GRØNLANDS GEOLOGISKE UNDERSØGELSE
BULLETIN No. 52

ON SOME PRE-CAMBRIAN METADOLERITES FROM THE CENTRAL IVIGTUT REGION SW GREENLAND

BY

ERLING BONDESEN AND NIELS HENRIKSEN

WITH 12 FIGURES IN THE TEXT
AND 1 PLATE

Reprinted from
Meddelelser om Grønland, Bd. 179, Nr. 2

KØBENHAVN
BIANCO LUNOS BOGTRYKKERI A/S
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Abstract.

After their consolidation, the Ketilidian gneisses were transversed by several generations of tensional, doleritic dykes—the Kuánitic dykes. During a later episode (the Sánerutian) these dykes were metamorphosed to varying degrees of alteration which increase in the described area from west to east. Along a specific metadolerite, which can be traced approx. 40 km, the metamorphic grade changes from greenschist to amphibolite facies. In the western parts static conditions and in the eastern parts dynamic conditions, prevailed during the alteration. Sánerutian shear zones in the eastern parts depict the dynamic conditions found here.

CONTENTS

Page

Abstract 2

Introduction and acknowledgements 5

General geology 6

The Kuánitic dykes 9

The chronology of the Kuánitic dykes 9

General description of the Kuánitic dykes 12

Description of the Kuánitic dykes in the areas mapped 12

A. *The Islands:*

a) The oldest generation I, in NNW 12

b) The NE- and NNE-trending generations II and IV 13

c) The E-W-trending generations Va & b 13

d) Strongly sheared minor dykes 15

B. *The Mainland:*

a) The NE-trending generations II and IV 15

b) The NNW-trending generations III a & b 16

c) The E-W-trending generations Va & b 16

d) Irregular dykes 16

Petrology of the Kuánitic dykes 19

General petrographical description 19

Subdivision of stages of alteration 21

Stage 1. The lowest stage of alteration, the western part of the Islands 21

Stage 2. The eastern parts of the Islands 23

Stage 3. The lowest stage of alteration on the Mainland 24

Stage 4. The stage of alteration in the Kuánit area 26

Stage 5. The stage of alteration in the Central Mainland 26

Stage 6. The highest stage of alteration on the Mainland 28

The metamorphic alterations in the Kuánitic dykes 29

The Sânerutian episode 32

Field relations of Sânerutian events 32

The Sânerutian effect on the dykes 32

Post-Kuánitic shear zones 34

Metamorphic alterations in the post-Kuánitic shear zones 36

The pre-Kuánitic metamorphic facies of the surrounding gneisses 37

Conclusions 38

References 42

INTRODUCTION AND ACKNOWLEDGEMENTS

In the last decade extensive mapping has been performed by the Geological Survey of Greenland (G.G.U.) in the Ivigtut region of Southwest Greenland. During this mapping, detailed structural work in the pre-Cambrian gneisses and shists has lead to a general chronological synthesis of which a provisional scheme has been published by A. Berthelsen (1960). Several other authors, N. Henriksen (1960), A. Berthelsen, E. Bondesen and S. Bak Jensen (1962), Oen Ing Soen (1962), S. N. Ayrton (1963) and M. Weidmann (1963), exemplify this chronology in detailed areal descriptions. A significant marker in the chronology are postorogenic dykes representing a period of dyke intrusion named the Kuánitic period, derived from the fjord Kuánit, around which these dykes are especially frequent (Berthelsen 1960, Henriksen 1960). The Kuánitic dykes have been subjected to later Sânerutian metamorphism.

During the field work it became evident that the metamorphism of the dykes increased from the islands Tôrnârssuk and Sermersût in the west, through the mapping areas of the present authors, towards the east and south.

It is the aim of this paper to describe the field occurrence and the petrology of the Kuánitic dykes through the mapping areas and describe the detailed chronological development of the Kuánitic period in its type area.

The present authors are greatly indebted to the board of G.G.U., under the auspices of which the mapping was carried out, for permission to publish the results. Our thanks are extended to all members of the G.G.U. staff for valuable discussions. We would like to direct special thanks to prof. dr. A. Berthelsen for his inspiring guidance in the field and for the manner in which he supervised the excellent team work on the Ivigtut sheet (1:100.000). Our thanks also to the Mineralogical-Geological Institute, University of Copenhagen for the excellent working conditions there offered and to P. R. Dawes, B. Sc. who kindly criticized and corrected the English manuscript.

GENERAL GEOLOGY

Based on extensive teamwork A. BERTHELSEN (1960, 1962) has compiled the results of the geological mapping in the Ivigtut region, SW Greenland. This work is a further and more refined development of the classical investigations of C. E. WEGMANN (1938) in which the Ketilidian orogenic cycle, together with the Gardar period of cratogenic events, were established.

The general picture of BERTHELSEN's synthesis shows the Ivigtut region as a culminating migmatitic infrastructure surrounded and partly covered by a metamorphosed non-migmatized suprastructure, the material of which was formed from the Ketilidian sediments and volcanics. The infrastructure partly includes migmatized Ketilidian geosynclinal material and partly earlier basement of which some is preserved (BERTHELSEN 1962, and in press).

After three phases of folding, the consolidated orogen was transversed by tension fractures into which swarms of basic dykes were intruded. These dykes have been called "the Kuánitic dykes". They have in the northern part of the region preserved their original structures, whereas in the southern part of the Ivigtut region they are sheared, folded, broken and partly granitized amphibolites. The alteration of the originally doleritic dykes took place in a period called the "Sánerutian", covering the events from the final Kuánitic intrusion to the beginning of the Gardar period. The Sánerutian events in the Ivigtut region cover metamorphism, faulting, reactivation and mobilization including granitization, all with different spatial arrangement. The Gardar period involved dyking, faulting and emplacement of plutonic centres. Post-Gardar NW-NNW trending dykes of supposed Tertiary age were intruded and finally the Quaternary glaciers left the deeply dissected country very well exposed.

The general chronological scheme, including isotopic age determinations from published sources (MOORBATH, WEBSTER and MORGAN 1960), can be given thus:

Quaternary		— Glaciation.
Tertiary?	Post-Gardar	— NW-NNW trending dykes.
Pre-Cambrian	Gardar	— Faulting, dyking and plutonic centres. 1077–1240 $\times 10^6$ years.
	Sánerutian	— Reactivation (SE of Arsuk fjord) and metamorphism, faulting. 1590 $\times 10^6$ years.
	Kuánitic	— Intrusion of doleritic dykes, faulting.
	Ketilidian	— Orogeny.
		— Sediments and volcanics.
	Pre-Ketilidian	— Basement.

The quoted isotopic age determinations are not derived from rock samples from the area described in this paper.

It might here be mentioned that recently the above chronological scheme has been subject to some criticism, directed mainly at the position of the "Kuánitic dykes". According to a hypothesis based on the view that the country gneisses are reworked pre-Ketilidian basement, these dykes could be of Ketilidian age (WATTERSON in press). However, from the area described here no conclusive answer can be given to the question concerning the chronological position of the dykes and therefore the old established and published chronology will be adopted in this description. Moreover the discussion of the actual position of the dykes does not in any way affect the main purpose of this paper.

The area in question is situated in the central and western part of the Ivigtut region (plate 1), between Arsuk Fjord in the southeast and Tigssalûp ilua (Tigssaluk Fjord) in the north. Towards the west, the area extends to islands in the Davis Strait. The western part, hereafter called the Islands, composed of Tôrnârssuk and Sermersût, has been mapped by E. BONDESEN, whereas the eastern part—here called the Mainland—was mapped by N. HENRIKSEN.

Geologically the area is placed in the central and western part of the Ketilidian infrastructure. The rocks are strongly deformed migmatitic gneisses of lithologically different units. Of these "the Fladland division", consisting of banded and veined quartzdioritic and granodioritic gneisses with characteristic bands of mica schists, is only found in the northern part of the Mainland. The "Gabbro-anorthosite division" is an excellent persisting structural guide zone, made up of quartzdioritic and granodioritic gneisses with bands, boudins and inclusions of gabbro-anorthosite, ultrabasics and amphibolites. In the last unit, the "Sermersût division", numerous amphibolitic and mica schist bands show well the internal structure in quartzdioritic and granodioritic gneisses. All three units can be followed through extensive parts of the Ivigtut region.

Detailed structural work shows three phases of superimposed pre-Kuánitic deformation of which the earliest probably was pre-migmatitic. During the second deformation the main migmatitic structures, with a fairly constant NW-SE trending axis, were formed. The youngest deformation gave rise to a large scale bending and twisting of the main structures, with any variation of the local structures being controlled by the position of the structural planes resulting from the second deformation. (BERTHELSEN 1960, BERTHELSEN et al. 1962). The two last phases of folding were separated by the emplacement of ultrabasic bodies and on Sermersût by an intrusive breccia (BONDESEN 1964).

The geology of the Kuánitic dykes and of the later Sánerutian effects in the area will be dealt with in detail in the following as the main scope of the paper.

Finally the Gardar events in the area are restricted to extensive dyke intrusion, faulting and to the emplacement of the Kûngnât alkaline igneous complex (UPTON 1960). The numerous Gardar dykes range in composition from lamprophyres to granophyres, forming a complicated chronological pattern. Doleritic dykes up to several hundred metres wide are outstanding. Faulting in this period as well as in earlier periods took place to great extent along big wrench faults, together with movements along smaller faults and crush zones. One big fault (WNW-ESE) —the Laksenæs fault—which divides the area, has been analysed in detail and shows a maximum horizontal sinistral displacement of 6 km (HENRIKSEN 1960).

THE KUÁNITIC DYKES

As already mentioned the Kuánitic dykes are especially frequent around Kuánit Fjord. The distribution in this region can be seen in pl. 1. In the following, the field relations of these dykes will be described after an introductory discussion of the chronological relations.

The chronology of the Kuánitic dykes.

Based on intersections and trend directions, as shown on the geological map, the Kuánitic dykes can be divided into an incomplete succession of different generations. Taking into consideration information from the area north of the Tigssalûp ilua (AYRTON 1963) an expanded chronological scheme can be established and this is given below. The frequency of the dykes of the different generations varies from one to several dozen.

V a and b	E-W-trending large dykes		Multiple generations
IV	Younger NE-trending dykes		More than 20 in number
III a/b	a) N60W	b) NNW	a) a smaller dyke b) persistent large dykes
II	Older NE-trending dykes		Probably more than 20 in number
I	NNW-trending dyke		One large persistent dyke

The oldest generation (I) is clearly distinguished from a complex of intersecting dykes belonging to the generations IV and V (see fig. 2). The relations to the dykes of generation II is somewhat dubious, but in one locality a certain small apophysis from one of the generation II dykes on Tôrnârssuk is seemingly intersecting the NNW-trending dyke. Therefore this dyke is regarded to be older than III, although it has the same direction. It should however be emphasized that the generations I and III could be one and the same, as the above mentioned separating criteria are weak.

In the area investigated by the authors several intersections are found between the generations II and IV, but not all northeast-trending dykes can be classified in one or other of these generations. On the Mainland one small N6OW-trending dyke (III a) has intersections with dykes of generations II and IV and it is found to separate these generations in the chronology. One big dyke trending NNW traversing the area on both sides of the sound between Tôrnârssuk and the Mainland and other dykes of the same direction have a somewhat dubious position. They are here referred to one generation—III b. In the area these dykes do not show any intersection with the NE-trending generations II and IV. However, north of the Tigssalûp ilua the same big dyke as found around the sound between Tôrnârssuk and the Mainland is considered as belonging to a generation older than the NE-trending dykes (AYRTON 1963). These NE-trending dykes are here regarded as generation II and/or IV and the dyke called III b, could therefore be classed with either the dyke III a, or with the dyke of generation I. As however the only absolute determinative intersections with a "NW-trending" dyke in the area place this between the generations II and IV, these NNW-trending dykes are here referred to as generation III b.

The youngest generations (V a–b) are represented by irregularly intruded dykes, one of which can be followed from the western Tôrnârssuk to Arsuk Fjord (approx. 40 km). They show intersections as well as multiple intrusion with internal chilling, and because of their close connection in space and in petrological appearance these two generations (V a–b) are regarded as not being far divided in time.

Faulting probably occurred between the different generations, but as most important faults has been rejuvenated during the Gardar epoch, fault criteria cannot in practise be used to distinguish the generations. Moreover it is only possible to correlate one characteristic dyke of the youngest generation (V) across the Laksenæs fault (HENRIKSEN 1960). Furthermore the mapping has not been carried out to such detail that the frequent minor faulting could be applied chronologically.

Based on the geological maps, the directions and frequency of the Kuánitic dykes have been analysed (fig. 1). The diagrams cannot be taken as a true quantitative indication of the different generations since no regard has been taken to the widths of the dykes. Also all smaller dykes below the scale of mapping 1:20,000 have been omitted i. e. dykes less than 2 m. wide. The diagrams clearly show the prominent bifurcation of the northeastern directions corresponding to the generations II and IV. Compared to the determined intersections, the northernmost of these bifurcations corresponds to the older generation II, but this, however, is not the case in one of the dykes on northwestern Tôrnârssuk (see fig. 2).

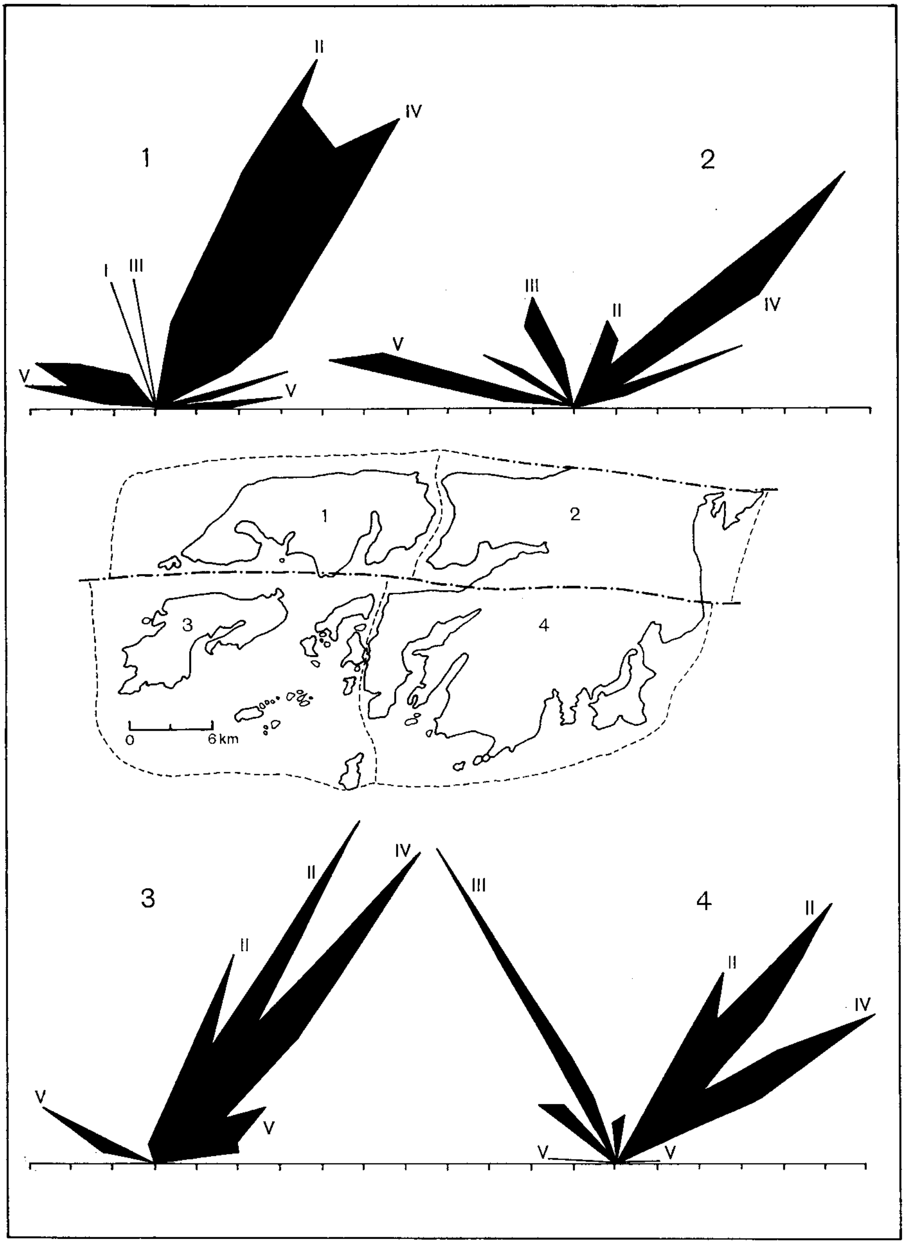


Fig. 1. Analysis of the trend directions of Kuánitic dykes in four subareas, as shown on the map. The Roman numerals correspond to the different generations established. The unit interval used for the diagrams is 1 km, shown on the base line.

General description of the Kuánitic dykes.

On the Islands as well as on the Mainland the Kuánitic dykes show several features in common. Exceptions from these will be treated separately in the following regional description.

The Kuánitic dykes, although metamorphosed, are nearly always clearly dyke shaped, intersecting the gneissic structure. The dyke character is accentuated by numerous structures indicative of intrusive dykes, i. e. apophysis, en echelon, en bajonet trend and megacrysts (phenocrysts and xenocrysts). Multiple intrusions are also present. The dykes are nearly always vertical or very steep in attitude and vary in width from a few centimetres to more than 100 m. With the variation in width, the grain size also varies, together with grain size differences between the central part and the marginal parts of the same dyke. Normal chilling therefore occurred. It should also be noted that in numerous cases the texture in hand specimen can be recognized as originally doleritic over vast areas. However, textural relations will be treated in the petrographical section.

The dykes are generally of a greenish black colour, being somewhat lighter when weathered than as fresh material, and they are often characterized by their rather closely spaced jointing resulting in sharp edged rhombohedra. This joint system seems restricted to the dykes and cannot be recognized in the surrounding gneisses. In the western part of the area shearing and local folding in the dyke margins is common with the rock having been transformed to a schist with strongly deformed quartz veins. The margins then are often mineralized by carbonates, pyrite and chalcopyrite. The above mentioned structural features—jointing and shear zones—suggest that the later Sánerutian movements to a great extent in the western part of the area were restricted to the dykes.

Relic transverse joints are rarely met with but where seen, they occur only as quartz-fillings perpendicular to the contacts. No sign of relic pyrometamorphic effects on the wall-rock have been noted.

Because of the secondary characters mentioned the Kuánitic dykes are clearly distinguished from the numerous later non-metamorphic doleritic dykes of Gardar age. The Kuánitic dykes, in the well exposed terrain, can be traced continuously for up to tens of kilometres.

Description of the Kuánitic dykes in the areas mapped.

A. The Islands.

a) The oldest generation I in the NNW.

This generation is only represented by one dyke approx. 40 m wide, which can be followed across western Tôrnârssuk. Its age relative to other dykes is as mentioned somewhat uncertain; it is certainly older than generation IV (see fig. 2) and possibly also older than generation II.

In its field occurrence this dyke differs somewhat from other Kuánitic dykes. It is light green in its weathered colour, and greyish-green in fresh section. Also the joint pattern is different, not resulting in the characteristic rhombohedron shapes, but in cubic blocks. It also seems to have been less resistant to erosion as in most places it is exposed in a trench.

b) The NE- and NNE-trending generations II and IV.

As mentioned earlier the existence of two NE-trending generations of different age can be demonstrated. It has however proved impossible to refer most of the dykes to one of the two generations with any certainty, and therefore both generations are here and in the following dealt with under the same heading.

The majority of the Kuánitic dykes of the Islands are placed in this group. Their widths vary from 1 m to 50 m, but in few cases they exceed this upper limit. They have all the general characteristics of the Kuánitic dykes mentioned on page 12.

On eastern Sermersût a swarm of 20–50 m broad, slightly curving dykes have this direction. This swarm might be the same one which traverses western Tôrnârssuk, thus being sinistrally displaced approx. 4,5 km by the Laksenæs fault (Henriksen 1960). On Sermersût the dykes are displaced 20–30 m by several small faults possibly of Sánerutian age.

Although being extremely well preserved both texturally and structurally, the dykes on Sermersût generally are sheared along the contacts. The shearing is often accompanied by calcite and quartz veining and these are frequently strongly shear-folded.

On Tôrnârssuk, the NE-trending dykes are moderately well preserved and can generally be traced across the island (6–7 km). Here the most strongly contact sheared examples are found. A few smaller dykes are schistose in character and in the larger dykes it is not uncommon to find local schistose zones in the interior of the dykes. Often joint faces in the dykes show slickensides.

Generally it seems that the NE-trending dykes are much more tectonized than the other more E-W-trending generations. They therefore seem to have been more vulnerable to later shearing.

c) The E-W-trending generation V a and b.

These dykes are distinguished from the other generations by their size and irregular complex trend. Their direction allows them to be followed for the longest distances, not only on the Islands but also

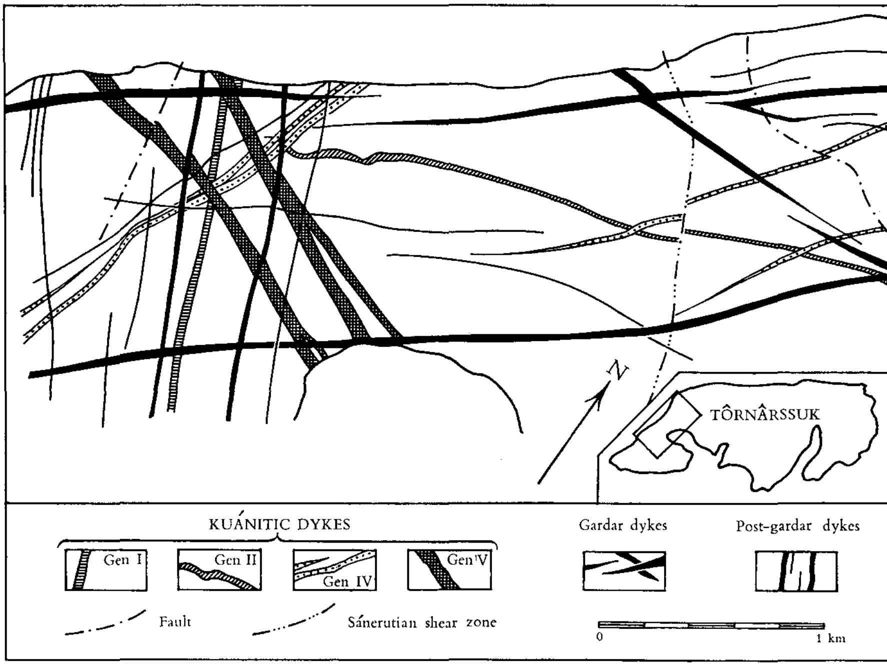


Fig. 2. An example of dyke tectonics from western Tôrnarssuk.

throughout the whole area. One of them is traceable for approx. 40 km from western Tôrnârssuk to Arsuk Fjord. It is because of their persistence and diagnostic peculiarities such as the presence of megacrysts that some of them have been subject to detailed mapping and subsequently to a more extensive petrographical investigation.

On Sermersût, two dykes of different widths exist but these are only partially exposed.

On Tôrnârssuk these dykes have an irregular trend which is partly en echelon and branching. The branching seems merely to be caused by the multiple intrusion of the two generations Va and b, the oldest one being megacrystic. This consists of two 100 m broad dykes, the northernmost one of which is strongly megacrystic and seems to die out in a swarm of xenolithic apophyses. From this dyke a non-megacrystic younger dyke branches out, having an ENE–WNW curving trend for 12 km. The southernmost one of the two large E-W dykes on Tôrnârssuk also branches and has complex trend. Further towards the east on Tôrnârssuk, the E-W dykes again branch and these attain widths of 100–150 m and are in places strongly xenolithic. These dykes show relic doleritic texture in the coarse grained hand specimens from their central parts together with relic gabbro-pegmatitic patches (Eskola 1936). The megacrysts are generally randomly orientated but tend marginally to be parallel to the contact. Although rarely observed, the contacts seem to be moderately sheared.

One strongly megacrystic dyke, as mentioned above, can without doubt be followed throughout the whole area. For field relations on the Mainland see p. 16.

d) Strongly sheared minor dykes.

This group, which has proved impossible to place chronologically, contain strongly schistose biotite rich melanocratic dykes, with subordinate plagioclase, hornblende and epidote. Tourmaline is also found. These dykes are all less than 1 m wide and are softly weathered making it difficult to trace them for distances satisfactory for chronological purposes.

Dykes of this category are found in several directions especially on western Tôrnârssuk, where there is an intense development of larger dykes, both Kuánitic and Gardar.

The strongly sheared minor dykes are regarded as smaller Kuánitic dykes of one or more of the already established generations but because of their small size they have been strongly attacked by the post-Kuánitic movements. It seems that shearing throughout the entire width of the smaller intrusive dykes here corresponds to the sheared contacts of the larger dykes. Their great similarity to established sheared apophysis of larger dykes seems to justify this classification.

However it should be mentioned that these dykes could represent older more tectonized generations or possibly dykes of diverging compositions, as for instance lamprophyres.

B. The Mainland.

a) The NE-trending generations II and IV.

The width of the dykes in this group varies from centimetres to 10–15 m, and often both their widths and their trends are somewhat irregular. Most of the dykes are rather persistent and can be followed up to some km, but a few can only be traced up to 50 m or even less. The grain size of the dykes in their central parts never exceeds medium grained and the margins are always fine grained or even dense. No shearing has been found along the contacts.

Plagioclase phenocrysts are often found, both in the margins and in the central parts, while xenoliths are seldom and seemingly only found where dykes cross old mylonitic zones.

The NE-trending dykes are found over the whole of the Mainland, but with a somewhat denser intensity in the eastern parts of the region.

b) The NNW-trending generations III a and b.

This generation which is found mainly south of the Laksenæs fault is composed of 6 larger dykes and some smaller ones. The bigger dykes are all very regular and can be traced for distances up to 6–7 km. Their width varies from 20–30 m and they are medium-coarse grained in the central parts and fine grained along the margins. In the central parts a relic, blurred ophitic texture can often be distinguished. Phenocrysts are only seldom encountered and when found, they are always small. The weathering colour is a lighter green than is seen in most of the other Kuánitic dykes and this is probably caused by the relatively coarser grain size in the NNW-trending dykes.

c) The E-W-trending generations V a and b.

This category on the Mainland exhibits the same varying trends and structures as have already been described from the Islands. The most prominent dyke is the persistent megacryst bearing dyke, which can be traced from western Tôrnârssuk to Arsuk Fjord. Most of the other dykes are smaller and only some of them contain megacrysts and their habit differs in many ways from the bigger dyke. It is therefore possible that we are dealing with two separate generations, but this cannot be substantiated here.

The big megacryst bearing dyke varies in width from 150 m in the west to approx. 20 m in the east near Arsuk Fjord. Throughout the entire length of the dyke plagioclase megacrysts are found, often occurring with an irregular density. Where the dyke is comparatively narrow, the megacrysts can be found over the whole width, but in its broader parts the megacrysts are mostly restricted to the marginal zones of the dyke. The megacrysts can be up to 10 cm and often have irregular shapes, which suggests that they may be xenocrysts. Such felspar xenocrysts are described from both Kuánitic and Gardar dykes from many parts of southwest Greenland, (BRIDGWATER and HARRY in prep.) and are believed to be derived from a regional common source in the crust.

The big dyke shows a curved trend, and it exhibits two characteristic "en echelon" features. Furthermore it is characterized by evidence of multiple intrusion, one example of which is illustrated in fig. 3.

d) Irregular Dykes.

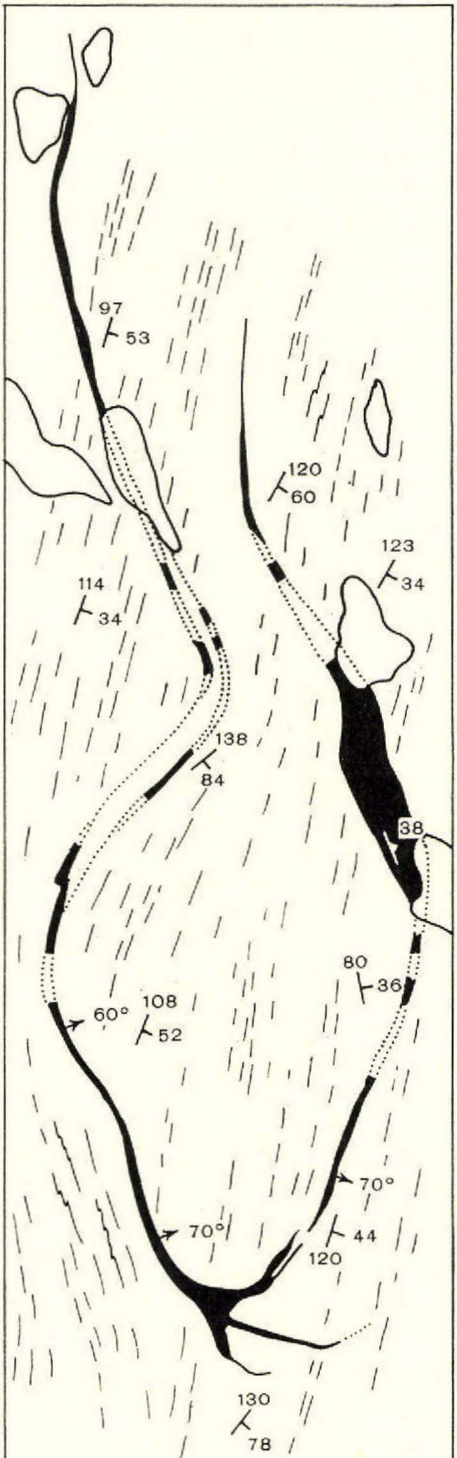
As a special group with no preferred orientation, some very irregular dykes and sills will be mentioned here. They cannot be referred with any certainty to the established generations, since intersections have not been found and since no trend directions are prominent. However, the dykes are regarded as truly Kuánitic, because of the many similarities with these dykes. It should be mentioned that the dykes of this

Fig. 3. An example of multiple intrusion in the big megacryst bearing, E-W-trending, Kuánitic dyke. East of lake 260 m, near Arsuk Fjord.

group cannot be compared to the strongly sheared minor dykes of group (d) of the Islands (see p. 15).

The irregular dykes are found just west of Arsuk Fjord, north of the Laksenæs fault. They are often low dipping and sill-like and occasionally they are concordant to the gneissic structures. Sometimes the same intrusion can change from a dyke to a sill form. Where the dykes are concordant, they are guided by the coarser structural features in the folded gneisses but they in fact cut the small scale folding. When sill shaped, the dykes are normally 1–3 m thick and these often show a schistosity parallel to the margins and to the gneiss foliation. If however a sill changes attitude and becomes dyke shaped, this schistosity will disappear with the dyke normally becoming wider than the corresponding sill.

Just north of the Laksenæs fault one of these irregular dykes is intruded into the closure of a small synclinal structure (fig. 4). The dyke is semi-concordant to the gneissic structures and appears to be folded. However, the almost horizontal mineral lineation parallel to the contact in the dyke, suggests that the lineation has not been formed by the deformation producing the small syncline. It is therefore believed that the intrusion has taken place after the folding, along planes of least resistance. Moreover another horseshoe shaped intrusion, which can be followed more than 3 km (fig. 4), shows no relation to any closures and this clearly demonstrates the possibility of odd intrusive shapes in this area. It must however be mentioned here that Berthelsen (1962) states that the Kuánitic dykes are in fact folded south of Arsuk Fjord.



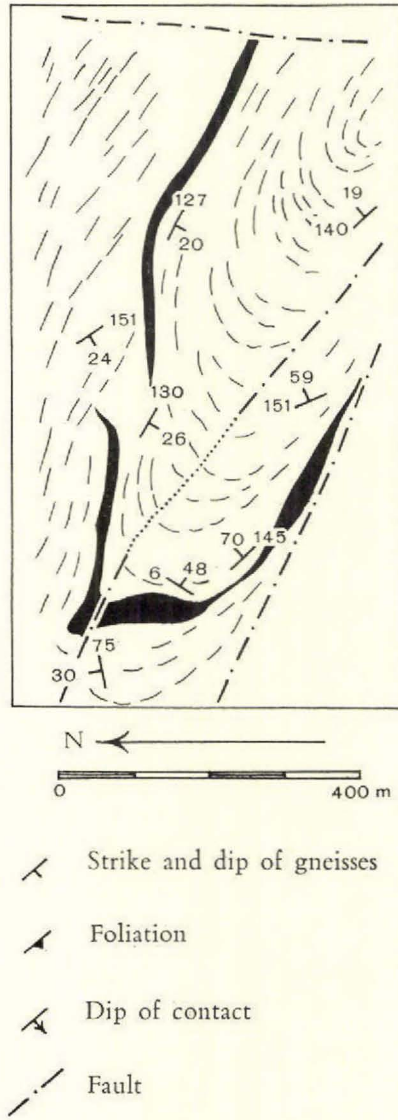


Fig. 4. Two examples of irregular "horseshoe-shaped" Kuánitic intrusions, in the area west of Arsuk Fjord on the northern side of the Laksenæs fault. The sketch to the right shows a semiconcordant intrusion in a small syncline and to the left a similar shaped dyke, intruded in a uniformly striking area.

PETROLOGY OF THE KUÁNITIC DYKES

General petrographical description.

The Kuánitic dykes in the area described here are all amphibolitic. They never, apart from a few exceptions on Sermersût and Tôrnârssuk, contain pyroxene and any primary olivine has been completely altered. The rocks are composed mainly of plagioclase and hornblende, and these two minerals often make up more than 90 per cent of the bulk. In most of the dykes ore is common and biotite, epidote, chlorite and quartz may be found in smaller quantities, depending on the degree of metamorphic alteration. Apatite normally occurs in accessory amounts. The Kuánitic dykes show an increasing degree of alteration from west to east. This can be demonstrated in all generations, but it is most clearly expressed in the NE- and the E-W-trending systems. The rocks in these two systems are, except for the feature of the megacrysts, petrographically alike and are roughly made up of the above mentioned minerals. The NNW-trending system is compositionally a little different, being characterized by a somewhat higher biotite content.

The Kuánitic dykes represent originally doleritic or olivine doleritic dykes. This can be interpreted from the relic ophitic texture seen in the least altered rocks and from the mineral association found in later contact metamorphosed recrystallised Kuánitic dykes. One of these Kuánitic dykes, otherwise amphibolitic, is completely recrystallised at the intersection with a 50 m broad doleritic Gardar dyke. Approaching the intersection, the Kuánitic dyke shows an increasing contact metamorphism, starting with the green hornblende being altered to brown hornblende, after which pink titan-augite (similar to that found in Gardar dolerites) and finally olivine appear. Fig. 5 shows the texture in proximity to the intersection. It is evident that this new mineral assemblage is derived from a direct transformation of the amphibolitic rock, which itself represents the recrystallized primary rock type. The contact metamorphic stage therefore probably represents a mineral composition which is very close to the one found in the initial intrusive rock. Furthermore it is important to mention that no trace of metasomatic processes has been found in connection with either the Kuánitic, or with the doleritic Gardar dykes.

To demonstrate the increasing stages of alteration, the conditions in one particularly persistent dyke belonging to generation V will be described. The stages of alterations which have been found in the other

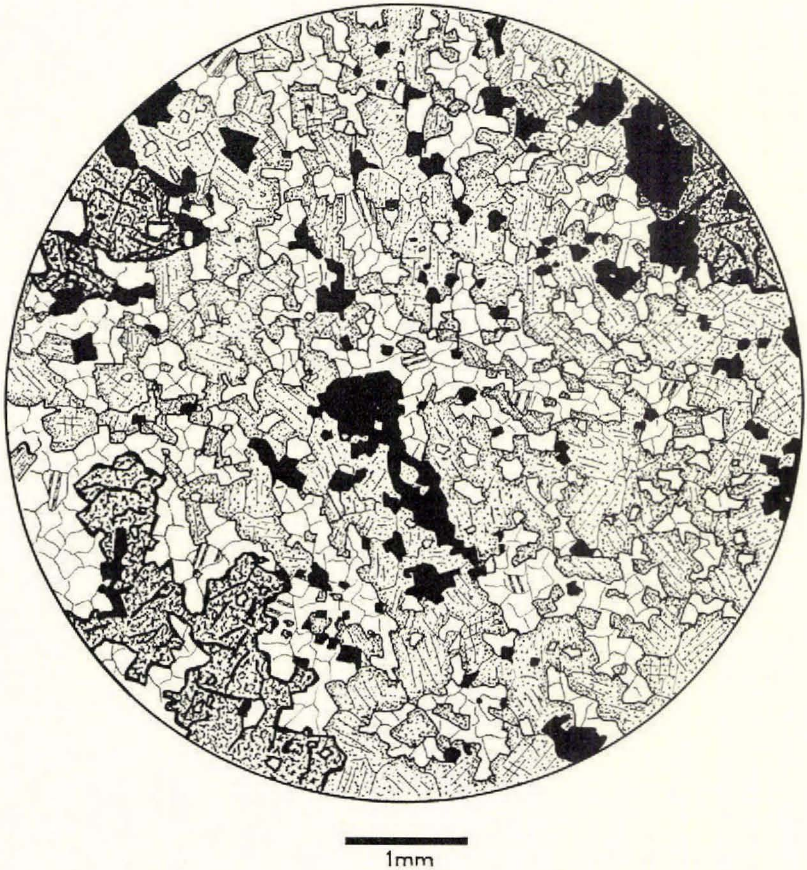


Fig. 5. Sketch of rock texture in a contact metamorphosed Kuánitic dyke, showing plagioclase, augite, olivine and ore.

dykes correspond closely to those in the above selected dyke, and thus they do not need special treatment. Describing the conditions in one particular dyke only, means that the trend and the possible primary petrographic differences between the generations, can be eliminated as possible causes for any differences in alteration.

The described dyke is easily recognisable because of its content of plagioclase megacrysts. The field conditions of the dyke have been described already and in the following six progressively increasing stages of alteration will be examined. The mineral percentages in the thin sections has been determined by modal analysis and in some cases staining has been used to make the quartz stand out from the oligoclase. The plagioclase measurements are mostly made on the universal stage, as are the hornblende measurements. The last mentioned are often quite difficult to obtain accurately and these results should therefore be regarded with reservation.

Subdivision of stages of alteration.

The stages of alteration in relation to their geographical position can be stated as follows:

Stage 1. Preserved primary plagioclase and uralitic hornblende. Chlorite present. Ophitic texture. The western part of the Islands.

Stage 2. Alteration of primary plagioclase (saussuritization and sericitization). Uralitic hornblende. Relic ophitic texture.
The eastern part of the Islands.

Stage 3. Recrystallization of plagioclase ($^1/_{10}$–$^1/_{20}$ mm grains) and uralitic hornblende. Traces of ophitic texture.
The western Mainland.

Stage 4. Further recrystallization of plagioclase (up to $^1/_5$ mm grains) and amphibole. Hemi-granoblastic texture.
The Kuánit area.

Stage 5. Non-oriented completely recrystallized amphibole and granular recrystallized plagioclase often showing twins. Hemi-granoblastic texture.
The central Mainland.

Stage 6. Parallel oriented and lineated amphibole aggregates and up to $^1/_2$ mm well twinned plagioclase grains. Nematoblastic texture.
The eastern Mainland.

Between the above mentioned types of alteration all gradual transitions exist.

For location of the rock samples exemplifying the different stages described in the text see plate 1.

Stage 1. **The lowest stage of alteration, the western part of the Islands.**

This stage is exemplified by two samples (32012 and 32002) and is characterized by the presence of chlorite and preserved plagioclase almost without any recrystallization and little or mostly no saussuritization. The sample 32012 was taken west of 32002 and in this respect it is remarkable that, in contradiction to the general increase in alteration, the easternmost sample has the best preserved plagioclase (see p. 30).

The original ophitic relation between the plagioclase and the mafics is clearly seen. The hornblendes have shapes which reveal the forms of the original augite crystals. Also old augite twinning can be traced as

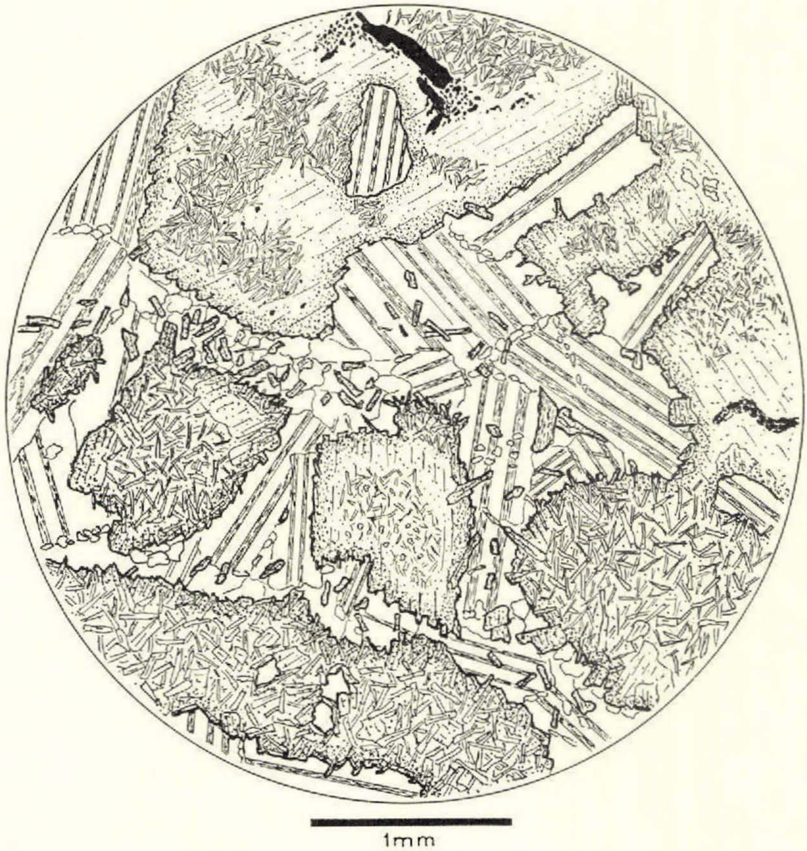


Fig. 6. Sketch of rock texture in stage 1 (sample 32002) showing plagioclase, hornblende and ore.

a sudden change in optics of the amphiboles and linear arrangement of tiny ore inclusions.

In 32012, the plagioclase exist as a megacrystic phase with normal zoning from 70–40 $^0/_0$ An and in the groundmass phase, compositions measured between 37 and 56 $^0/_0$ An. Sericitization and very weak saussuritization is only found along cleavage and twin planes. Along the borders to the mafics, pennine chlorite occurs. In 32002 the plagioclase varies in composition between 37 and 60 $^0/_0$ An and the crystals are clean, without alterations. Otherwise the relations correspond to 32012.

In the two slides amphibole is next in abundance to plagioclase and it occurs as two types: 1) an inclusion rich pale green uralitic type making up the main central part of the former augite fields. 2) bluish green, pleochroic, needle shaped, hornblende often found along the borders of the former augite fields and mostly perpendicular to these.

The uralitic inclusion rich hornblende has a $2\,V_x$ of 80–70° and a $Z \Lambda c = 17$–$20°$. The needle shaped hornblende has a more constant $2\,V_x$ of 75° with a $Z \Lambda c = 15$–$17°$. The pleochroism is from x: pale green, nearly yellowish, to y: green and z: bluish green for both types, the bluish shade being more prominent in the needle shaped type.

The inclusions found in the uralitic type are: 1) tiny ore grains often arranged in line, which as previously mentioned are believed to represent old augite twin structures, 2) small amoeboid quartz grains, 3) small highly birefringent often pink grains, isolated and weakly pleochroic. These grains, of which no optical data could be obtained, could from their mere occurrence be interpreted as relic pyroxene. Also 4) small frequent hornblende needles of the same type as found around the uralitic hornblende and 5) flakes of pennine chlorite have been found.

Chlorite is found in two types: 1) the above mentioned pennine in contact with plagioclase and in the uralite and 2) a pale green weakly pleochroic and very weakly birefringent clinochlore in comparatively large subidiomorphic corroded flakes.

Brownish biotite is common in connection with ore and larger leucoxene grains. Often biotite and ore form clusters which from their position could be interpreted as evidence of olivine in the primary rock. Besides the quartz described from the uralitic hornblende, larger quartz grains have been observed interstitially between plagioclase grains. Accessory apatite is seen in long, often broken needles.

Stage 2. **The eastern parts of the Islands.**

This stage is exemplified by sample 32025 taken approx. 5 km east of 32002. Characteristic of this stage are the alterations of plagioclase and the presence of epidote.

The texture of the rock is still easy recognizable as originally ophitic, but compared to stage 1 the groundmass plagioclases are encroached upon by strongly growing amphibole crystals.

The megacrystic phase of plagioclase is moderately preserved and the compositions measured vary between 39 and 56 % An. Recrystallization of the plagioclases in small rounded untwinned grains is common especially along cleavage and twin planes. All the plagioclase has been strongly saussuritized and small grains of phyllosilicates (mainly biotite) are prominent. Also small amphibole needles are found within the plagioclases.

The amphiboles of this stage are of three types. In the centre of the large patches of mafics, the same inclusion rich uralitic hornblende as found in stage 1, occurs. Pleochroism is the same and $2\ V_x = 75–77°$ and $Z \Lambda c = 17–18°$. Besides the inclusions already mentioned under stage 1 epidote occurs here. This epidote seems to be an iron-rich pistacite in contrast to the clinozoisite found in the plagioclases.

Marginally to the uralitic hornblende, a new type of platy clean hornblende with $2\ V_x = 78°$ and $Z \Lambda c = 18°$, is found. The pleochroism is slightly different from the uralitic type and it seems to be darker green when compared in the same slide. Besides the colour, the lack of inclusions is the most characteristic feature of this type. The third type is the same needle shaped type as found in stage 1 and here also this type is dominated by bluish green pleochroism.

Biotite, pleochroic from yellowish to reddish brown, is common. In a few cases chlorite intergrown with the larger biotite grains has been observed. A "biotite isograde", which has not been established regionally, seems thus to be found in central Tôrnârssuk.

Besides the minerals mentioned, ore and leucoxene occur, together with accessory apatite in broken needles.

Stage 3. **The lowest stage of alteration on the Mainland.**

This stage is exemplified by sample 19715, having a composition of approx. 53 $^0/_0$ hornblende, 40 $^0/_0$ plagioclase, 4 $^0/_0$ biotite, 2 $^0/_0$ ore and 1 $^0/_0$ quartz. The ophitic texture occasionally can weakly be recognized, but usually the original texture is completely blurred and the minerals are arranged in irregular, indistinct bands or seams.

The rocks contain single relic primary plagioclase individuals, but the main part of the plagioclase has recrystallized into a saccharoidal granoblastic mass, with an average grain size of $^1/_{10}$–$^1/_{20}$ mm. The primary plagioclase individuals show normal zoning with a composition corresponding to andesine-labradorite. The recrystallized granular plagioclase is only occasionally twinned and in these cases the composition has been determined as 30–35 $^0/_0$ An.

The amphiboles are mostly concentrated in clusters, which usually are made up of a fibrous aggregate, surrounded by a more homogeneous border zone, possessing a uniform optical orientation. The larger amphibole clusters are often poikilitic with quartz inclusions. The amphibole is also found as small laths among the plagioclase, having grown with no preferred orientation. The amphibole is dark green, pleochroic to light yellowish green, and has a fairly constant $Z \Lambda c$ of 14–15° with a measurement of $2 V_x$ of 74° indicating a normal hornblende composition.

The larger fibrous amphibole clusters are believed to represent almost *in situ* replacements of the original augite, which is indicated by the form and distribution of the hornblende clusters. The smaller,

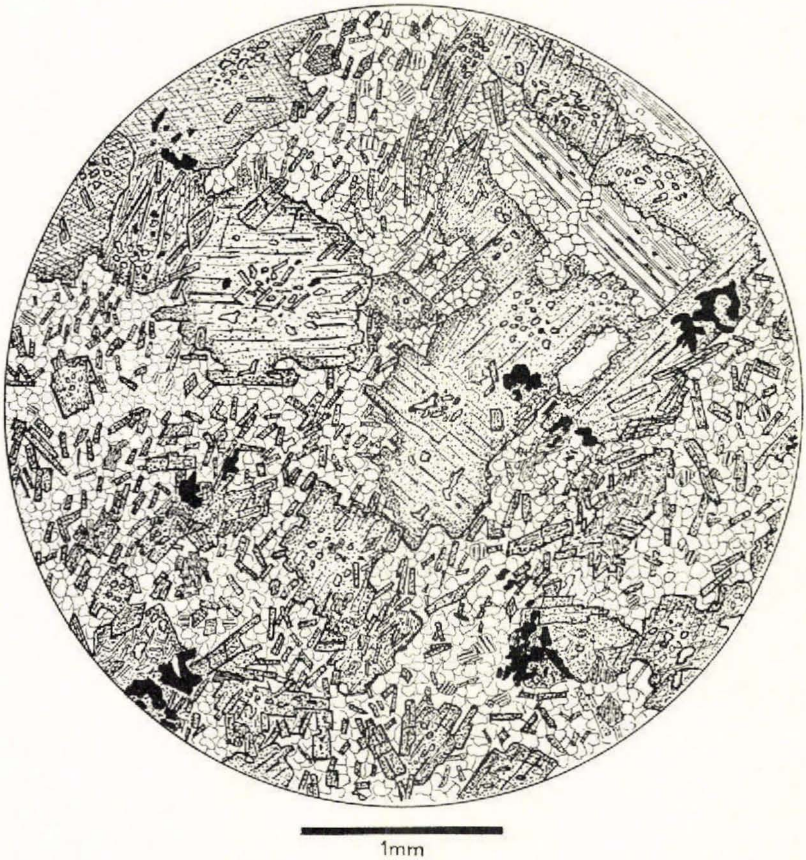


Fig. 7. Sketch of rock texture in stage 3 (sample 19715) showing plagioclase, hornblende, ore and biotite.

dispersed amphibole laths seen more clearly outside the hornblende clusters are probably formed by more mobile components and therefore do not exhibit the uralitic character seen in the clusters.

The biotite, which is light brown, together with the ore, seem to be completely recrystallized. The mica components must have been rather mobile during the recrystallization, since the biotite is often found as small scattered inclusions in the partly recrystallized plagioclase megacrysts. The ore on the other hand is concentrated in small clusters and has probably been more stationary during the recrystallization.

Stage 4. **The stage of alteration in the Kuánit area.**

This stage can be illustrated by two samples (19480 a and b) taken from: a) the border zone with plagioclase megacrysts and b) the central part of the 50 m wide megacryst bearing Kuánitic dyke.

The composition of the rock varies in the four different thin sections made from this rock type, but the hornblende content on average is approx. 60 %, the plagioclase approx. 30 %, the biotite approx. 5 %, the ore 2,5–3 % and the quartz 1–2 %. In some of the sections a little clinozoicite and accessory apatite occurs.

The megacrysts are partly recrystallized and the primary plagioclase relics are zoned normally with labradorite cores and andesine margins. In these primary plagioclases some clinozoicite can be found, but in the recrystallized parts the clinozoisite is absent.

The groundmass plagioclases are more recrystallized than in stage 3 and the grain size of the granular plagioclase aggregates has now increased to an average of $^1/_5$ mm. The grains have semi-saccharoidal borders and in some cases they show twinning, a measurement from which shows a composition varying between 30 and 35 % An.

The amphibole is pleochroic from light green to bluish green and has a $Z \Lambda c$ of 14–16° and a $2\ V_x$ of 66–68°, which corresponds to a normal hornblende. The uralitic character is less distinct than in stage 3 and the amount of hornblende in the fibrous aggregates decreases in relation to the number of lath shaped individuals, which are often intergrown in clusters. In these clusters the bigger laths are often poikilitic, containing quartz droplets. It has not been possible to demonstrate any difference in composition between the two hornblende types.

The biotite and the ore relations correspond to the conditions found in stage 3.

No evidence of a later strain influence in the relic minerals has been found and the recrystallized minerals have grown with no preferred orientation. The alterations therefore seem to have taken place under quiet conditions. The rock of the contact sample (19480 a) is more intensely recrystallized than the rock from the central part of the dyke, but there is no sign of a cataclastic shearing recrystallization in the contact. It is therefore supposed that the central parts of the dykes have been partly protected against the alterations by the outer zones of the dyke.

Stage 5. **The stage of alteration in the central Mainland.**

This stage is found in rocks half-way between Kuánit and Arsuk Fjord where the minerals in hand specimens start to show a weak macroscopical orientation. In the illustrative example (19797), the composition is approx. 65 % hornblende, 32,5 % plagioclase, 1 % biotite, 1 % ore and 0,5 % quartz.

The amphibole has a $Z \Lambda c$ of 15° and is pleochroic from yellowish green to dark bluish green. Mostly the amphibole is gathered in clusters or aggregates with a semiparallel orientation of the individual laths.

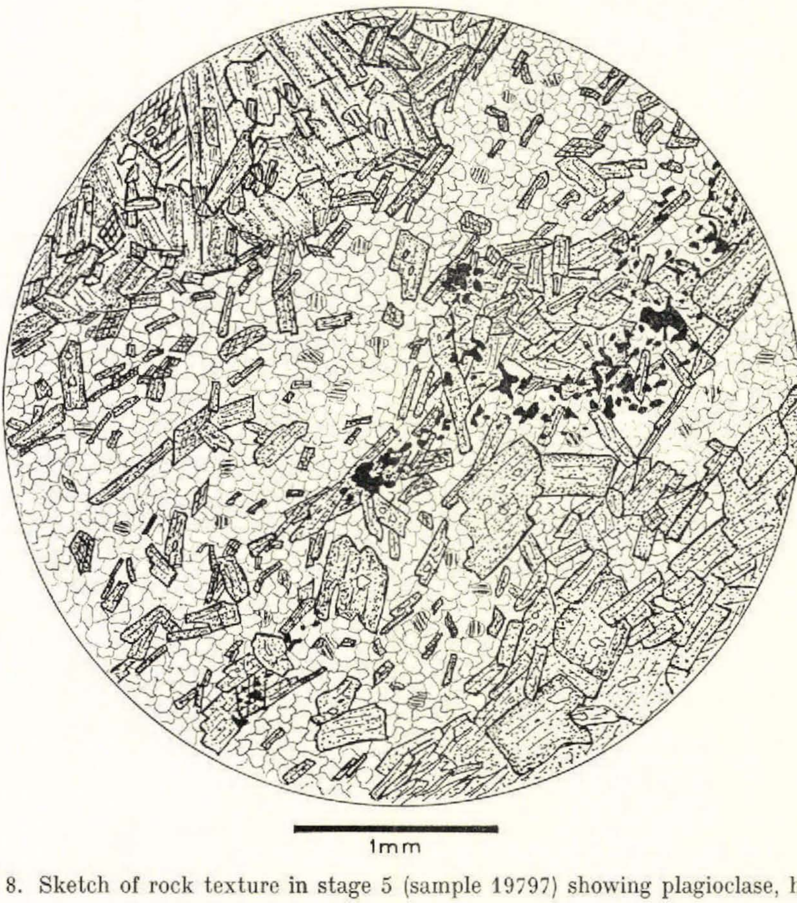


Fig. 8. Sketch of rock texture in stage 5 (sample 19797) showing plagioclase, hornblende and ore.

The earlier encountered fibrose character of the hornblende has completely disappeared and now the tendency is for the development of greater crystals.

The primary plagioclase, except in very big megacrysts has been completely recrystallized and forms a saccharoidal mosaic in which the average grain size is somewhat bigger than in the earlier stages. Twinning is here rather common. The composition corresponds to an An content of 30–35 %.

Stage 6. **The highest stage of alteration on the Mainland.**

In this stage, seen W of Arsuk Fjord, the rocks show a clear mineral lineation. The chosen example (sample 19785) contains 50 % hornblende, 40 % plagioclase, 5 % biotite, 2 % ore and 3 % quartz.

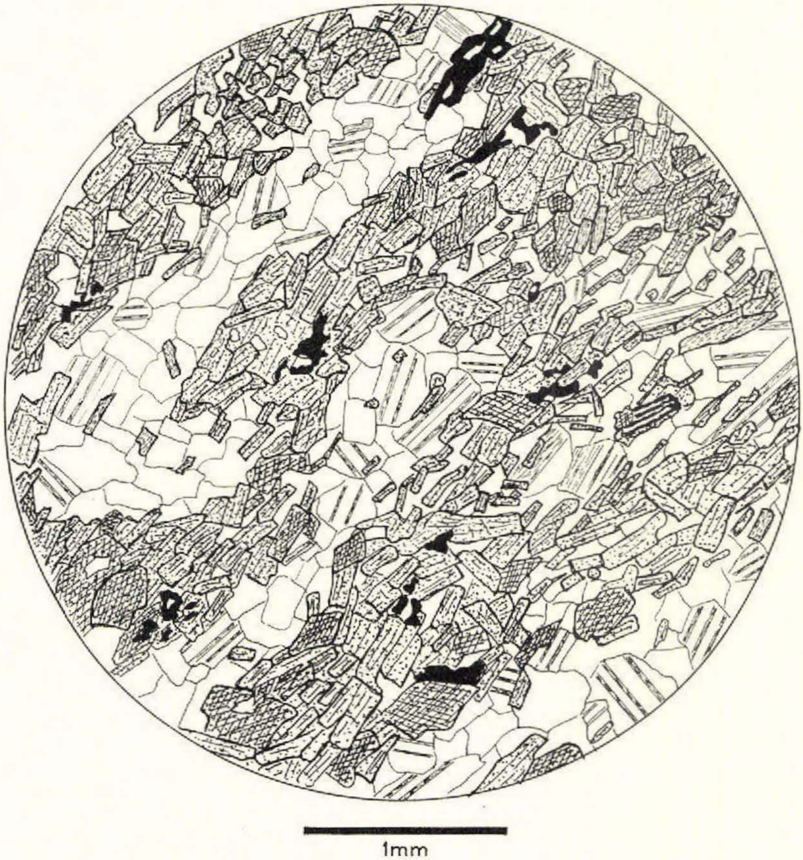


Fig. 9. Sketch of rock texture in stage 6 (sample 19785) showing plagioclase, hornblende and ore.

The mafic minerals are concentrated in irregular parallel schlieren, in which the aggregative intergrown hornblende individuals mostly are oriented parallel to the orientation of the mafic schlieren. A few of the bigger hornblende individuals are poikilitic with quartz inclusions, but usually the quartz is found as separate granular grains. The hornblende, which has a $Z\Lambda c$ of 14–15° and a $2\,V_x$ of approx. 72°, is pleochroic from light yellowish green to dark olive green and the individuals reach up to approx. 1–2 mm in length.

The biotite is brown and often replaces and is intergrown with the hornblende.

The plagioclase is totally recrystallized and intergrown to a granular saccharoidal aggregate, with a grain size of up to $^1/_2$ mm. Twinning is common and the composition varies from 33–40 $^0/_0$ An. Often the plagioclase is weakly zoned.

The metamorphic alterations in the Kuánitic dykes.

The petrographical investigations have shown that the mineral composition of the dykes of the four highest stages is fairly constant. Nevertheless the modal analysis of these four reveals some variation, but this is considered to fall within the expected spread in rocks of that grain size. In stages 1 and 2, the composition is especially characterized by chlorite and biotite respectively, as well as the minerals common with the higher stages.

The amphibole composition probably changes slightly through the different stages of alteration, but this cannot be demonstrated exactly. The $Z\Lambda c$ readings are fairly constant at 15° in the higher stages, but in stage 1 and 2 the extinction angle seems to be a little higher for the different types of amphiboles. The $2\ V_x$ is too uncertain to base any conclusions on its variation.

The recrystallized plagioclase on the other hand can be shown to vary and an increase in its An content from 30–35 $^0/_0$ in the western part of the area to 40 $^0/_0$ in the eastern part, can be demonstrated.

Starting from a primary dolerite, the mafics are the first to be altered. The alteration products are uralitic hornblendes with the excess components resulting in inclusions of quartz and ore. These lowest stages are characterized by stable chlorite. Biotite, otherwise unstable, could, when found in the lowest grade, be derived from the primary rock. In a still less altered stage, the uralitic hornblende might be without marginal needle shaped amphibole, and this is supported by observations on other dykes from Sermersût. Additional to the uralitic hornblende and the needle shaped amphibole types, a clean third type is formed at a slightly higher grade. All these types at higher stages are recrystallized to larger and more well defined crystals.

At low grade, corresponding to approximately stage 1, tourmaline is present in numerous cases, although not in the samples described. The mineral is always idiomorphic and is pleochroic from light blue to dark blue often with brownish pleochroic rings and centres. According to Barth (1952) tourmaline is an accessory mineral of green-schist facies, and this is in good accordance with the conclusions otherwise reached.

At the lowest stages of uralitisation, plagioclase with few exceptions is not altered, although unstable. However, only a little rise in temperature corresponding to the chlorite-biotite inversion is sufficient to activate plagioclase, which firstly becomes saussuritized. In this stage epidote also occurs in the mafics. At still higher grade the plagioclase is recrystallized, and at progressive stages the grain size and An content increase presumably in accordance with the further hornblende recrystallizations.

The large megacrystic grains are not recrystallized in accordance with the groundmass felspars by increasing steps, but they reflect a retarded development. This is in good agreement with the general impression of the relationship between samples from margins and centres where a similar phase retardation causes the more coarse grained central parts to be less altered than the margins. Thus different primary grain sizes may cause errors in the comparisons along the dyke. However, the grain size in the samples examined has, as far as can be judged, been of the same magnitude.

No trace of newly introduced material has been found in the dyke. It is therefore supposed that the alterations have taken place with the addition of only water. The quartz found in the rocks is probably released at the pyroxene—amphibole reaction, as is indicated by the poikilitic nature of the quartz seen in the uralitic hornblendes of the first stages of alteration. Besides this, a primary tholeitic composition could explain superfluous quartz. As can be seen from the textural variations, the mechanical conditions during the metamorphism have not been the same throughout the area. The three lowest stages of alteration have taken place under static conditions, without destroying the original ophitic texture. In the higher stages, the formation at first of seams and then later of mineral lineation shows that the recrystallization has taken place under dynamic conditions. These are related to the Sânerutian movements, which will be dealt with later.

A comparison of the Kuánitic dykes with the Scottish epidiorites as described by WISEMAN (1934) shows that the stages on the Islands correspond to the conditions found in the chlorite and biotite zones in Scotland, except for the plagioclase not being recrystallized in the Greenland examples. The stages of alteration found on the Mainland correspond most closely to the epidiorites of the garnet zone. Garnets are not found in the Kuánitic dykes. According to WISEMAN, however, this mineral can also be missing in the garnet zone dykes, as the occurrence of the mineral is dependent on the chemical milieu. The other minerals found in stages 3–6 are directly comparable to the ones in the garnet zone, with the exception of sphene which is very seldom found in the Kuánitic dykes. The textures on the other hand are different in the two types, since the textural variation found in the Kuánitic dykes has no isofacial parallel in the Scottish epidiorites.

The metamorphosed dolerites from NW Highlands have been described by, among others, SUTTON and WATSON (1951), who can demonstrate six stages of progressive metamorphism in the dolerites. The Greenlandic dykes show good agreement with some of the stages described from the NW Highlands. The stages found on the Islands are comparable to stage 2 in the Highlands, and the stages of alteration found on the Mainland correspond nearest to stage 3 and 4 of SUTTON and WATSON. Here the plagioclase recrystallizes with a partial modification of the primary texture and thereafter the quartz-hornblende aggregates are recrystallized with a complete destruction of this primary texture and development of a planar or linear orientation of the amphibole.

The development of the lineation in the NW Highlands is connected with the formation of belts of intense shearing in the outer zones of the Laxfordian metamorphism. As will be described later such zones of shearing, younger in age than the dykes, are also found, in the area here described.

The metamorphic facies of the dyke rocks seems to be high green schist facies on the western parts of the Islands and epidote-amphibolite facies on the eastern part of Tôrnârssuk. On the Mainland all four stages correspond to amphibolite facies. The border between epidote-amphibolite facies and amphibolite facies is here used, as pointed out by RAMBERG (1949), as the stability condition of

$$\text{An } 30 \underset{400^\circ \text{ C.}}{\rightleftharpoons} \text{ epidote}$$

The composition of the recrystallized plagioclase, which on the Mainland is everywhere greater than 30 $^0/_0$ An, and the lack of epidote in the same places, show that the rocks have recrystallized at temperatures higher than 400° C.

The isofacial conditions of the different four highest stages of alteration therefore indicate that the difference in alteration is not caused by a variation in metamorphic grade. The difference is believed to be due to a difference in *duration* of the metamorphic conditions, connected to the influence of a catalysing kinematic factor.

THE SÁNERUTIAN EPISODE

Throughout the whole of South Greenland plutonic activity of different episodes can be established. Of these the Ketilidian and the Sánerutian are the most dominating, but their correlation from area to area leads to some difficulties.

In the Ivigtut area as a whole, the Sánerutian is regarded as an activation after the intrusion of the Kuánitic dykes. The effect of this activation is highly different from place to place, changing from static metamorphism to folding, mobilization and granitization. This change in Sánerutian influence is for example demonstrated by the alteration of the Kuánitic dykes as described in the preceding pages.

Field relations of Sánerutian events.

The Sánerutian effect on the dykes.

After the intrusion of the Kuánitic dykes, the rocks were recrystallized under the now described regional metamorphism. The dykes became amphibolitized and in some of them a mineral orientation was developed. This orientation, which can be seen as an amphibole lineation, is only found in the dykes near Arsuk Fjord. In the western part of the area, the recrystallized dyke rocks are homogeneous and possess no preferred mineral orientation. Gradual transitions exist between the lineated and the non-lineated dykes, and in the transition zone dykes with lineated margins and homogeneous central zones can be observed.

The map (plate 1), shows the above mentioned transition zone, which, however, can only be approximately indicated. To the east of this, lineated Kuánitic dykes occur and to the west, non-lineated. The transition zone is sinistrally displaced along the Laksenæs fault approx. 4,5 km, corresponding to the displacements on the youngest Kuánitic dykes (Henriksen 1960).

The mineral lineation in the Kuánitic dykes can usually be seen throughout the entire width of the dykes and the lineations are nearly always parallel to the borders, being almost horizontal or plunging at a low angle. Some of the Kuánitic dykes contain feldspar megacrysts which are often elongated parallel to the mineral lineation.

Fig. 10. Example of a Kuánitic dyke cut by Sánerutian pegmatites and aplites. Immediately north of the Laksenæs fault, west of Arsuk Fjord.

It is possible that the mineral lineation in the different dyke-directions (generations) was not initiated in exactly the same region, which adds to the uncertainty in placing the above mentioned transition zone. However, the material is too restricted to give any definite evidence of this, but it is nevertheless supposed that the transition between the lineated and non-lineated NE-trending dykes has a tendency to a more westerly position than the same transition in for example the dykes with a NNW direction.

On Tôrnârssuk and Sermersût the Kuánitic dykes are nearly always sheared along their margins, and often a distinct schistosity is developed parallel to the borders of the dykes. In the NE-trending dykes this schistosity is especially prominent.

On the Mainland the dykes generally lack sheared margins, although, in a few cases, where the intrusions are concordant to the gneiss structures, a schistosity parallel to the contact is developed. Also in these cases the shearing is more intense or sometimes exclusively concentrated along the margins of the hypabyssal intrusions.

In the eastern parts of the area the Kuánitic dykes are often cut by aplites and pegmatites, but this aplite and pegmatite intensity rapidly decreases towards the west. For example in the area around Kuánit Fjord, these later leucocratic dykes and veins are very few and on Tôrnârssuk and Sermersût are they almost totally lacking.

Most of the cross cutting veins are aplitic with only a few pegmatitic and these may reach a maximum width of about 1 metre, although usually they seldom exceed $^1/_2$ m. The veins have in general no preferred trends. Quite often the aplitic veins have a pegmatitic central part or a pure quartz core. The leucocratic veins are composed of quartz-feldspar material with only a little biotite.

Quartz veins, probably related to the above mentioned acid veins, also cut the Kuánitic dykes, but the density of these veins is more even, being found both on the Mainland, and on Tôrnârssuk and Sermersût.

Post-Kuánitic shear zones.

On the Mainland some prominent post-Kuánitic (Sánerutian) shear zones exist and these are cut by the Gardar faults and dykes. These shear zones often resemble strongly schistose mica schist bands, with a compact arrangement of the planes of schistosity. The sheared rocks vary according to the surrounding rock types, hence in the gneisses they are predominantly made up of quartz, feldspar and mica, while where the zones cut the Kuánitic dykes, the sheared rocks are strongly chloritic with a dark green colour.

A characteristic small scale folding can often be seen in the shear zones. The folds are irregular shear folds, which may pass into folds showing a plastic style of deformation. The sizes of these folds vary from microscopic scale to folds with an amplitude of about 15–20 cm.

The shear zones sometimes contain thin, almost pure quartz veins which have a trend parallel to the shear zone and which often show pinch and swell structures or boudinage. Also ptygmatic folded quartz veins can be found in these zones of movement.

The width of the shear zones varies from 1 or 2 m up to 30 m and where thin they are mostly rather distinct, but when wider, they tend to be more diffuse. Pronounced shear zones can be followed for some km, while others can only be traced a few hundred metres. The shear zones usually die out gradually in zones of schistosity, which lack the above mentioned small-folds.

The trend of the shear zones is concordant or semi-concordant to the general surrounding gneiss orientation, but in relation to small folds they are discordant and cut the structures. The shear zones are grouped in two sets, one trending approx. 70–80° and the other trending approx. 100–125°, depending on the surrounding gneiss structure between which the distribution is almost even. Displacement along the shear zones can only be demonstrated in a few places but where this was possible the maximum measured is around a few hundred metres.

Fig. 11. Sánerutian shear zone with shear folding and pinch and swell veins. West of Arsuk Fjord.

On Tôrnârssuk and Sermersût, the Sánerutian shear zones seem to be represented by minor mylonites and crush-zones in the gneisses and to shearing along the dyke margins. Although common, these movements are difficult to establish chronologically. Except in the margins of the dykes plastic deformation is rarely observed.

The unmetamorphosed Gardar dykes cut most of the shear zones and only a few are crushed, and none displaced. This shows that, even if some of the post-Kuánitic shear zones have been reactivated in Gardar time, most of them at this time had ceased their role as primary zones of weakness.

The relatively plastic deformation, as implied from the style of folding in some of the shear zones, indicates that the deformation took place at some depth at an comparatively high temperature. It therefore seems reasonable to regard the above mentioned movements as contemporaneous with the post-Kuánitic metamorphism, under which the Kuánitic dykes were amphibolitized. Moreover this chronological scheme is in accordance with the relative position of the shear zones between the earlier Kuánitic dykes and the later Gardar dykes and faults.

Metamorphic alteration in the post-Kuánitic shear zones.

The petrographical investigation of the post-Kuánitic but pre-Gardar shear zones reveals a thorough recrystallization of quartz, feldspar and mica. This suggests that the sheared rocks must have been recrystallized under comparatively high and long-lasting temperatures. The recrystallization of biotite indicates that the metamorphic facies corresponds to at least epidote-amphibolite facies, which in turn means that the temperatures of recrystallization must have been around 250° C. or maybe even higher. Such temperatures could have been derived from the heating caused by friction alone, but it is more probable that the isotherms in the crust were elevated somewhat, at the time of the shear zone formation. This is suggested from the comparison with the later Gardar fault zones, which often represent much bigger differential movements (HENRIKSEN 1960). Here the mechanical crushing is the predominant characteristic of the fault zone rock, while only a few of the leucocratic minerals are slightly recrystallized with the dark minerals somewhat chloritised.

The comparatively extensive recrystallization in the post-Kuánitic shear zones indicates that the elevated temperature conditions must have lasted some time, which probably would not have been possible if the temperature rise was caused only by friction along specific planes of shearing. This tends to confirm that the shear zones were formed by the same episode which amphibolitised the Kuánitic dykes.

THE PRE-KUÁNITIC METAMORPHIC FACIES OF THE SURROUNDING GNEISSES

The metamorphic facies in the Ketilidian gneisses varies within the area investigated. On the Islands and in the western part of the Mainland the rocks have been retrogressively metamorphosed from a primary amphibolite facies to a secondary epidote amphibolite facies, with a partial recrystallization under the last mentioned conditions. In the eastern part of the Mainland only one metamorphic state i. e. corresponding to amphibolite facies, can be demonstrated.

The traces of two metamorphic events found in the above mentioned retrograde metamorphic rocks are probably connected to the existence of various folding phases (Berthelsen 1960) and it seems also likely that the eastern parts have had a similar double metamorphism in Ketilidian time. As this cannot be demonstrated now, it seems reasonable to suggest that the latest metamorphic alterations have been isofacial to the former or that they have completely blurred the mineral paragenesis from the different former facies.

CONCLUSIONS

After the Ketilidian folding followed a tensional episode under which basic dykes were intruded throughout the area. The existence of at least 5 different dyke generations with various trends shows that the tensional conditions in this cratogenic period must have changed a good deal.

The relic chilled margins of the dykes suggests that the wall rock must have been comparatively cold at the time of emplacement. It is because of this, and the tensionally formed dykes, that it is believed that the Ketilidian thermal front had been withdrawn before the dykes were intruded. The intrusion of the dykes therefore clearly demonstrates the change in crustal conditions after the folding and it marks the termination of the compressive condition, which must have prevailed during the period of deformation.

The irregular Kuánitic dykes, which have only been found in the easternmost part of the area, must have had a different intrusive mechanism, as their odd forms cannot be explained by supposition of folding. It is therefore thought that the special conditions here represent an intermediate stage between the clear discordant tensional dykes found in the west and the conditions found in the east on the Ivigtut peninsula. Here the dykes, even allowing for the effect of a later folding, often have a less persistent and semiconcordant nature (BERTHELSEN 1960, 1962) which is completely different from the clean cutting character seen in the western part of the area. It is suggested that these conditions in the eastern regions are produced by either a higher position of the thermal front or a less pronounced manifestation of the tensional conditions, at the moment of intrusion. A combination of the two could of course also be possible.

After the *mise en place* of the dykes, the rocks were amphibolitized under a regional metamorphism. According to BERTHELSEN, the Kuánitic dykes are slightly folded further south on the Ivigtut peninsula, but on the north and west side of Arsuk Fjord no folding has been demonstrated and from this BERTHELSEN concludes that the folding intensity and effects decrease to the north. However, the area is crossed by shear zones which are concentrated in two sets with different trends, which are semiconcordant to the main structures in the Ketilidian folded gneisses. These shear zones can probably be interpreted as being formed by the same deformational forces that caused the folding of the Kuánitic dykes further to the south.

This above mentioned transition is indicated on the Mainland by the decreasing amount of post-Kuánitic acid veins from east towards west. These pegmatites, aplites and quartz veins are related to the post-Kuánitic regional metamorphism and are possibly the northwestern equivalent of the reactivation and granitization found south of Arsuk Fjord, as mentioned by BERTHELSEN.

The subhorizontal lineations found in the dykes in the eastern parts of the Mainland are parallel to the margins as also are small megacrysts orientated with their elongation direction parallel to the dyke margins. These linear arrangements cannot be referred to either the influence of a specific fold axis, nor to the influence of the post-Kuánitic shear zones. This is seen from the fact that the dykes keep their lineation parallel to the contact independent of their sometimes irregular trend which is often oblique to the shear zones. It therefore seems likely that the lineation is a product of specific stress conditions in the dykes, at the same time as the metamorphic recrystallization took place. Further to the west, where the lineation is not developed, these conditions could have died out. On the Islands, where the Kuánitic dykes are sheared along their margins and where the post-Kuánitic shear zones are only weakly developed, it is believed that the shearing along the dykes corresponds to the shear zones on the Mainland.

It has been shown that the metamorphic alterations in the Kuánitic dykes took place under conditions of high green-schist to epidote-amphibolite facies on the Islands and under conditions of amphibolite facies on the Mainland. This indicates an increasing degree of metamorphism from west to east, but not all variations can be attributed to the varying metamorphic degree. On the Mainland all alterations took place under amphibolite facies conditions and here for instance the different steps can be explained as being controlled by, among others, a time factor. The most altered eastern dykes are assumed to have been exposed to the metamorphic conditions so long that the reactions could be completed and reach a stability stage. In addition the processes could have been catalyzed by differential movements along the dykes. In the western parts however, the metamorphic conditions has not prevailed long enough to permit a complete reorganization of the dyke rock. These rocks therefore contain for instance relic primary plagioclases.

If the metamorphic conditions of the Kuánitic dykes are compared to those found in the surrounding gneisses, a complete accordance in the eastern part of the area becomes evident. Here both gneisses and dykes are totally recrystallized under amphibolite facies conditions. In

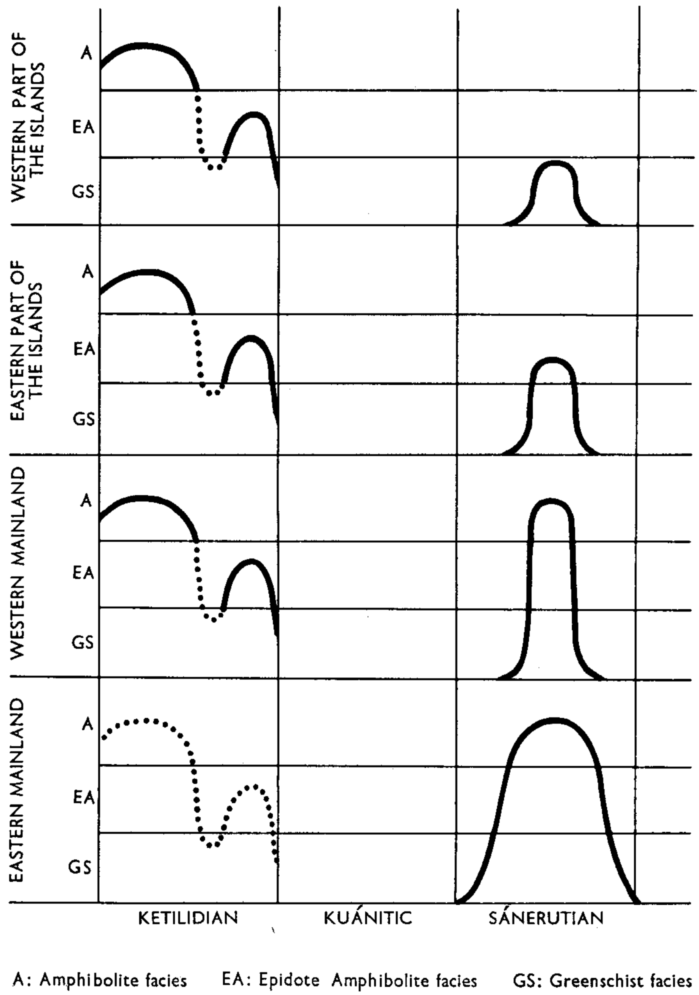


Fig. 12. Relationship of the metamorphic conditions at different times throughout the whole area. (See text below).

the western parts of the Mainland on the other hand paradoxal conditions are met with where the gneisses represent epidote-amphibolite facies retrogressive from amphibolite facies and the Kuánitic dykes represent amphibolite facies. On the Islands the gneisses are retrogressive from amphibolite to epidote-amphibolite facies and the dykes have recrystallized under green-schist to epidote-amphibolite facies conditions.

The conditions found in the western parts of the Mainland indicate that the area there has been influenced by metamorphism at least three times, first under amphibolite facies which was followed by metamorphism under epidote-amphibolite facies and finally under amphibolite facies again. The last one is post-Kuánitic, the first two being Ketilidian. The question must be raised: "Why cannot the last post-Kuánitic metamorphism be traced in the Ketilidian rocks?". Here it must be remembered that the post-Kuánitic metamorphism is regarded to be of rather short duration in the western parts of the Mainland. At the same time it must also be remembered that the Kuánitic dykes had a doleritic composition prior to the Sânerutian metamorphism and therefore would be exceedingly unstable under metamorphic conditions. At the same time the Ketilidian rocks were already partly recrystallized under epidote-amphibolite facies conditions and had retained a good deal of their former amphibolite facies mineral assemblage. This means that while the dykes were highly unstable, the gneisses were already more or less adjusted to the new P. T.-conditions. It therefore seems likely that the "short" post-Kuánitic metamorphism, which lasted long enough to affect the doleritic dykes, was too short to cause any visible recrystallization in the Ketilidian gneisses.

The interpretation of the metamorphic events from the western Mainland can be extended to the whole area, which accordingly is believed to have suffered at least three different metamorphic episodes. These conditions can be demonstrated diagrammatically, (see fig. 12) showing the conditions on the Islands, the western Mainland and on the eastern Mainland. On this diagram the time axis must be regarded as rather flexible, as the real intervals between the different episodes up to now are unknown. The part of the diagram that represents the eastern part of the Mainland gives the supposed character of the Ketilidian metamorphism here, but this can only be done by regarding this area as analogous with the western part, because the post-Kuánitic metamorphism here completely obliterates any traces of the supposed intervening epidote-amphibolite facies.

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