no reasons to doubt the classification drawn up.

One of the most interesting problems raised by the study is the mechanism of differentiation in the older dykes. The authors find it reasonable to suppose on structural and mineralogical grounds, that the older dykes belong to two distinct but related episodes. What is far from clear is the relationship between dykes of the apparent series seen in the 10° set.

It seems clear that the rocks such as to be found in the present erosional surface of the Sister dykes are not formed by the "freezing" of a primary magma and that a fairly intensive differentiation must have taken place, to account for the large concentration of mafic minerals. The chilled margins of the dykes show that the composition was determined before injection and is not due to differentiation in the dyke fissures.

It is tempting, especially in the laboratory, to postulate that the apparent series illustrates the tapping of one large differentiating magma body, each dyke receiving its distinctive composition from one facies developed in the chamber. A magma chamber large enough to feed the dykes exposed in the present area (3000 square km) would surely have a larger effect on the structural environment than a rather sparse scatter of parallel dykes, especially when it is remembered that the erosional surface is quite deep. (The present surface is thought to be of the order of 3 km lower than the surface at the time of the Fiskefjord faulting. The facies relations seen along these faults were used in conjunction with BARTH's data (BARTH 1952, fig. 137) to arrive at this figure).

The alternative to this theory which would seem to require a partial remelting of a subcrustal layer not connected to the tectonic pattern of the basement is outside the scope of this paper.

Postscript:

After this report went into print, A. RITTMANN has published an interesting paper on the origin of magmas (Zur Herkunft der Magmen, Geol. Rundschau, Bd. 48, pp. 1—10, 1959). RITTMANN's concepts of hypo- and pyromagmas may offer a clue to the differentiation problem posed by the older group of dykes.

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Færdig fra trykkeriet den 31. december 1960.

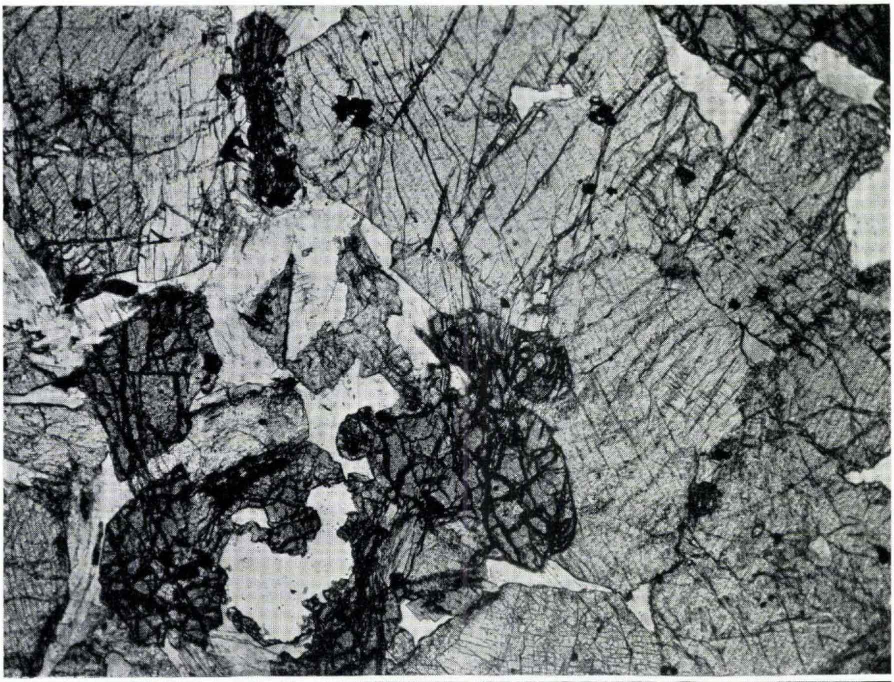
PLATES

Plate 1.

a) The Sister dyke. G.G.U. No. 14917. 33×. 1 nicol. Note the high relief of the olivine, and the way in which this mineral has been crushed between the pyroxenes in the top left. The interstitial nature of the plagioclase can be seen, and the interfering nature of the pyroxene boundaries which prevent the formation of euhedral crystals.

b) The Feeder dyke. G.G.U. No. 14989. 27×. X nicols. The euhedral orthopyroxene (light) is enclosed in a large poikilitic plagioclase.

Photo: C. Halkier.



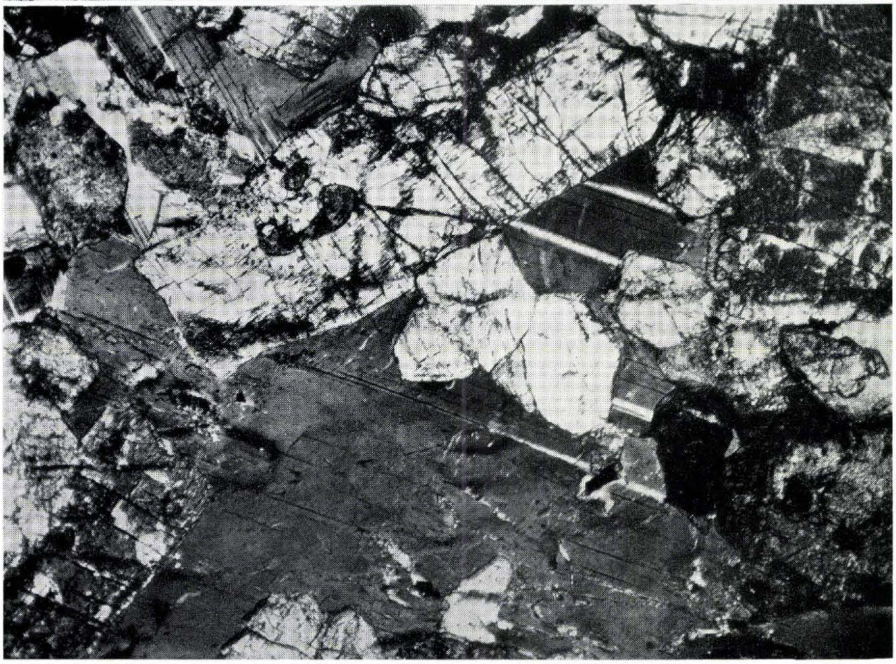


Plate 2.

a) The Aornit dyke. G.G.U. 19391. 67×. X nicols. The Quartz-Plagioclase-Microcline intergrowth.

Note that the plagioclase of the intergrowth is in optical continuity with a "parent" grain and that the quartz felspar boundaries are plane surfaces. Microcline twinning can be seen in the centre of the intergrowth.

b) The Talerulik dyke. G.G.U. 6289. 33×. X nicols. Note the ophitic texture, and the bent nature of the felspar lath in the centre, probably due to movement of the crystal during solidification of the rock.

Photo: C. Halkier.

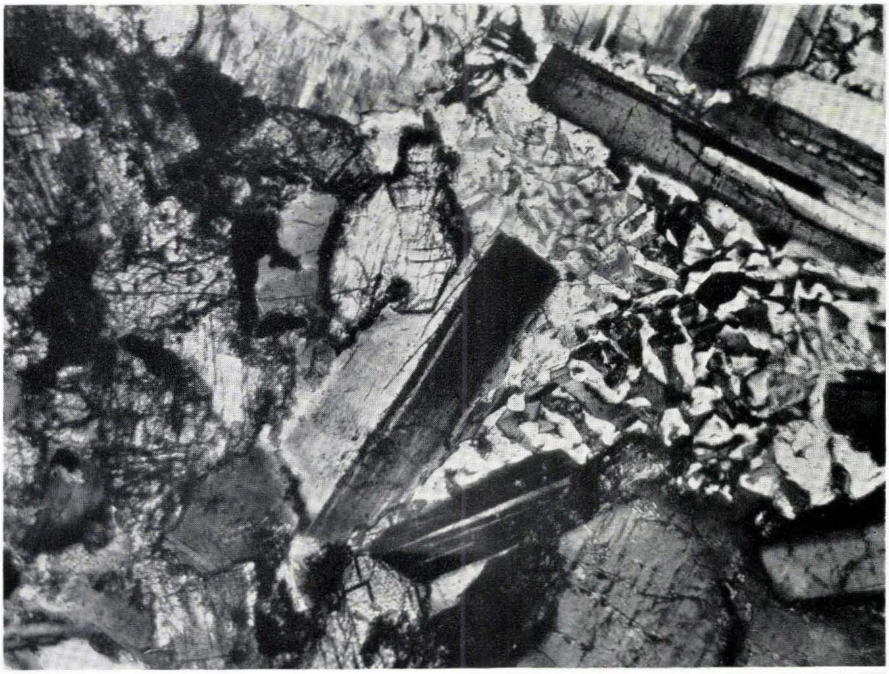


Plate 3.

a) The Red dyke. G.G.U. No. 14806. 33×. 1 nicol. Note the large pyroxene phenocrysts with inclusions of calcite in them, the zoning can be seen on the euhedral faces in the centre. Biotite, plagioclase, pyroxene, and ore minerals can be seen in the ground mass. Photo: C. HALKIER.

b) The Pâkitsoq dyke, chilled margin. G.G.U. No. 31103. 10×. No nicols. Note the euhedral orthopyroxene and the less regular augite as phenocrysts. The fine augite needles in the ground mass can also be seen.

Photo: P. POVELSEN.