The petrology and structure of the country around Julianehaab, South-West Greenland

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THE

PETROLOGY AND STRUCTURE

OF

THE COUNTRY AROUND JULIANEHAAB,

SOUTH-WEST GREENLAND.

by

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Preface and Acknowledgements

The work presented in this thesis is based on six months field work in Greenland, as a member of the Greenland Geological Survey. During this period (the summers of 1958 and 1959) specimens were collected from the area and the thesis includes petrographic and mineralogical studies on this material. Specimen numbers used are part of the system of numbering used by the Greenland Geological Survey (e.g. 23409).

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The Petrology and Structure of the Country around Julianehaab, South-West Greenland.

ABSTRACT.

Field relations of several granite types, gabbroic and dioritic plutons and amphibolitic gneisses are described and discussed, as well as amphibolitic, doleritic and alkaline dykes A camptonitic sill is also described.

From the study of the amphibolitic dykes, two granite generations are differentiated by their relationship to the dykes. These are termed the Ketilidian and Sanerutian Granites. On the basis of xenoliths within the granites and petrological observations, it is suggested that the older granites formed in situ while the younger (Sanerutian) granite was intruded as a magma which resulted from the fusion of the Ketilidian Granites.

Detailed petrographic descriptions are given of all the major rock types. It is suggested that the gabbro-norite rocks are remnants of a differentiated basic intrusion, now represented by amphibolites and that the dioritic amphibolites are probably metamorphosed igneous plutons.

Modal data on the coarse-grained rocks using a technique devised during this study is shown to be reliable and results obtained on the granite are discussed.

Chemical and X - ray analyses of ten representative micro-

-clines separated from the Ketilidian and Sanerutian Granites, are used to show that the method of analysis of alkali feldspar by X - ray techniques (Orville, 1957 and 1960) is as accurate as conventional chemical analysis. Homogenisation studies and the effect of temperature on triclinicity are discussed. It is suggested that the albite molecule strongly affects the order - disorder relationship. Results from X - ray diffractometer studies on granite microclines, as well as phenocrysts from an alkaline dyke and dioritic gneiss are used in the construction of a phase diagram for the orthoclase - albite system at normal pressure. Using the method derived by Barth (1956), estimations of the last temperature of crystallisation of the various formations are given.

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CHAPTER 1.

Introduction.

"... geology is not the totality of available rocks and the events that have given rise to them, but it is merely our knowledge of them:"
C.E. Wegmann (1938)

The area covered during this investigation is situated in the south-west of Greenland, where a small portion of that island protrudes from beneath the mantling ice-cap. At this southern tip where the inland ice is at its narrowest, the western coast supports the largest indigenous population in the whole of the island.

Historically, Greenland was first populated by Europeans when Eric the Red left Iceland in 982 A.D. and settled in this south-west region. There is a good deal of archaeological evidence to show that the area also supported an Eskimo population at about the same period (Vahl et. al. 1928) and the present Greenlander is a descendant of this stock and are a result of intermarriage between the Eskimo and European.

The area studied is in the region of 60° 45' N lat. and 46° 5' W long. and includes the peninsula on which stands the settlement of Julianehaab, the islands immediately to the east and the elongate peninsula on the north side of the fjord Kangerdluarsuk. Fig. 1.1. shows the geology of the surrounding region and Fig. 1.2. illustrates the approximate position relative to the rest of Greenland. Fig. 1.3. is a locality map of the district covered by this thesis; most of the names used are approved by the Geodetic Institute in Copenhagen.

Julianehaab (situated 60° 43' N lat. and 46° 1' W long.)

is one of the largest settlements in south-west Greenland, with a dominant Greenlander population and a few Danish personnel. This settlement is the only populated part of the area studied and is located on the narrow neck of land between the large lake of Taserssuaq (or Stor Sø) and the Davis Straits. The ice cap from its nearest point is about 25 kilometres from the area and is situated immediately to the north and east.

The relief of the country in and around the area can vary from a rounded undulating nature to the sheer faces of the mountains in the north-east, Iviangiussat and Kitdlavat being the most spectacular (see Ussing 1912). In the south-east, the ground is dominated by the high ground of Sarqarssuaq (412m.) with the lake of Taserssuaq immediately to the west just above sea level. To the west of Taserssuaq the ground rises sharply again to about 300 m. and from there gradually increases in height to about 400 m. in the area of Nordfjeld. Essentially the whole of the southern region is a peneplain at an average height of 300 metres which has been thoroughly dissected and extensively glaciated. Consequently there are no mountains as such, only broad areas of higher ground which for various reasons have withstood erosion better than the surrounding districts.

North of Nordfjeld the ground falls rapidly away to much lower altitudes (about 150m.) until it meets the fjord of Kangerdluarssuk. In this region, the peneplain is cut into segments by narrow valleys containing either streams or small lakes. These valleys are accentuated fault zones which have been gouged out by glacier action and as a result most of the major fault zones can easily be traced from aerial photographs.

The highest ground is in the north-east where the peak of Iviangiussat (673m.) rises majestically in an almost vertical western face from the fjord. Immediately to the north of the area under consideration, a similar shaped peak of 800m. overlooks the eastern margins of the Ilimaussaq batholith. These unusual mountains together with the comb shaped peaks of Kitdlavat reflect the harder weathering quartz rich Sanerutian granite.

The islands to the east of Julianehaab are dome shaped with high ground (up to 400m.) in the centre falling rapidly to sea-level on either side, whilst the northern part of the long peninsula (Alangorsuak) reaches over 600 metres, with extremely steep cliffs on either side of a long ridge.

There is abundant evidence in this region of former sea-levels and in the south of the area pebble beaches have been found at about 30 metres. Accompanying these is the cave at 70 metres known as Karussugssuak which can be clearly seen from the fjord. This cave is probably the result of wave action on a set converting fault zones, the zones themselves are traceable across the mouth of the cavity. Other pebble deposits have been mapped at 30 and 45 metres on the east coast near Eqalugkat.

Most of the drainage in the area consists of a series of linked streams and small lakes occupying the fault zones. The largest lake in the region is that of Taserssuaq to the north-west of Julianehaab, which is 3.5km. long and has a maximum breadth of 1.5km. An area equal to that of Taserssuaq is covered by a multitude of small lakes and occurs to the north-east of this lake. These small lakes occur in a large basinlike area which opens outwards to the west into another region of lakes. These have been termed the Central and Eastern Lakes Regions by the writer for convenience in description, although these terms are not among the officially approved names.

Previous work.

The exploration and geological investigations, commenced by Giesecke in the years 1806-13, have for the most part been concentrated on the alkaline complexes in the region, more especially the Ilimaussak batholith, to the north of the area under discussion. Giesecke, there is no doubt covered a much greater area than later investigators who were interested in the unique mineralogical assemblages offered by the syenite complexes. Mineralogists such as Steenstrup, Kornerup, Bøggild and Flinck all showed more interest in the complexes than the granite-gneiss area. Ussing (1912) in his now famous account of the alkaline rocks of Ilimausak and Igaliko includes a short description of the "Julianehaab granite", dealing very generally with its appearance and mineralogy, and suggested a possible age for the granite-gneiss rocks.

Wegmann (1938) visited south-west Greenland for three months in 1936, and from this comparatively short visit emerged the basis for the classification of the rocks of this area. There can be little doubt that, although highly speculative in part, this work formed the foundation for later work on the granite-gneiss terrains and as a result must be recognised as a classic description. Wegmann criticised the earlier classification of Ussing on the basis that it was an attempt to correlate over large distances rocks which could not be definitely linked to any other Pre-Cambrian terrain. Instead he suggested a subdivision based on orogenic cycles, and with this in mind he proposed the following classification:

Gardar	Including sandstones, volcanics and alkaline plutons.
Ketilidian	Julianehaab Granite Arsuk Group Sermilik Group.

A strong unconformity exists between the Ketilidian (the term is after Ketils-Fjord) and the Gardar (the term is taken from the bishopric of Gardar, an Icelandic name), and it was suggested that the folding of the Arsuk Group was largely completed before the emplacement of the Julianehaab Granite. The dolerite and alkaline dykes were assigned by Wegmann to the Gardar cycle, as well as the Igaliko sandstone, the volcanic porphyry-formation and the alkaline intrusions.

The basal member of the Gardar is the Igaliko Sandstone which rests with strong unconformity on the Julianehaab Granites. The sandstone-volcanic series of the Gardar is preserved in a trough like depression (probably bordered by faults in part) between Brede and Tunugdliarfik fjords. In all previous maps of the region the area included by this study ~~have~~ has been shown as granite and there can be little doubt that there has been no previous mapping done on this peninsula. It is likely that the ground has been covered to determine if any alkaline bodies existed and Wegmann (1938) includes a map of the Gardar formation (Wegmann 1938 Plate 6) in which systems of "younger dykes" are shown. Those marked on the Julianehaab Peninsula and adjoining regions are largely incorrect both in respect to actual locality and direction (c.f. Plate 3).

Geologically this was the situation in South-west Greenland in 1955 when mapping was commenced in the Ivigtut region, north-west of Julianehaab and in 1958 mapping commenced on the granites and gneisses between the ice-cap (inlands is) and Brede fjord (Scharbert) the peninsula north of Igaliko fjord (Allaart) and the Julianehaab district (Nesbitt and Watt). The work on these areas up to the present time (1961) is unpublished but preliminary reports and maps have been compiled for the Greenland Geological Survey in Denmark.

Some of this work has been incorporated into the regional study of South-west Greenland, particularly that of the Ivigtut region by Berthelsen (1960), who has, on the basis of the identification of amphibolitised dykes and a younger granite suggested that a period termed the Sanerutian should be introduced to cover the younger granite, and the dykes, which are well exposed in Kvanit Fjord, should be termed Kuanitic Dykes. The revised classification is as follows:

Gardar	Alkaline Plutons and Associated Dykes. Volcanics Igaliko Sandstone
Sanerutian	Fine Grained Leucocratic Granites. Kuanitic Dykes (Amphibolitised)
Ketilidian	Porphyritic Granites Arsuk Sermilik Series

Thus, two periods, (Ketilidian and Sanerutian) are separated by the intrusion of the Kuanitic Dykes. This subdivision is extremely well displayed by the area covered by this thesis.

Present Study and Conditions.

The present study was made in connection with the systematic mapping of the south-west of Greenland by the

Greenland Geological Survey (Grønlands Geologiske Undersøgelse) and the writer was one of a team of geologists mapping in the area around Narsaq and Julianehaab. The field work commenced in July 1958 and in that year, three months mapping was carried out on the main Julianehaab peninsula. The work on this peninsula together with adjacent areas was completed the following year when a period covering mid-June to mid-September was spent in Greenland.

Mapping was on the scale of 1 : 10,000 the map sheets being enlargements of 1 : 20,000 sheets which were drawn up from aerial photographs by the Geodetic Institute in Copenhagen. Position in the field was fixed by a combination of map, aerial photograph and altimeter reading, the small lakes forming the basis for much of the field location. The area covered during the two field seasons was about 170 sq. km. and as a consequence the mapping must then be regarded as semi-reconnaissance in nature. Several areas were studied closely because of their unusual geological implications, for instance the island of Mato (00/960845) several sections along the vein gneiss horizon and the island of Karramiut where an abundance of diorite, and unusual pseudo-agmatite structures are well exposed.

Most of the mapping was carried out from two-man camps which were shifted regularly by helicopter or boat so that reasonable coverage could be made of the ground to be surveyed,

Because of the excellence of the facilities, abundant samples of rock were collected, especially in the second season. In addition, because of the nature of the survey and likelihood that no further geological investigation would be attempted for several years, numerous photographs of the rock types and structures observed were taken using the facilities provided by the Greenland Survey.

Climate and Vegetation.

Although the winter in this area is of an Arctic nature, the summer months can be extremely mild and frequently uncomfortably warm. In the late spring and early summer pack ice blocks the fjords preventing an earlier start to the field season and isolated icebergs remain in most of the fjords throughout the summer. Snow in this low region soon disappears except for sheltered hill and mountain slopes, so that exposure is not limited by this factor. The field season is forced to a close in early or mid-September by the oncoming of winter, snow falling on the higher ground and visibility generally worsening. Rain fall is unpredictable for in the first season there was an acute drought whilst in the second season, at least two weeks work was lost because of inclement weather. The rain is invariably accompanied by mist which envelopes the higher ground, a factor which makes identification of location virtually impossible. Several times during the second season strong föhn winds made transportation by helicopter and boat extremely hazardous although fortunately the wind is not normally accompanied by rain.

Vegetation is restricted to low growing plants and spindly willow. Edible black and blue berries grow in profusion in the latter part of the summer, partial compensation for the concomitant decrease in exposure. Most of the rock surface inland is covered by a black thin veneer of varying types of lichen which effectively screens any large scale structures or contacts and which must be scraped away if any detail is to be seen. There is only one large area of swampy ground and this occurs on the north side of the main Julianehaab Peninsula. This also constitutes the largest portion of unexposed ground apart from the central portion of the island of Arpatsivik which is covered by gravel and stunted vegetation.

CHAPTER 2

GRANITES

FIELD DESCRIPTION

Julianehaab Granite

The term Julianehaab Granite was given by Ussing to a "... widely distributed rock ... which is supposed to be of late Algonkian age ..." (Ussing 1912). Ussing states that rocks of similar type to this granite cover an area which in an east-west direction measures about 300 kilometres and probably an even greater distance from north to south. Wegmann (1938) criticised the use of Algonkian, as it was an attempt at a long distance correlation with rocks of Europe and he also viewed unfavourably the attempt by Ussing to make the degree of metamorphism a prime factor in the classification of the rocks.*

Wegmann preferred to introduce a new term - "Ketilidian" which classified the rocks into a tectonic cycle whilst rocks younger than the Julianehaab granite were grouped together under the Gardar period. This terminology, with slight modifications, is still in use at the present time and is set out schematically below.

Gardar	including Igaliko Sandstone and volcanics and plutonic centres.
Ketilidian	Julianehaab Granite Sermilik-Arsuk series.

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* Wegmann states that Archaean means "highly metamorphosed crystalline rocks" and Algonkian "not highly metamorphosed rocks belonging to the Pre-Cambrian". The use of Algonkian by Ussing is thus a metamorphic grade classification.

The question of classification has been dealt with more fully elsewhere (Review of previous work) so it is sufficient here to note that the Julianehaab granite is placed at the top of the Ketilidian period and is succeeded by a period of dyke injection, followed by emplacement of the Sanerutian granite.

The area under discussion represents about 170 sq. kilometres, only a small portion of the exposed "Julianehaab granite". Within this area there is considerable variation of granite type and it would be extremely difficult if not impossible to designate a specific variety as "type" Julianehaab granite. It is now realised by workers in the area that the term Julianehaab granite is an extremely wide one useful only in that it designates the granite in question to pre-Gardar times. As will be described in the following pages it has proved possible to subdivide this large body of granite into several types many of which are separated in time.

After several weeks work over the area it was found that it was possible to broadly subdivide the granites on a textural and mineralogical basis. The primary feature used was the abundance and size of the phenocrysts and secondarily a visual estimate of the quartz content. It was found that it was impracticable to classify them on the type of dark minerals as the majority have both biotite and amphibole. On the coast of the fjords the granite surfaces are perfectly exposed and in most cases there was no difficulty in designating the granite to its particular category. Inland however where the rock face is obscured by clinging lichen a small hand specimen is generally inadequate for classification on a textural basis.

It was soon realised that apart from the early intrusive younger granite there were very few contacts between the major recognisable types. In almost all cases the contacts are gradational except when two types are brought together by faulting.

The granite types recognised are set out below and Table 2.1. is a summary of the mineralogical characteristics.

Sanerutian Granite
Porphyritic Aplitic Granite
Euhedral (Feldspar) Phenocryst Granite
Small (Feldspar) Phenocryst Granite
Big (Feldspar) Phenocryst Granite
Melanocratic Microgranite.

Table 2.1. Summary of the Mineralogical Characteristics of the Granite Types.

Sanerutian Granite ... Leucocratic, quartz rich, albite or soda oligoclase. Dark minerals scarce, biotite only. Occasionally foliated. Much finer grained than the rest of the granites with a white weathered surface.

Porphyritic Aplitic Granite ... Leucocratic, quartz rich, and of similar appearance to Sanerutian granite. Well developed feldspar phenocrysts .5cm long which are often zoned. Dark minerals scarce only biotite developed.

Euhedral Phenocryst Granite ... Medium to coarse grained rock. Often large quartz nodes or segregations developed. Strongly euhedral feldspar phenocrysts from 1.5 to 2cm. long. Sphene prominent. Dark minerals up to 10% with both biotite and amphibole.

Small Phenocryst Granite ... Generally coarse to medium grained with dark minerals prominent. Feldspar phenocrysts up to 3cm. but normally about 1-2cm. in length. Quartz present but not abundant. Dark minerals amphibole, biotite, and some sphene.

Big Phenocryst Granite ... Coarse grained massive granite. Amphibole, biotite prominent and sphene can generally be seen in hand specimen. Quartz present in varying quantities. Feldspar phenocrysts over 3cm. long as well as numerous smaller phenocrysts.

Microgranodiorite ... Grey even grained rock without strong phenocrysts developed. No pink feldspar developed, quartz present in the general groundmass. Amphibole and biotite spread evenly throughout the rock which is medium to fine grained. Sphene present. Occasionally basic clots remnant in the granite.

Sanerutian Granite.

This is perhaps the most characteristic type of granite in the field and can be readily distinguished. It is undoubtedly the youngest granite type in the area. In the field on the clean coastal sections it is a white granite. Often there are long stretches in which no xenoliths are included. In hand specimen the high quartz content is most obvious with small feldspar phenocrysts which vary in quantity. On the weathered surface the quartz stands out as small nodes which are especially noticeable on the wet granite surfaces. The feldspars are anhedral, rarely exceed .2cm., and they have a creamy white appearance on the weathered surface. The dark constituents are conspicuously absent with a very small percentage of biotite developed. The absence of amphibole is significant and is a useful indicator as to the origin of this granite type. However this will be discussed in more detail when the mineralogy of this granite is described.

In effect this is a typical late-kinematic granite as described by Marmo (Marmo 1958) as the plagioclase feldspar is albite or acid oligoclase with a fine grained texture, a high quartz content and a suppression of the dark minerals. Recently (Berthelsen 1960) has grouped these granite types into the SANERUTIAN which he places at the end of the Ketilidian period but divided from it by the intrusion of intermediate and basic dykes. As will be shown later this is an excellent term as the geology of the Julianehaab peninsula fits so well into it. The Sanerutian is characterised by the lack of geosynclinal sediments over the whole of South-west

Greenland in comparison to the Ketilidian and the Nagssugtoqidian. Berthelsen (personal communication) describes it as a period of block and transgressive faulting in which parts of the basement have been suddenly let down into regions of high pressure and temperature. This has caused a very rapid remobilisation or rheomorphism of the downfaulted blocks, causing the most easily fusible material to be driven off into the overlying rocks. As will be discussed in a later section this concept of palingenesis and injection fits both into the field characters and mineralogy of this granite type.

Mapping of the contacts on the ground west of Tartoq shows that it is sheet-like with an apparent intrusive nature. The contact is not sharp but can be described as agmatitic with a gradual swamping of the older granites as the main body of the younger granite is approached. The edges must consist of a large number of anastomosing large veins of the Sanerutian granite cutting into the older rock. A few hundred metres from the major contact, the Sanerutian granite can still be seen in small quantities cutting through the porphyritic coarse granites as a series of veins along the prominent joint directions and isolating large blocks of older material (Fig. 2.1.).

This granite must have been remarkably mobile, for in the areas of porphyritic granite many kilometres away from any large outcrop of the material, small veins and occasionally patches are found lying isolated within the older granite. Undoubtedly some of these occurrences can be attributed to a period in which aplite veins not necessarily related to the Sanerutian granite were injected. However the Sanerutian granite does cut some of these veins on the south coast of the Alangorsuak peninsula (10/047927) showing that there has either been a series of aplites directly related to the porphyritic granites or that the emplacement of the Sanerutian granite was heralded by a series of aplitic veins.

Very frequently in areas of younger granite lobes of xenolithic porphyritic older granite are exposed. These xenoliths tend to be rounded showing that some assimilation of the coarser granite by the younger has taken place and it is an indication that the granite was fairly rich in volatiles (Fig. 2.2.).

The distribution of the Sanerutian granite is shown on the geological map of the area (Plate 1). The principal occurrence is on the islands to the east of the Julianehaab peninsula. On the island of Karrarmiut, the more southerly of the two islands, the granite shows its best development, especially on the southwest coast where the granite is exposed on gleaming white clean surfaces. The formation of the silica rich skin due to the differential weathering of the primary constituents gives to the granite this characteristic white colouration. Apart from the large stretches of diorites and amphibolitic rafts this granite type occupies the whole of the island, either as a homogeneous granite or as part of the large mass of agmatites found throughout the island. The granite is found over a wide area on the island of Arpatsivik to the north of Karrarmiut and on the north-eastern coast the relationship to the older porphyritic granites can be examined on the clean surfaces. The high ground east of Tartoq is made up of this granite and the high percentage of quartz accounts for the greater weathering properties. Mapping by Allaart (1958, 1959) has shown that the Iviangiussat peaks are also of that granite type.

The relation of this younger granite to the early dykes is of great importance in the understanding of the geological history of the area. As it is shown in the chapter on these dykes, the field evidence points to the Sanerutian granite being younger than the Kuanitic dykes. (See Chapter 5)

Measurements of the foliations and lineations seen in this granite on Arpatsivik and banding on Karrarmiut are shown in Plate 2. These measurements were taken on two apparent directions and later converted to a true dip reading by plotting on a Wulff net, using the method outlined by Phillips (1958).

The banding seen in this granite occurs mainly on Karrarmiut (Fig. 2.3) and is due to the concentration of the dark minerals in a normally leucocratic rock. As can be seen from Plate 2 the disposition of the banding is in no way consistent and it seems that it was produced by crystal settling in dyke and sill bodies intruded into the Sanerutian granite at a late stage. In the same way, the readings of the foliations and lineations are not consistent and it is suggested that this is due to a late movement in a partly consolidated granite mass.

It is erroneous to consider that this granite type is everywhere homogeneous. Within it lie large amounts of a light grey fine grained dioritic gneiss, coarse diorites, amphibolites and remnants of the porphyritic granites. As has been shown in the case of the block of porphyritic granite within the Sanerutian granite there had been some resorption causing a rounding of the block. It would appear that in some cases there has been total digestion, for the granite may contain up to 12% of dark minerals. An alternative suggestion would be that the remobilised granite had brought up with it portions of the older granite in which the separation of the leucocratic minerals had not been effectively completed. These blocks may well have originated at much higher levels. Whatever their origin the fact remains that within the main body of the Sanerutian granite there can be found gradations from a granite without biotite, containing albite, alkali feldspar and quartz to a type with acid oligoclase, quartz, alkali feldspar and up to 12% biotite. These mineralogical relationships are discussed in a later section.

The texture of this granite varies in a simple way for although being quite distinct and recognisable as the Sanerutian granite, it can vary from fine grained to a much coarser grain. With these considerations in mind it can be appreciated that under the term of Sanerutian granite is gathered quite a variety of rock types which still can be differentiated from the older porphyritic granites.

An interesting problem associated with the Sanerutian granite is the occurrence of aplitic material along the contact between this granite and the older rocks. An example of this is seen on the east coast of the main Julianehaab Peninsula (10/082889), where the granite cuts into a fine grained dioritic gneiss. Contained in the granite here are blocks of older porphyritic granite, fine grained gneiss and coarse grained diorite. The diorite can be seen cutting through the gneiss in diffuse stringers. Along the granite-gneiss contact is an aplitic vein, the contact dips at a high angle and is followed by the vein (Fig. 2.4). There are many other similar exposures in the area, one of the best is seen to the north where the Sanerutian granite is in contact with a porphyritic granite, a lobe of which can be seen within the younger granite (Fig. 2.5). Along the contact there is a thin aplitic vein.

The interesting feature is however, that such veins along contacts are rarely seen on the islands to the east where the main mass of the younger granite lies. There can be little doubt that the veins seen represent late stage fluids along cooling cracks, and there must be some difference between the various phases to account for their absence to the east.

Porphyritic Aplitic Granite.

This granite is intimately associated with the Sanerutian granite and is distinguished from it by the presence of small phenocrysts which are conspicuous on the weathered surface. The actual age of the Porphyritic Aplitic granite cannot be determined with any precision. Nowhere has it been seen to cut the porphyritic granites, yet at all times it is associated with Sanerutian granite. Rather than regard it as a separate intrusion of granitic material the writer feels that the close association of the two types must point to a common origin. The actual distribution of this granite type is shown in Plate 1. It occupies only a small area of the part mapped and is exposed to the west of Tartoq and on the high ground of the Alangorsuak peninsula.

Any theory regarding the origin of this granite type must take into account the fact of the association between it and the Sanerutian granite as well as the presence of plagioclase phenocrysts which may be zoned. This granite type may represent partially remobilised older granite material, in which case the phenocrysts would be xenocrysts of undigested granite, caught up in the Sanerutian granite. This would explain satisfactorily the zoning seen in the phenocrysts. Observations on the large porphyritic feldspar seen in the amphibolitised dykes (Kuanitic dykes) show that feldspars are very resistant to metamorphic effects, so that it is possible that the zoned porphyritic feldspars in this granite are of Ketilidian age.

We have now the tentative picture of large blocks of granitic material being let down to sufficient depth so that there has been a remelting and consequent remobilisation and injection. The early phase of this is seen on the east coast of the Julianehaab peninsula where the Sanerutian granite can be seen cutting the older granites. This was followed by a period of aplite injection now represented by prominent vein cutting the older granites and seen along contacts between different rock types. The main phase of the Sanerutian granite emplacement followed with a sheet like body of the granite on Tartup qaqa and on the higher ground on the Alangorsuak peninsula. The intrusive younger granite also makes up the major parts of the islands of Arpatsivik and Karrarmiut and the high ground of Iviangiussat peaks. During the remobilisation,parts of the older granites especially in the higher levels escaped digestion and so were caught up as blocks within the upwelling Sanerutian granite. In some cases the phenocrysts of the older granites alone resisted complete digestion and these two were mixed in with the granite fluids. These phenocrysts were then the nucleii for crystallisation and so formed zoned crystals. The resulting granite, the Porphyritic Aplitic granite was thus intimately mixed with the Sanerutian granite and is thus always associated with it in the field.

Big Feldspar Phenocryst Granite.*

This is the "typical" or "type" Julianehaab Granite for the township of Julianehaab is built upon it. The granite has hornblende, biotite evenly distributed and develops microcline and plagioclase phenocrysts which are over 3cm. in length. Quartz is often conspicuous in hand specimen as disseminate grains and only rarely as masses.

The rock is moderately leucocratic, generally coarse grained and fairly fresh in hand specimen. In the field it is fairly resistant to weathering with a thin oxidation zone only occasionally developed. Normally it is fresh at the surface especially on the coastal strips where the textures in small areas can be seen in detail. In many areas the granite shows a lineation and occasionally a foliation, due to biotite and amphibole. It is unusual for the phenocrysts

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* Literature on the Julianehaab Granites must be viewed with caution for various writers have used the term Big Feldspar Granite as a prominent type developed in a particular area. In this case, the term is applied to granites with feldspar phenocrysts over 3cm., but Upton (1957 and 1959) describes a Big Feldspar Granite in which phenocrysts over 6cm. are developed. The present writer's view was that the terminology enabled a finer distinction to be made between this and the granite with smaller phenocrysts.

to show any form of alignment, which may be an important point when the origin of the granite is considered.

The distribution of the granite can be seen on Plate 1 occurring principally in the south east of the area around Taserssuaq. The best sections are seen along the south coast immediately to the west of Julianehaab itself. In this region the granite is cut by several amphibolitic and doleritic dykes as well as containing abundant xenolithic material with the general strike of N.E. - S.W. (Fig. 2.6.). The granite occurs again on the Alangorsuak peninsula on the coasts below the peak itself and is overlain by the Porphyritic Aplitic Granite. On the islands of Karrarmiut and Arpatsivik the granite is exposed on good coastal sections, and in the case of the more southerly island it crops out on the north west coast and as a small patch on the prominent north peninsula. Within the granite on this peninsula are two rocks rich in mafic minerals. The first generation occurs as a crude form of "flow banded" partially digested xenolithic material striking 040° and the second as amphibolitic bands, dyke-like in form but cut into disjointed pieces by the aplites and pegmatites which also cut the granite. From this evidence it would appear that a period of granitisation intervened between the almost digested xenoliths and the dykes now represented by amphibolites. Later, Sanerutian Granite was emplaced cutting all the other rocks. Whether this granite caused the amphibolitisation of the dykes cannot be proved but it is quite possible that this was the case. However the possibility that there have been several periods of metamorphism and concomitant granitisation before the emplacement of the Sanerutian Granite cannot be overlooked. This is discussed more fully in the section dealing with the amphibolitic dykes. The matter of several periods of metamorphism and granitisation is relevant however to the genesis of the granite, it is therefore significant that there is evidence for at least one period of metamorphism prior to the intrusion of the Kuanitic dykes (as shown by the last locality).

The granite is again exposed on Arpatsivik where it is seen on the coastal sections at the north east end of the island. Here again amphibolitic dykes cut through the granite, both of which are cut by the Sanerutian Granite.

The age of the granite seems to be fairly well established, There is abundant evidence that this granite is older than the Kuanitic dykes (see Chapter 5) indicating that it is Ketilidian im age. As described in the section under Sanerutian granite, there is much field evidence to show that the Big Feldspar Phenocryst Granite is much older than this Sanerutian granite.

Relics in the granite consist essentially of amphibolitic gneisses, acid gneisses and streaks of quartzite. These essentially are last remnants of the oldest rocks in the whole of South west Greenland, namely the Arsuk-Sermilik series. Contacts with other granite types apart from the Sanerutian granites are negligible. There appears to be a gradational contact between this type and the Small Feldspar

Phenocryst Granite, whilst there is a fault contact with the Melanocratic Microgranite.

With faulting, this granite develops a typical red colouration with an almost complete suppression of the dark minerals or their alteration to chlorite. Quartz is generally expelled and is found as veins through the breccia. Hematite is normally associated with this type of granite. True mylonites (Lapworth 1885) are rare and this type of granite is best described as a fault breccia (Fig. 2.7.).

The best specimens of the granite can be obtained from the quarries in the township of Julianehaab and biotite from one of these has been used by Moorbath et. al (1960) for age dating purposes. Rubidium-Strontium measurements give an age of 1590 ± 70 million years and Potassium-Argon 1597 ± 100 million years. The same authors report an age of 1086-1095 million years, for the Ilimaussaq using Polylithionite (Rubidium - Strontium).

<u>Small Feldspar Phenocryst Granite</u>.

This granite variety is genetically linked with the granite just described, but it is possible to map out approximate boundaries between the two where the size of the feldspar phenocrysts decrease to below 3cm. The granite is essentially a porphyritic medium dark type with a medium to low quartz content. The feldspar phenocrysts are (by definition) less than 3cm. but are numerous. On the weathered surface these phenocrysts have the appearance of being crowded together and have a tendency to be rounded. Hornblende and biotite are both developed in the granite as is sphene. In patches, especially bordering the amphibolitic masses the rock grades into a diorite, generally devoid of quartz and contains little or no alkali feldspar. This process appears to be one of de-silication and increase in dark minerals so that finally the diorite grades into a dioritic amphibolite.

The distribution of the granite is centred on the northern central portion of the Julianehaab peninsula and also within the ground to the west of Tartoq (Plate 1). The contact with the Big Feldspar granite is gradational, occurring in the region north of Taserssuaq. The Sanerutian Granite cuts this rock type as is well displayed on the ground north of Eqalugkat Alanguat. In age this rock type must be grouped with the Big Feldspar Phenocryst Granite as it is older than the Sanerutian Granite and is also cut by the Kuanitic dykes.

Euhedral Feldspar Phenocryst Granite.

This granite type is best developed on the west coast of Tartup qaqa (10/100950) where it is the granite in direct contact with the Sanerutian Granite (Plate 1). The phenocrysts which are frequently rimmed can reach over 1cm. in diameter and are conspicuous in hand specimen. Quartz segregations are also prominent, biotite and hornblende occur and euhedral sphenes are easily seen.

Although cut by veins of Sanerutian Granite in this section, the granite in all probability owes its character in some measure to the intrusion of the younger granite. It may, in fact, be regarded as a metamorphosed granite as its best development occurs in juxtaposition to the Sanerutian Granite. The field evidence seems to point to the fact that the euhedral nature of the phenocrysts is due in some way to the effect of the later granite. These effects may have been produced by solutions emanating from the mobile Sanerutian Granite and petrographical evidence (Chapter 6) also favours this conclusion.

Mafic Microgranodiorite.

This granodiorite is seen only in one locality in the area under discussion. Along the south coast about five kilometres west of Julianehaab this distinctive rock type is extremely well exposed for 3 kilometres on the gently sloping coast section. The total exposure is bounded to the north by a low angle fault which has brought this unique granite type into the area. The fault itself must have moved at least twice for on the eastern margin there is a faulted trachyte dyke with only a small amount of displacement. In hand specimen the rock is grey and much darker than the normal porphyritic granite which surrounds it. There are no prominent feldspar phenocrysts and the general texture is homogenous and fairly fine grained. The abundant dark minerals impart to the rock a foliation which is more readily seen on large surfaces than in hand specimen. The structures within this granite are described elsewhere (see Chapter 4 and Plate 2). As well as the prominent linear directions there are characteristically numerous elongate thin basic amphibolitic xenoliths with prominent alignment in this granite.

The exact age of the granite is unknown. A Kuanitic dyke cuts through it but apart from this Pre-Sanerutian age there is no evidence to fix it more definitely.

In conclusion, a tentative sequence of granites is given below.

Sanerutian	Sanerutian Granite
	Porphyritic Aplitic Granite
	Euhedral Feldspar Phenocryst Granite
Ketilidian	Small Feldspar Phenocryst Granite
	Big Feldspar Phenocryst Granite
	Microgranodiorite.

CHAPTER 3

Xenolithic Rocks Within the Granites

The rock types lying within the granites are predominantly basic in character with a smaller quantity of acid gneiss and quartzites. It is intended first to describe those rocks which are generally conformable to the granites and later those discordant pre-granite(?) intrusions represented now by diorites, amphibolites and occasionally remnant basic igneous rocks.

The Vein Gneiss Band

Plate 1 shows the distribution of this remarkable gneiss horizon. The known length of the band is at least 10 km. from the small skerries south east of the island of Mato (00/960845) striking N.E. - S.W. across the total breadth of the main peninsula up to Nunarssuatsiaup iterdla (10/050895). From here remnant patches are found immediately to the north of Qasigianguit (10/100930) lying within the Sanerutian Granite. Assuming that these remnants were once part of a continuous band this increases the length of the band along the strike to 18 km. Several major faults cut across the band especially in the region of Trekant Sø where there is a sinistral displacement of 700 metres. The gneiss band has proved valuable in interpreting the structure of the area for it is one of the few horizons which can be definitely correlated on either side of the fault lines.

At its south west end the gneiss band is over 300 metres across (assuming there has been no thickening due to faulting) but this decreases to 100 metres in the Trekant Sø region and maintains this width going north east across the rest of the peninsula. The actual width north-east of Pile Sø is uncertain as the gneiss has been faulted by a large (N.E. - S.W.) fracture which is parallel to the strike of the band. Inland the gneiss makes a prominent feature especially in the Trekant Sø region as Fig. 3.1. shows.

Petrographically the gneiss is characterised by an amphibole-biotite-plagioclase-quartz assemblage. At the northern end the gneiss is predominantly acid in nature with abundant quartz. The rock is leucocratic with an almost vertical foliation, parallel to the margin of the band. In the centre of the peninsula where the best veining is developed (fig. 3.2.) the rock is much richer in dark minerals often becoming amphibolitic with occasional small folds developed at the edges of the band. The axial planes of these folds are vertical and approximately parallel to the strike of the gneiss band. The dominant amphibolitic gneiss is found exposed on the southern margin at the south-west end (on Mato) but in the centre of the peninsula there is an abrupt change from the southern to the northern margin. On the island of Mato the amphibolitic gneiss develops a prominent banding with a strike parallel to the margin of the band and dipping 80°N. (fig. 3.3.). (This material bears a strong resemblance to that figured by Dietrich 1960 a). This material is in striking contrast to the rest of the band and from the very nature of the contact with the normal gneiss it would seem that this material was originally intrusive in origin. (fig. 3.4.). Nebulitic acid veins are much more prominent in the acid gneiss than in the amphibolitic type (perhaps an argument in favour of exudation from the acid body?) and the basic type appears to be wedged into a fold core of the acid gneiss. (fig. 3.4.) As little is known of the pre-granite folding sequence in this general region it is difficult to postulate in a set time sequence the course of events. From the available evidence it would seem that the basic gneiss being less competant would break off into segments on folding and hence now appears as wedges within the fold axes (c.f. the Scourian dykes involved in the folding in the Glenelg region, especially well exposed on the north shore of Loch Hourn) The banding is thought to be more a metamorphic shearing effect producing segregation, rather than an original feature of the amphibolitic gneiss (c.f. the striped amphibolites of Connemara described by Evans and Leake 1960). The problem is further complicated by several exposures which show the acid gneiss apparently cutting into the amphibolitic type (fig. 3.5.). In addition to this, conformable horizons of acid gneiss occur within the banded gneiss and these serve to pick out the folding within the material. The acid material itself displays a type of banding suggesting that this too is a segregation effect (fig. 3.6.).

The actual interpretation of these structures is hampered by the lack of evidence and the subjective observations of the individual, but it is suggested that a combination of intrusion, folding and mineral segregation produced the situation where an amphibolitic type is intercalated in places with the acid gneiss, both displaying banding which is much stronger in the more basic type. There is good evidence of isoclinal folding in this short strip and fig.3.7. is a sketch of a vertical face in which both acid and amphibolitic types have been folded and possibly refolded as the axial planes of the isoclinal folds are bent. The axial planes of the major folding are parallel to the banding directions, the axes plunging to the south-west.

It seems that with more detailed field work on this part of the gneiss horizon much of the pre-granite history, obliterated elsewhere, will be elucidated.

Mention should be made of the broken aplitic vein cutting the amphibolitic gneiss, for it indicates the strong pressures and their direction (N.W. - S.E.) which were in operation during the period of granite emplacement. The locality is shown in fig. 3.8.

The contacts of the gneiss horizon are of interest because by their very nature they demonstrate the fact that the gneiss is in fact pre-granite. Inland where exposure is not so good the contacts generally appear sharp. On Mato and the coast of the mainland to the north there are however excellent exposures of the junction. Invariably the granite invades the gneiss leaving blocks of this material stranded often up to 40 metres away from the main contact. It can be seen from this that there has been a swamping of the gneiss by the granite the intensity of which increases outwards from the centre of the band. This is seen on the mainland opposite Mato (00/968849) where a block of banded amphibolitic gneiss is caught up in the granite. Not only is this of interest because it demonstrates the nature of the contact but also as this block occurs on the northern side of the band it shows that this rock type must be transgressive across the normal gneiss band. The contact in this case is remarkably sharp perhaps due to small fractures. This swamping action is characteristic of the contact between the granite and gneiss on Mato. However on this island there is evidence of migmatisation and digestion of the gneiss blocks. Fig. 3.9. shows a partial assimilated gneiss block within the granite and fig. 3.10. the migmatitic contact between gneiss and granite.

Before leaving the field discussion of the gneiss band it is worth while to spend some time on the description of the veins so characteristic of the gneiss. Fig. 3.2. shows a typical development of the veining in the centre of the peninsula (10/003860). In this example the veins have a steep dip to the north and are, as is usual, parallel to the foliation of the rock. On flat surfaces the veins weather out due to the high quartz content and so form a striking feature of the rock. In detail they are an anastomosing series with a set of dominant veins some 3 mm. across with a general parallel disposition, connected by thin cross veins. This type of veining is in contrast to that developed at the south west end at Singitsut, the mainland opposite Mato. Here the veins fall into two categories. The first is a sparse spidery type in which the veins themselves are thin rarely exceeding 2 mm. Although appearing to have a haphazard arrangement they are again largely controlled by the foliation within the rock. The other type can perhaps be best described as ptygmatic veining for these, as shown in fig. 3.11, show small folds along their length. The axes of these folds are generally parallel to the foliation although in many cases the axes may diverge up to 20^{o} from each other. The veins are best seen on the north shore of Singitsut in the gneiss which here is fairly dark with a moderate development of amphibole.

The mineralogy of the veins is quartz and feldspar (actually microcline - see petrographic description) with small quantities of dark minerals (hornblende and biotite). The strike of these veins and the trend of the axial planes where they are folded is shown on the structure map (Plate 2). From this, the gradual thinning of the horizon to the north-east can be seen as well as the sudden change in strike of the veins at the southern end of Mato. This direction change is again seen on the west coast of Tartoq (10/102930).

Summary and Conclusions on the Gneiss Band

The gneiss band horizon has been shown to be rock type lying within a younger granite and having a known length in a north east - south west direction of 18 km. Characteristically it is penetrated by acid veins of granitic composition along the whole of its length, the parallelism of the veins being pronounced in the centre of the body. The width decreases toward the north east and there is a definite tendency to become more acid and leucocratic in the same direction.

The gneiss band is extensively faulted, especially in the central region of the peninsula and at the north east end, the gneiss is left as patches within the Sanerutian granite.

Foliations developed within the rock conform to the N.E. - S.W. trend as do the majority of the acid veins. Typically where exposure is good, the contact with the granite is shown to be agmatitic with blocks of gneiss left stranded in the granite, some dis-oriented. It has also been shown that there is a series of xenolithic blocks often greater than 50 metres long on the northern margins of the gneiss up to ½km. away from the band.

At certain localities an amphibolitic gneiss has been mapped on the southern margin of the band. This occurs at the south-western end and in the centre of the peninsula, but east of this area the rock type occurs on the northern margins. Within the amphibolitic gneiss small scale folds can be seen particularly on Mato at the south west end of the band. The axial planes of the folds are for the most part vertical having a N.E. - S.W. direction. The axes dip at a low angle to the north-east and on Mato there is some evidence suggesting a re-folding of the axial planes.

Other Xenolithic Bodies

A remarkable feature of the area which becomes apparent from the mapping is the apparent conformity of the majority of the xenoliths to the N.E. - S.W. to E.N.E. - W.S.W. pattern. The reader is referred to a more detailed description of this on the section on structure (Chapter 4).

Under this section are included those rock types found within the porphyritic and younger granites and thought to be older than the granites. The basic and dioritic bodies as well as the unusual gneiss bodies found within the younger granites will be discussed under a separate heading. The main types to be described in this section are those conformable small remnants found especially in the south of the area, the larger bodies found scattered on the northern margins of the vein gneiss and the zone of brecciation in the south west of the main peninsula.

Minor Conformable Xenoliths

The small elongate xenoliths seen especially on the southern coast have a size range of 1 cm - 20 cm. in length and are invariably oriented in a general N.E. - S.W. direction. (Fig. 2.6.) The rock type is fairly constant being a dark fine grained compact amphibolitic gneiss. Occasionally feldspar phenocrysts are developed within them, representing their partial felspathisation by the invading granite. Both the xenoliths and the host granite are cut by aplitic veins but no example was seen where the host granite invaded the xenolith. The xenoliths are perhaps best seen within the Microgranite but they are also common within the Big Phenocryst Granite on the south coast of the peninsula. When seen in vertical section the short axes of the xenoliths are almost vertical. Thus this alignment of the xenoliths occurs in a horizontal as well as vertical plane. In one exposure the xenoliths are seen to be folded with axes parallel to the lineation of the granite. Hence it is possible that the whole of the xenolithic bodies preserved in the granite are the remnants of a folded sequence. From the close parallelism of the xenoliths these folds must have been of the tight isoclinal type and from the nature of the lineations within the granite their axes must have had a shallow plunge to the south west.

Of a different nature are the larger bodies seen to the north of the vein gneiss band at 10/029886 and 00/029886. It is a significant feature of these bodies that they are found in this position relative to the gneiss horizon. Smaller bodies of the same type occur in a similar position in the region of Eqalugarssuit tasiat (10/005867). Mineralogically these blocks which are up to 60 metres long are biotite - hornblende gneisses which are considerably altered and iron stained. In part they resemble portions of the gneiss band.

Another unique rock type occupying an apparently consistent position in the peninsula in relation to the gneiss band can be seen to the east of Piletrae Sø. This is a distinctive quartzite horizon up to 10 metres wide striking conformably to the gneiss band. The horizon can be traced from north-east of Piletrae Sø south-west to Eqalugarssuit tasiat (ref. 10/004867). The rock types grade rapidly into the country granite with the incoming of feldspar and dark minerals. It is remarkable that the mapping of the band shows that it strikes in a N.E. - S.W. direction, without any major breaks for over 3 kilometres.

Of a different character is the unusual area of xenoliths in the south west of the Julianehaab peninsula (00/970830) directly opposite the island of Kilagtok. Within this area are spectacular areas of breccia lying in the Porphyritic Granite. Some of the blocks reach 1 metre in length with a weak orientation of their long axes whilst there are numerous smaller pieces of assorted sizes. (Fig. 3.12.). The significant feature of this locality is the wide assortment of rock types found within the breccia zone. Principally the blocks are amphibolitic gneisses but there are also diorites present, reminiscent of the varieties found on the islands of Karramiut and Arpatsivik. There are also banded siliceous gneisses or banded quartzites appearing sporadically which are seen in no other locality in the area. The nearest rock type to this is the quartzite band just described, and the acid gneisses described by Allaart (1958 & 1959). Fig. 3.13. is a photograph of a single block of granite from this region, which contains an assortment of xenolithic types.

Moving west from the area of large blocks their size decreases until at the margin of the brecciation zone there is a contact with a granite containing xenoliths only a few cm. in length in contact with a porphyritic granite in which the xenoliths are just discernible. (Fig. 3.13). This latter granite type grades into the normal porphyritic type within a metre.

In interpreting this zone the significant factors are the variety and angularity of the rock types as well as their progressive decrease in size toward the margin of the body. It seems that the brecciation occurs within a pipe like body about 300 metres across and of unknown width. The problem of the origin of this body is open to several interpretations and the first of these is that this zone of brecciation is a pre-granite feature which has resisted granitisation. In such a case the assumption must be that the original enclosing material was easily converted to granite. However there is no sign of felspathisation within the blocks nor any sign of corrosion and rounding so this hypothesis is not favoured by the writer. Other alternatives are that the material came from above originating from a collapse structure, but the absence of granite blocks makes this unlikely.

It appears to the writer that there are two critical factors in this problem, namely the absence of any granitic blocks and the nature of the contact. The intense brecciation which occurred near the margins breaking down the xenoliths to their present size can be ascribed to faulting or to the fluidisation process described by Reynolds (1954). If the brecciation is due to the fluxing action of gases, as the fluidisation process suggests, then the release of large quantities of this material must have caused some considerable change in pressure. This may have been sufficient to cause the remobilisation of the granite basement which moved upward through the pipe or neck vent. This upward movement of large quantities of remobilised material brought with it the variety of blocks now seen in this locality. These bodies would be derived from pre-existing xenoliths lying within the now remobilised granite. The temperature of the granite magma would not be sufficient however to affect the basic or quartzitic blocks but has allowed them to become disoriented and thoroughly mixed. Later there was forcible injection of aplitic material (See fig. 3.12) which cut across the rigid granite and xenolithic blocks. The finely brecciated material at the edges of the vent have been preserved in a granite which had a higher viscosity than the material in the centre because of the proximity to the cool margins of the vent.

It may of course be possible that some blocks have fallen through the ascending granite material due to their greater density. This has been suggested by Cloos (1941) Reynolds (1951) and Pitcher and Read (1952). However all of these workers suggested that there was no magmatic material involved, only gas fluxes, which has caused the rounding of the xenolithic fragments. In view of the angularity of the blocks in the centre of the body and the absence of granitic xenoliths it seems likely however that in the case of this diatreme some magma has been in operation. Whether the blocks have moved up or down would depend on the rate of flow of the magma the relative density and size of the xenolithic blocks. Pitcher and Read (1952) faced with a similar problem contemplated on the mathematical relations of elutriation but concluded that "in some circumstances however, intuition is as good as arithmetic." Walker and Leedal (1954) described breccias consisting of Dalradian schists and amphibolites, embedded in comminuted granite and schist, from the Barnesmore Complex in Donegal. It was suggested that the occurrence was not a true eruptive vent but that the blocks have been driven violently upwards as wedges being smashed in the process. It appears to the writer that this hypothesis does not suitably explain the particular diatreme on the Julianehaab peninsula.

If the granites are considered to have been generated in place, then it would be expected that the abundance of xenolithic material would be greater in higher levels of the crust. It is then possible that the blocks observed in the diatreme have sunk down from these levels, through the mobile granite matrix.

Basic Igneous Intrusion

5 km. north of the township of Julianehaab a basic pluton crops out. The body is exposed for about 2.5 km. from north to south and is about 0.5 km. wide (10/068862-074888).

Examination of specimens in the laboratory has shown that the main rock type within the area is a biotite amphibolite within which lie differentiated basic rock types. The different types are difficult to identify in hand specimen, both being dark heavy crystalline rocks with a characteristic pitted weathered surface. In the field the basic types appear to weather out as knolls above the general level of this area which is covered by numerous lakes. Fig. 3.15. shows the area viewed from the centre of the body looking south toward the most prominent of the knolls. The sketch map (Fig. 3.16) shows the distribution and type of the igneous rocks lying within the biotite amphibolite.

Within the basic rocks a banding has been recognised which appears to be due to a mineral segregation with the units being repeated at about 30 cm. intervals. Unfortunately the banding is not seen frequently but from about four localities in the south of the mass it was seen to dip just north of west at about 15°. This tendency of mineral segregation is seen on a larger scale within the mass itself for the various rock types ranging from olivine norite to gabbro have been distinguished.

The contacts of the mass against the granite are sharp with little or no apparent basification of the acid rock. In the north of the body especially there are good exposures of aplitic veins cutting across the margins of the body.

The relationship of the amphibolites to the igneous rocks is problematic. Owing to the similarity of the rock and the reconnaissance nature of the survey no definite boundaries between the types can be distinguished. The knolls previously described are the only clue to the outlines of the basic masses and these are not seen in the north. The simplest explanation, and the one adopted by the writer, is that the amphibolites represent the altered mantles surrounding the unaltered cores of igneous rock. Theoretically then, systematic sampling across the contact toward the centre of the body should reveal progressive alteration. Unfortunately there exists no such simple relationship as fig. 3.16. shows, for some of the basic igneous rock occurs at the margins of the mass. A possible explanation is that pre-granite faulting has caused the dislocation of the body, the fault planes being later obliterated, as there is no field evidence to suggest that faulting has occurred.

Bloomfield (1958) describing the ultrabasic rocks of Chimwadzulu hill derives the envelope of amphibolites from the pyroxenic core, but in this case there is no granite influence to produce this and the agent is said to be tectonic. In the Julianehaab bodies the association of the igneous rocks and amphibolites points to a similar origin although the agent may be of a different character. The knolls of igneous rock represent the relic cores of a much larger body now metamorphosed to amphibolite. The mass is probably pre-Ketilidian granites and is certainly pre-Kuanitic as it is cut by Kuanitic dykes. However there is no definite field evidence available to show that the mass is older than the porphyritic granites, for the contacts are sharp and veins of Ketilidian granite do not cut into the mass. The metamorphism which has affected the mass may have been that which altered the Kuanitic dykes, but there is also the possibility that the emplacement of the Ketilidian granites was also a factor in the evolution of the rocks. Finally little or nothing is known of the history of the area in early Ketilidian times so that it is quite possible that the mass was metamorphosed at least once during this period.

In the centre of the body there is a wedge of granite which poses another problem in the interpretation of this mass. The intrusion of the mass may have caught up a wedge of granite, thus indicating that it is late-Ketilidian in age, or alternatively it is a wedge of country rock which was later granitised. Further field evidence however can help to fill in part of the time sequence, for in the south of the body xenolithic dioritic blocks occur both in the amphibolite and gabbro. These may be regarded as desilicated granite veins, the common occurrence in other areas has been noted by Kennedy (1934). To the west, dioritic rocks, similar in character to those seen in the amphibolitic-gabbroic mass are exposed and it is likely that these have a common origin. There is little doubt that these dioritic masses are older than the Ketilidian granites as the contact of the northern edge of the mass shows. (fig. 3.17.)(10/058870). This type of injection contact is similar to the type of contact seen on the island of Arpatsivik (fig. 3.18.)

Basic and Ultrabasic plutons have already been recorded from this region, Wegmann (1938) from Hollaender Ø and Pulvertaft (1959) from Nunarssuit. Both these writers have interpreted the masses as being of pre-Ketilidian granite age. Although the evidence is not strong the present writer tentatively suggests that the basic pluton found on the Julianehaab peninsula was intruded into the Julianehaab granite, wedges of diorite and granite being caught up in the intrusion. Later metamorphism (probably post Kuanitic) caused the partial alteration of the mass into a rock of amphibolitic composition.

The reasons for this suggestion are two-fold; the absence of contacts normally associated with the older granites and pre-granite rocks (see fig. 3.17 and 3.18) and the wedge of granite found in the centre of the mass.

The Dioritic Plutons

Diorites occur in five significant localities in the area under discussion. Two occur on the main Julianehaab peninsula to the south and west of the main gabbro-amphibolite mass. The more southerly of the two (10/065860) could be more properly termed amphibolite, for the majority of the material is extremely rich in hornblende. To the west, the dioritic mass is more leucocratic with gradational contacts against the granite to the south, with the development of basic granites which are seen nowhere else on the area. At the margin this "basified" granite contains angular blocks of amphibolite, diorite and gradations between the two . Fig. 3.19. illustrates the fact that the granite was fairly mobile, and that this variety of rock was available within the vicinity. The northern contact with the granite is shown in fig. 3.17. Also around this body is developed a granite type which has been termed a Porphyritic Quartz Monzonite because its texture and composition are distinctive in the region.

Blocks of diorite found in the gabbro-amphibolitic mass to the east are similar in appearance and mineralogy to this dioritic mass, so it seems probable that the basic mass is younger.

The diorite which occupies the southern tip of Karrarmiut is almost perfectly exposed on the coast section. The rock itself is coarse grained, feldspar rich, fairly homogeneous diorite. The contact with the granite on the west is not seen because of the intrusion of a large dolerite dyke but to the east a sharp contact against the Sanerutian granite can be seen (10/128802) (Fig. 3.20). This locality is remarkable because of the accumulation of numerous basic, angular, brecciated xenolithic blocks. No definite conclusions can be reached from this locality as to the relative ages of the diorite and Sanerutian Granite, but it is fairly certain that the diorite acted as a solid block against which the broken blocks congregated whilst floating in the molten granite. The Sanerutian Granite penetrates into this diorite as dykes and sills which are large but not numerous. The resistance of the mass must have been strong because of the scarcity of granite intrusions which normally are abundant over the island.

Occasionally faint schelerion of darker bands can be seen in the diorite one of which is shown in fig. 3.21., and in fig. 3.20 two faint streaks parallel to the contact can be just detected.

Immediately to the north across the small bay (10/130813) a large amphibolitic body is exposed high up in the cliff. Below the mass is the Sanerutian Granite and it appears that this is a raft of xenolithic material "floating" in the younger granite. To the west, the basic mass is again seen in the cliffs (10/125813) this time both above and below is granite, as is seen in figs. 3.22 and 3.23. Mapping has shown that this bødy is faulted with the downthrow to the east but with a small vertical movement.

Dioritic bodies are again exposed on the northern peninsula of Karrarmiut (10/133835) and the rock type shows much more variation than that seen on the south coast of the island. The rock varies from a dark amphibolitic rich to leucocratic diorites, which are extensively cut by large sills and dykes of Sanerutian age. The abundance of the granite material is a remarkable feature of this locality, for the diorite is almost swamped by them in places. (Fig. 3.24).

The occurrence of a dioritic body on the island of Arpatsivik demonstrates that the masses show a type of layering. The diorite occurs in the centre of the island (10/125880) and it is continuously exposed from its base to the top. The gradation from amphibolite to meladiorite to leucocratic diorite and then back into amphibolite at the top of the mass can be followed easily. The whole body is cut by veins of Sanerutian granite which are not as abundant as those seen on the north coast of Karrarmiut. The base of the diorite is in direct contact with the granite so here again the raft of basic rock is suspended within the younger granite.

The features of the diorites can be summarised to give a general picture of the mode of origin and metamorphism. It is suggested that these bodies were emplaced as plutons of intermediate to basic composition, with a development of differentiation producing layering, which is now preserved in some of the bodies. The Ketilidian granites rarely were intruded into the diorites, but often there is a type of "lit par lit" injection at the margins of the bodies. This is seen on Arpatsivik (fig. 3.18) and on the main peninsula (fig. 3.17). There is also some indication that hybridisation took place along some margins, with gradational contacts into the surrounding granites.

Metamorphism occurred during the emplacement of the Ketilidian granites, and was repeated after the injection of the Kuanitic dykes and on the emplacement of the Sanerutian granite. The "rafting" of some of the diorites occurred with the injection of the younger granite.

Diorite blocks found within the gabbro mass on the main peninsula suggests that the diorites are older than this layered body, but exactly how much older is not known.

CHAPTER 4

Structure of the Julianehaab District

Introduction

Structurally the area surveyed is relatively simple, with a development of several fault systems which can be subdivided in time by means of their relationships to the dykes, especially the alkaline dykes. Structures within the granite are easily overlooked especially inland, but on the south coast numerous measurements have been taken of lineations and foliations preserved within the granite. The xenoliths enclosed by the granite possess structural characteristics themselves and frequently in well exposed tracts these occur with their long axes in line forming what has been termed "flow banding". (Fig. 2.6). The vein gneiss band has the best preserved structures especially at the south west extremity on the island of Mato where small scale folds have been observed, a feature seen only rarely elsewhere in the region.

Faults

The history of faulting in the area is complicated by the fact that several rejuvenations have undoubtedly taken place. The evidence for this is derived from a study of the alkaline dykes and most of the details pertinent to this question are given in the section dealing with their field relationships. The fault zones described here are all post-Sanerutian and most of the movement appears to have ceased, in this region at least, before the emplacement of the major dolerite dykes.

The earliest fault zones in the area are sets of N.W. - S.E. fractures, the largest of which can be seen at the north-west end of the large lake Taserssuaq extending across the peninsula to Eqalugarssuit (10/000870). The same fault or one closely related is thought to cross the island of Tuqtutoq over 10 km. to the north-west. Another of these faults with a more W.N.W. trend branches off the north-west fault at Trekant Sø (10/014863) and can be traced as a prominent feature eastwards. Just north of Taserssuaq there is an impressive north facing scarp due to this fault with much quartz veining and a red discolouration in the granite. The fault can then be followed further to the east where it again forms a strong feature in the cliffs overlooking Iterdlak (10/080840).

From the evidence of the alkaline dykes it appears that this fault direction was rejuvenated at least once and then quickly followed by movement in a N.E. - S.W. direction. This direction is thought to have moved twice because dykes crossing the fault zone appear to have turned sharply along a plane which afforded easy access. Later movement has fractured the dykes which remain fresh away from the fault zone. The final movements were in an E.W. direction, and it appears that all the major alkaline dykes are faulted in this direction.

Some of the most spectacular fault zones are found on the peninsula north-west of the Julianehaab Peninsula, where steep sided gullies often 30 metres deep result from the rapid down cutting of streams along the brecciated zones.

Plate 2 is a structural map of the Julianehaab Peninsula showing the major faults in the region.

Structure of the Granites

Plate 2 shows the structures found within the granites of the region. There is an important factor in the difference between the younger Sanerutian Granite and the older Porphyritic Granites as regards their structure, which has a bearing on the origin of the granites. In the well exposed south coast numerous measurements were taken of the lineations and foliations within the older granites and these, as shown on plate 2 are consistently in an E.-W. to E.N.E. - W.S.W. direction or close to it. The Sanerutian granites develop a weak to moderate foliation due to the orientation of biotite but these directions appear to be in no way consistent or logical.

In most cases, the true strike and dip of the foliation and the trend and plunge of the lineations were obtained by plotting apparent values on a Wulff net using the method outlined by Phillips (1955). This was found to be a rapid and reliable method both as a field and laboratory technique. The results obtained by this method for the older granites show that in the south of the area the foliations have a dip from vertical to 70° and strike in an E.-W. to E.N.E. - W.S.W. direction. The lineations trend in the same manner and plunge to the south west at a shallow angle.

In many parts of the area the granite appears structureless as far as foliations or lineations are concerned. The few readings available however show that there is no apparent break in this conformity.

Structures Within Xenolithic Rocks.

Foliations and lineations are, when present, more easily seen in these rocks than in the granites. Plate 2 shows the structures found within the xenoliths. The vein gneiss band which cuts across the Julianehaab Peninsula (see plate 1) has provided the most information in this respect. Acid veins cutting the gneiss horizon tend to be parallel to the main foliation within the host so that the symbols used in plate 2 for these veins can also be taken to mean foliation. The strong E.N.E. direction noted in the granites is also seen within this gneiss horizon except for a strong turn to N.N.E. at the south west end of the band on the island of Mato. The axis of ptygmatic folds* although far from parallel tend to be sub-parallel to the foliation developed within the gneissic rocks. Finally the banding developed within the amphibolitic gneiss on Mato also conforms to this regional N.E. - S.W. trend as do the small-scale folds observed in the banded rocks. On the flat coastal surfaces the axial planes of these structures trend N.E. - S.W. and the axes plunge to the S.W. There is some evidence to suggest that these have been refolded (fig. 3.7)

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* Dietrich (1959) states that "ptygma" is preferable to "ptygmatic folds" as there is then no inference of folding in the definition.

as the axial planes are bent about a low dipping axis. Unfortunately exposure was not adequate to determine the exact trend of the later axis but it appears to be in a more easterly direction than that of the older folding.

Elsewhere, structures noted in the amphibolitic rocks scattered about the region maintain the same N.E. - S.W. to E.N.E. - W.S.W. trend. One of the most remarkable features within the xenoliths, particularly on the south coast of the Julianehaab Peninsula is the alignment of the long axes of the xenoliths. Plate 2 shows this feature and the similarity in direction between this and the structures preserved within the granites.

Conclusions

The structure within the older granites where observed is shown to be closely conformable with both the foliations and lineations within the xenoliths and the alignment of the long axes of the xenoliths. Fold axes noted in the gneiss band also conform to the regional N.E. - S.W. to E.N.E. - W.S.W. trend observed in the granites.

Foliation and lineation within the Sanerutian granite show no such agreement and there does not appear to be any dominant direction within this granite (Plate 2)

CHAPTER 5

The Minor Intrusives.

Kuanitic Dykes.

The term Kuanitic has been given by Berthelsen (1960) to a time gap between the emplacement of the late Ketilidian granites (Julianehaab granite) and the Sanerutian granite. Much of the evidence in favour of this subdivision has been accumulated from the work of the geologists mapping the area around the Julianehaab district . The dykes had been first described by Wegmann (1938) as pre-Ketilidian, from the field relations seen around Hollaender Ø to the west of the Julianehaab Peninsula. The mapping of the area by the Greenland Geological Survey , commenced in 1958, showed that the dykes were a more difficult problem and more abundant than the reconnaissance of Wegmann had revealed. The dykes were particularly abundant on the Julianehaab peninsula and adjoining islands so that the writer had a good opportunity of testing the hypothesis of the earlier worker.

Mapping of the dykes, especially in the area of Iterslek (10/088 850) revealed that they are definitely younger than the granite in which they are found. The typical appearance of the dykes in this area is shown in Fig. 5.1. To the east however, where the main Sanerutian granite is exposed, there can be little doubt that dykes, similar in character to those seen on the main peninsula are pre-granite in age. This is one of the most important aspects of the work in the area of

Julianehaab granites, for it is now possible to subdivide the granites in time by the observations of the metamorphosed dyke rocks within the granite. The writer would dare to suggest that these observations have much in common to the work of Sutton and Watson (1950) on the Scourie dykes of north-west Scotland, and the epic work of Sederholm in Finland (1923, 1927). Certainly their significance is far reaching and has done much to elucidate the geological history of this part of Greenland.

Field Characters.

This discussion must be divided into two sections covering the two regions, the main peninsula and the islands to the east.

1. The Kuanitic Dykes on the Julianehaab Peninsula.

The principal factor in any discussion on these dykes is their metamorphism which can not only be seen in the mineralogical sense but structurally also they are deformed (Fig. 5.1.) . This undoubtedly led Wegmann to suppose that the dykes that he observed were pre-granite in age (see Fig. 9, Wegmann 1938). This of course does not necessarily follow, for the dykes could have been intruded into the granite which later was re-mobilised or at least become partially mobile at a later date. In addition any movement in granite mass is, if not impossible, extremely difficult to detect. The dyke however is an excellent marker for any movement as Fig. 5.1. shows, for not only are pinch and swell structures developed but also the dykes are completely broken apart and often have a boudinage form.

In the field, especially inland, the dykes are difficult to trace over significant distances. The pulling apart and sudden dying out are familiar features together with the pronounced lineation in the amphiboles and biotites especially at the margins. The contact with the older granites is invariably sharp, and the width rarely reaches over four metres. More commonly they are 1 metre in width but occur in dyke swarms which are 20 to 30 metres across, striking approximately N.E. - S.W. The longest mappable dyke seen occurs to the south of Sarqarssuaq (10/070838), and can be followed for 700 metres. On the east coast, where the exposure is particularly good, the characteristics of the dykes can be studied in some detail.

In hand specimen, the dykes not only vary from place to place but also from edge to centre. In the case of the former, the original composition and degree of metamorphism plays an important part. The change in character from edge to centre is particularly noticeable in the thicker dykes for lineation in the dark minerals is most pronounced at the edges but towards the centre it either disappears with the coarsening of the grain size or the dark minerals form segregations whose long axes are parallel to the lineation at the edges. Some of the dykes are fine grained, homogeneous biotite, amphibole types, others are lighter in colour with the biotite-amphibole lenses forming prominent streaks on the white weathered surface. On the south coast of the peninsula, the dominant type is the coarse grained, green dyke, with strong lineation developing into elongate segregations of dark minerals in the centre.

Frequently the dykes are cut by aplitic veins (Fig. 5.1.) and this at first sight seems to justify Wegmann's conclusions as to the relative age of dyke and granite. However, the aplites do not necessarily belong to the Ketilidian granites, as the field evidence now to be discussed shows. It can be stated that in the writer's ground there has been no locality seen where veins of Julianehaab granite have been observed to cut across the dykes. Only aplitic veins, which also cut the granite, cross-cut the Kuanitic dykes.

The present writer bases his conclusions as to the relative ages of the dykes to granite on a series of observations made to the north of Iterslek (10/088850), where exposure of the granite-dyke relationship is excellent. Fig. 5.2. shows a Kuanitic dyke within a porphyritic granite and it will be seen that the dyke cuts across a xenolith contained in the granite. The significance of this is immediately evident, for the granite-xenolith relationship was obviously established prior to the intrusion of the dyke. The only other explanation is to state that granitisation has replaced some unknown rock in which the xenolith and dyke were contained but was unable to penetrate into the basic rocks. This locality occurs amid a strong dyke concentration on the north shore of Iterslek (10/085848).

On the south coast of the peninsula (10/048808) near Hvidenaes, blocks of granite are included within the dyke. These could of course be interpretated as veins cutting the dyke from below, but the field evidence is not strong in favour of such a suggestion. Fig. 5.3. illustrates the essential features of the locality. The important feature of this outcrop is that there are separate granite blocks between which the dyke occurs. Examination of the lineation next to the blocks shows a finely developed alignment of amphibole and biotite, which closely follows the outlines of the blocks of granite. Away from the blocks, the grain size of the dyke, especially the dark minerals increases, suggesting that there has been some chilling of the dyke against the cold granite blocks. Later metamorphism, although radically affecting the mineralogy and texture of the dyke has failed to reduce the discrepancy in grain size between the edge and centre of the dyke. The feature has been observed in most of the Kuanitic dykes, and has been interpreted as representing the difference in cooling rate at the time of emplacement. The lineation around the granite blocks is a result of a shearing process moulding the dyke around the granite , the difference in grain size between the dyke near the granite blocks and that further away being a relic feature. It is noteworthy that quartz segregations occur between the two blocks of granite, a feature which has been noted by de Sitter (1956) in connection with boudinage structures.

This general feature of including blocks of granite is seen in many cases but in one particular exposure north of Iterslek, a quartz vein is included within the block, but is cut off on both sides by the enclosing dyke rock (Fig. 5.4.). The same dyke contains a smaller granitic block into which a small vein of dyke material has been intruded (Fig. 5.5.) and it is difficult to imagine how this came about if the granite is younger than the dyke. Rheomorphism is a possible answer, but the intrusion of a granite magma could hardly be expected to remobilise a rock of andesitic to basaltic composition. Fig. 5.6. shows the bayonet injection which is a typical feature of many dykes. An alternative hypothesis to this is to suppose that the dykes have been pulled apart but the similarity of this to bayonet injection in dolerite dykes can hardly be coincidental (Fig. 5.24.).

It is possible that each observational fact set out in the preceding section can be explained in a different manner than that suggested here. However the cumulative evidence seems to point to one common origin, namely that the dyke intruded into the cold granite which at a later date has acquired a plastic state and allowed movement to take place. The origin of heat for such movement can only be guessed at, but certainly, the dykes were also converted (at least partially) to a plastic state, for they have been pulled apart and remoulded, not excessively fractured as would have been expected they had been rigid.

2. The Kuanitic Dykes to the East of the Julianehaab Peninsula.

Plate 1 shows the distribution of the main granite types throughout the area under discussion. It will be noted that the main mass of Sanerutian Granite is found on the islands of Karrarmiut and Arpatsivik to the east of Julianehaab. Coincident with this change in granite type is a distinct change in the relationship of the dykes to the enclosing granite. The best exposures of this relationship are to be seen on the north-east coast of Arpatsivik where there are excellent clean surfaces. The Kuanitic dykes are extensively cut and invaded by aplitic material, which is continuous with the country granite and not cutting it as on the main peninsula. Fig. 5.7. shows typical examples of the dykes lying within the Sanerutian Granite. It is worth noting that the dykes are excessively bent and faulted yet the enclosing granite shows none of these features. It would appear that after the emplacement of the granite there has been some fracturing which took place prior to the consolidation of the acid rock. Consequently, the cold dykes fractured but the plastic granite "mush" flowed leaving no trace of the fracturing period. The lineations and foliations within this granite add support to this conclusion, for although well developed they have no consistent directiom and it would appear that there has been movement after the initial foliations developed within the granite (which are taken to be magmatic foliations within the consolidating magma) but before final consolidation.

The dykes still retain the characteristic pinch and swell structure (Fig. 5.7.) seen to the west and it is reasonable to assume that this was formed within the plastic Ketilidian granites. It is difficult to find in this area uncontaminated Sanerutian granite for xenolithic Ketilidian Julianehaab granite is frequently seen, indicating that it has been partially assimilated by the Sanerutian Granite.

The possibility remains that the dykes seen on the islands to the east of the main peninsula are of a different generation. The probability of such a complete separation is difficult to imagine as at least a few of the dykes on the main peninsula should display this granite-dyke relationship seen on the islands.

The most intense veining of these dykes occurs in Arpatsivik. On Karrermiut the granite still penetrates into the dykes but is much less pronounced.

Dyke Generations within the Julianehaab Area.

Most of the sequences of dykes can only be worked out from the relationship of the dyke to the enclosing granite. Only once have two Kuanitic dykes been seen to intersect, so that the age relationships have to be deduced rather than observed.

Amphibolitic Dyke-like Bodies.

Perhaps the most enigmatical of the dykes are a series of amphibolitic bodies, often found only on the sides of pronounced gullies. Their strike and occurrence coincides with the more familiar dyke types, but their mineralogy is somewhat different. Principally is the abundance of hornblende and the suppression of plagioclase. In hand specimen, the rocks are strongly foliated green and coarse grained, often the gullies are 2-3 metres wide and in the Munkebugt (10/020820) area a band of the material reaches over 30 metres wide and is extensively cut by aplitic material. At this locality also, Kuanitic dykes have been observed to cut the band and Figs. 5.8. and 5.9. show the sill and two generations of doleritic dykes cross cutting it.

It is thus extremely difficult to show that these are in fact dyke bodies and also to demonstrate their exact relationship to the enclosing porphyritic granites. It is quite probable that these are xenolithic streaks which are older than the granite, in which case they may be regarded as segregations or relics of resistant horizons. The writer prefers to leave the matter open but has included their petrographical description within the section containing the undoubted Kuanitic dykes.

Kuanitic Dykes.

This group contains those dykes seen in abundance on the east side of the main peninsula and probably those so extensively cut into by the Sanerutian granite on the islands of Arpatsivik and Karrarmiut. There are however at least two generations of dyke within this group for north of Iterdlak (10/089858) there is an excellent exposure of the intersection of two of the dykes. Fig. 5.10. shows the actual contact of the dykes, the darker, spotted type being the older and a good chill can be observed within the more leucocratic dyke at the contact. Cutting through both dykes are veins of aplitic material one of which is shown on Fig. 5.10. It will be seen from the photograph that the vein displays ptygmatic features within the younger dyke, whilst in the other it is fairly straight. There are several interpretations of this feature one of which would take into account the foliation pattern in the younger dyke. This foliation is parallel to the axes of the folds in the aplitic vein, so that it could be argued that the foliation is the controlling feature. However the older dyke also possesses a foliation which although not parallel to that in the younger should have shown some controlling effect.

Some writers suggest that ptygmatic veining is produced by an actual force folding the vein. If this is so then the aplitic vein would have been intruded at a time when the younger dyke was unconsolidated, the stress which produced the folding of the vein also causing the foliation within the dyke, i.e. a N.W. - S.E. pressure. This direction certainly fits into the regional pattern of stress directions as observed from other structural features. It is to be noted here that there is an inherent difference between the two dykes rocks either in composition and foliation or in actual age and state at the time of emplacement of the aplitic vein.

Karrarmiut Dykes.

Exposed on the island of Karrarmiut are a number of dyke like bodies which appear at first sight to be pillow lavas for they have well developed rounded surfaces against the

Sanerutian granite which extensively cuts across them. These have been termed "cauliflower structures" and this is a good description of the rocks. Fig. 5.11. is a typical example of one of these bodies, in this case dyke like, but in other cases they are much more massive (Fig. 5.12) resembling agmatites.[*] It is very likely that these rocks are pseudo-agmatites for the basic rock has not been brecciated and moved but only cut into by the granite veins. The problem in many cases is the rounded surfaces of the basic rock as well as the net-veining of the acid, into the basic.

There are a number of alternatives to this problem all of which call for more detailed field observations and petrological evidence. If the basic gneiss had been intruded after the granite then there would have been a back-veining into the basic mass by the granite because of the remobilisation of the material with a lower melting point, but this does not really explain fully the cuspate margins developed in many cases. It is suggested that the basic and granite material were essentially contemporaneous the acid material, with a lower temperature would produce a chilling of the basic rock which may have produced this rounding effect as in pillow lavas.

The writer had arrived at this conclusion when his attention was drawn to an article by Wager and Bailey (1953) in which a similar conclusion had been reached independently by

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[*] Agmatite was designated by Sederholm (1923) as fragments of older rocks cemented by granite and genetically and petrologically different from many rocks termed eruptive breccias which often are volcanic rocks (p.117). He included them under the general heading of migmatite.

these two authorities working on St. Kilda and Slieve Gullion. In this case, it was suggested that the acid magma had actually moved after the chilling and crystallisation of the basalt, with a result that the basic rock was pulled apart producing the cuspate margins.

Rocks of this general nature have been described from the island of Rhum (Hughes 1960) and the Kungnat intrusion of S.W. Greenland (Upton 1960), but in the former case the blocks are more angular suggesting that the acid material was remelted and injected back into the basic rock without much movement. Sederholm (1934) has described a composite dyke which a breccia zone has found. The illustration (Fig. 11 1934) shows some of the dyke blocks with cuspate margins.

Finally the other alternative is that the remelting of the Ketilidian basement, envisaged to account for the production of the Sanerutian Granite, would produce partial anatexis of this fine grained basic rock with the result that the more easily fused elements within it would be expelled, producing a rock of granitic aspect. Here again, it is difficult to imagine how the cuspate margins were produced.

Leucocratic Dykes of Arpatsivik.

At the southern end of the island of Arpatsivik, there is a series of distinctive dyke rocks which are seen only in a locality on the main peninsula. These dykes contain abundant plagioclase phenocrysts which are relics of the original dyke prior to metamorphism. Part of the dyke shows hornfelsing with recrystallisation of the finer grained parts of the rock, so that there is little doubt that the dykes have been metamorphosed. It would seem that the age relationships of these dykes to the Sanerutian are not so clear cut, probably they were injected immediately after the emplacement of the Sanerutian granite, so that they have been subjected to the later stages of a metamorphism which was producing the granite. Table 5.1. is a tentative table showing the relative ages of the metamorphosed dykes, designated Kuanitic in age.

Time.	Leucocratic Dykes of Arpatsivik	Sanerutian?
	Cauliflower Dykes of Karrarmiut	
	Fine grained leucocratic dykes	True Kuanitic age
	Coarse grained, dark dykes	
	Amphibolitic green dykes	?

The Alkaline Dykes

Dykes of this type are for the most part restricted to the north of the area, except for an occasional example on the south coast of the peninsula. Approximately 70 specimens have been collected from them, as their correlation has for the most part depended on their composition which can only be determined from thin sections. The distribution of the dykes in relation to the dolerites, Kuanitic dykes and lamprophyric sill is shown on Plate 3.

In general, the intermediate dykes are normally thin, averaging about 4-6 metres in width but occasionally reaching 15 metres. Despite this some are remarkably persistent over a large area, some have been traced for distances up to 12 kilometres. Fig. 5.13 is a diagrammatic summary of the classification of the dyke types of this nature and their plutonic equivalents. The names given in brackets are the terms used by Ussing (1912), to describe the dyke rocks of the Igaliko region.

The dyke types recognised in the Julianehaab area are trachytes, microsyenites, nepheline microsyenites, and porphyritic trachyandesites. Occasional examples of andesite are found but these are not common. The term hedrumite (Brøgger) was applied by Ussing to dyke rocks with a strong fissility and a slight silky lustre. On weathering the rock is reduced to a series of thin slabs which is quite characteristic. For this reason, the term was retained as a field description although ignored in the petrographical classification. The trachytes can be subdivided into two categories depending on the nature of the alkali feldspar and the dark minerals, but this is dealt with more fully in the petrographic description. This subdivision is most difficult to recognise in hand specimen so for this reason the term trachyte remains unqualified in the field descriptions Usually the trachytic texture together with their grey-black colouration is a good field criterion but in some cases the texture may be absent. Invariably they are fine grained and show a distinct tendency to red colouration in fault zones.

The microsyenite, is a coarse development of the trachyte in which the texture is well developed and can be easily distinguished in hand specimen. This rock type frequently develops phenocrysts of alkali feldspar which in specific cases is accompanied by nepheline. (Fig. 5.14). Typically the rock is more mafic than the trachyte and develops riebeckite. Porphyritic trachyandesites previously termed "monzonite porphyries" by Ussing (1912) have a matrix in which plagioclase and alkali feldspar are in equal quantities and contain phenocrysts of both types of feldspar. The andesite is a dense black rock approaching dolerite in composition in which plagioclase of intermediate composition is the dominant feldspar and which is difficult to distinguish from dolerite in hand specimen.

Chronology of the Dykes

Observations as to the relative ages of the dykes both among themselves and to the faults has been one of the prime interests of the survey. From this a correlation can be attempted with the other rock types in this and adjacent areas, giving a more complete picture of the geological evolution. With a complete historical picture of the emplacement of the several rock types, we are then in a position to postulate on the thermal, magmatic and metamorphic processes which have been in operation.

The chronology of the dykes of intermediate composition has entailed recognition of the major types together with a careful examination of their relationship to the faults. As most of the dykes have a similar strike direction there are few dyke intersections, hence the chronology here presented is based mainly on the dyke-fault intersections. This point is one of importance for these dykes have a tendency to turn sharply into a fault zone and continue along its length for more than half a kilometre. The dyke then leaves the fault zone just as sharply as it entered it. It is thus probable that in a badly exposed terrain this would be mistaken for a transcurrent displacement of the dyke. The hedrumites are in some cases difficult to follow in the field so that their relative age to the other dyke types has often been complicated by the fact that they are unexposed at dyke and fault intersections.

One of the best intersections between two dykes occurs on the northern coast of the Alangorsuak peninsula, north west of Niaqornaq(10/003942). Here a non porphyritic trachyte striking 060° suddenly changes direction so that it swings across a more northerly porphyritic microsyenite. The crossing is oblique and the trachyte can be followed within the microsyenite for approximately three hundred metres. Both dykes cross a

N.W. - S.E. fault zone, but whereas the trachyte continues uninterrupted, the microsyenite changes strike from 060° to 130° and continues along the fault zone. However there can be no doubt that the fault does not cut the microsyenite for the dyke can be followed for 40 metres along the fracture before it returns to its previous strike direction. (Fig. 5.15.)

From this locality the following age relationships are derived:

Time ↑ Fine grained non porphyritic trachyte.
Porphyritic micrøsyenite striking N.E. - S.W.
N.W. - S.E. faulting.

Some of the best examples of dyke fault intersections can be seen at Piletrae Sø (10/032882) where two dykes both of trachytic composition enter a N.E. - S.W. fault zone. One of these dykes can be followed for 800 metres in a highly faulted condition along the length of the fault before leaving it. In both cases the dykes change strike by as much as 40° on entering the fault zone and a similar amount on leaving it. The solution seems to be in the rejuvenation of the fault zones. In this case the primary N.E. - S.W. movement was followed by the dyke injection for the mobile fluid, on entering the fracture zone took the direction of least resistance along the brecciated zone in preference to its former direction. After consolidation there was another period of movement along the fault (rejuvenation) producing a shattering of the dykes (Fig. 5.16).

In correlating this example of sodic trachytes with the nepheline trachytes and nepheline microsyenites which are found in the eastern part of the area there is an important point to consider. The two types are displaced by the same N.E. - S.W. fault and whereas already described, the trachyte is severely altered, the nepheline microsyenite although displaced dextrally for 10 metres shows only a slight amount of alteration. It thus appears that in order to explain this there must have been more than one period of rejuvenation of the N.E. - S.W. faulting, the first altered the trachyte and the second completed the brecciation while faulting the nepheline microsyenite for the first time. The alternative is that the very nature of the trachyte rock, given the same amount of movement has caused the difference in alteration. Considering the usual nature of nepheline bearing rocks, in which the feldspathoid normally alters rapidly, this alternative seems unlikely. Consequently it is probable that the following relationships exist.

Time ↑
Second rejuvenation of the N.E. - S.W. faulting.
Nepheline trachytes striking 080°
First rejuvenation of the N.E.-S.W. faulting.
Soda trachytes striking 070°.
N.E.-S.W. faulting.

Unfortunately there is no evidence of the relative ages of the Alangorsuak trachyte and microsyenite dykes, and the N.E.-S.W. faulting. In all probability they will be contemporaneous with the nepheline bearing trachytes to the south although there is no evidence for this.

The final group to be dealt with under this section include the porphyritic trachyandesites and the older trachytes. The former type is not abundant and is younger than the old trachytes. They are cut by E.-W. faulting but not by the N.W.-S.E. No intersection was found between these dykes and the

N.E.-S.W. faulting so that their relative age cannot be fixed definitely. They are set tentatively in the table as younger than the old trachytes but older than the hedrumites.

The old trachytes are the only set of dykes which are faulted by the N.W.-S.E. fault system with the exception of a few of the older dolerite dykes. In the fault zones they are found to be brick red in colour with the mafic minerals represented by chlorite. The trachytic texture is lost and the feldspars often have a radiating habit.

There must be some local rejuvenation of the N.W.- S.E fault system for there exist large discrepancies between the displacement of the gneiss band and trachytes on either side of the same fault line in the Eqalugarssuit kangigdlit area. The final analysis of the dyke and fault chronology is set out below.

Time

E.-W. faulting.
N.E.-S.W. faulting (second rejuvenation).
Non porphyritic trachytes.
Microsyenites and nepheline microsyenites.
Hedrumites.
N.E.-S.W. (first rejuvenation)
Soda trachytes.
N.E.-S.W. faulting.
N.W.-S.E. rejuvenation.
Trachytes and porphyritic trachyandesites.
N.W.-S.E. faulting.
Trachytes.

At several localities numerous black inclusions have been observed within the trachytes. In one case on the east coast at Eqalugkat (10/086895) these are seen in abundance where they assume various shapes, from almost spherical to irregular outlined lengths which have apparently been distorted when in a plastic state. (Fig. 5.17). These represent either the chilled margin of the dyke which has been caught in the upward surge of the molten dyke material or xenoliths of other dyke material. This topic will be dealt with more fully in a later section. It is interesting to note that the inclusions are found on both sides of the peninsula.

The source of these alkali rocks appears to be related either to the Ilimaussaq or Igaliko batholiths. The sketch map (Fig. 5.18) shows the relation of the strike of the dykes in the area to the two bodies. It would appear from this that they are related to the latter body which is over 40 kilometres away and that dyke activity reaching the Julianehaab peninsula from the Ilimaussaq batholith was rare. In addition as is discussed later these dykes are older than the Gardar dolerites which do not cut the Ilimaussaq. This means that the alkali dykes cannot be related directly to this body because of the intervention of the dolerite emplacement. From reconnaissance mapping of the more accessible parts of the Igaliko batholith around Narssarssuaq by members of the Greenland Geological Survey it appears that the Gardar dolerites (Emeleus personal communication) cut the Igaliko batholith. If this is so then this is further evidence for the relationship of the alkali dykes in question with this batholith. Allaart mapping to the east of the Julianehaab peninsula, around the western periphery of the Igaliko batholith has reported a great concentration of alkali dykes (Allaart, personal communication) and Poulsen also reports that the dykes occupy large portions of the exposed area around Igaliko

(Poulsen 1961). The weight of the evidence seems to point to a direct relation between the alkali dykes found in the Julianehaab peninsula and the Igaliko batholith.

As regards the relative ages of this group of dykes to the dolerites and the lamprophyric sill, it seems that here the field evidence is fairly conclusive. Apart from a few occurrences of older dolerites, the Gardar dykes as well as the sill are younger than the intermediate dykes just described. The main evidence on which this is based is the relation of the dykes and sill to the faulting. As is discussed in another section the Gardar dykes show little evidence of having been disturbed and therefore must be post-intermediate dykes. There is one good crossing of the sill cutting a hedrumite exposed in the north of the peninsula (10/050888) which again shows that the intermediate types are older.

The Lamprophyric Sill

Exposures of the sill are limited to the east of the Julianehaab peninsula, more especially in the vicinity of Julianehaab itself but also further to the north. These are shown in Plate 3. The most spectacular exposure of this body is along the west coast of the large lake north-west of Julianehaab (Taserssuaq) where it forms a prominent "roadway" at about 180 metres (Fig. 5.19). The width of this terraced area may be up to 10 metres across while the thickness of the sill rarely exceeds three metres. Normally the full thickness is not exposed but when a contact can be seen the chilled margin of the sill against the granite is prominent. That the sill was emplaced as a liquid body is well shown by the exposure to the east of Taserssuaq where granite has sunk into the basic body as fragmented blocks whilst still retaining contact with the granite of the upper contact. In the field the sill weathers a brown black colour with the surface pitted with many small holes due to the loss of the softer minerals. On a fresh surface the rock is crystalline with a deep brown colouration. Occasionally it contains feldspar phenocrysts but these are not common. The sill reaches its maximum altitude to the east of Taserssuaq at 360 metres. Any attempt to determine the actual inclination of the body must also take into account the faulting in the area. Before discussing this point however it is best to describe the general disposition of the sill over the area in question. As previously mentioned the sill is at a maximum altitude to the east of Taserssuaq but it is not found on the lower ground to the south. To the north the sill crops out at a general level of 225 metres and even further north is at 200 metres. On the west side of Taserssuaq the sill reaches a maximum height of 200 metres and is found at sea level on the south coast at Munkebugt. To the east of this locality the sill again dips seaward from 190 metres. Still on the west side of the lake but to the north the sill swings from a continuous north-south outcrop to an east-west one at 190 metres dropping to 140 metres towards the west.

Near the south coast in particular the exposure of the sill is not continuous and it may well be that there is more than one sill, for in some cliff sections the major sill is accompanied by a much smaller one several metres above. However there can be no doubt that there is only one major sill in this area having a thickness greater than one metre. The evidence for this is seen down the west side of Taserssuaq where the single sill is continuously exposed for over three kilometres. The body can be seen quite clearly in the cliffs at the side of the lake and nowhere along the length is any other similar body of such dimensions seen.

Perhaps the most interesting field aspect of this body is its relation to the faults. The best illustration of this is on the west side of Taserssuaq where the sill is apparently faulted by a southerly dipping low-angled S.W. - N.E. fault. The actual fault plane can be seen in the cliffs and the sill seems to be displaced about thirty metres vertically (Fig. 5.19). On examination of the fault plane however the sill is found to be fresh along the whole length showing that it has used this brecciated area as a convenient passage. There are similar examples exposed to the east of Taserssuaq and often associated with this are small scale monoclines within the sill. In such cases the limb of the monocline coincides with a fault zone with the granite in a highly altered condition, and the sill fresh.

Knowing that the sill does change its height along fault planes, then the values derived for the general dip of the sill over the area must be used with caution. Thus the westerly dip of 3° across Taserssuaq may be in part accounted for by the large N.W. - S.E. fault running through the lake. Similarly on the east side of the lake where the dip of the sill, when calculated from Sarqarssuaq to about 1½ kilometres to the north west is 5½° must in part be due to the "Scarpen" fault (a N.W. - S.E. fault). The sill crosses another large fault further north so that the most northerly exposure of the sill is 25 metres lower. Under such circumstances it is most difficult to give values for the dip of the sill but from the south of the area where the sill can be followed almost continuously and without any complications due to faulting it seems that dips of 8° to the south and south west are present. This adds weight to the general conclusion that apart from the northern section, the sill appears to have a slight tilt to the south west, which suggests that this was the source area. Further evidence in support of this conclusion is that there is a greater amount of sill material in the south of the area, whilst although the exposure is good and the elevation sufficient, no exposure of sill is seen north of Nunarssuatsiaup region in the area under discussion.

Fig. 5.20 shows profiles across the sill, illustrating the minor undulations which occur.

Very frequently the granite adjacent to the sill has a strongly developed horizontal jointing not normally developed elsewhere. Occasionally columnar jointing is developed in the sill but this is far from common. In the northern exposure of the sill a distinct layering can often be seen, parallel to the contacts and representing a coarsening of the grain size. (Fig. 5.21).

The age of the sill is firmly fixed relative to the dykes and faults in the area. In no case has the sill been seen in a faulted condition. It is cut by the large E. - W. dolerite dyke, by the N.W. - S.E. dolerites and by the youngest generation of the dolerites striking N.E. - S.W. The older dolerites striking E. - W. or E.S.E. - W.S.W. are cut by the sill and there are several good exposures of this in the south around Munkebugt. There is thus the following chronology:-

N.E. - S.W. dolerite dykes.
E. - W. dolerite dykes.
N.W. - S.E. thin dolerite dykes.
Lamprophyric Sill
E. - W. or E.S.E. - W.S.W. dolerite dykes.
Faulting.

As noted in the section on alkali dykes there is one good exposure in which the sill cuts across a hedrumite.

The Dolerite Dykes.

The dolerites are encountered in the south of the Julianehaab peninsula and are rarely seen to the north (Plate 3). These dykes have been described in some detail by Wegmann (1938) who divided them into two groups, the Brown and the Black Dykes. This is a somewhat misleading field criterion for although two groups can certainly be distinguished in the field in the major dykes it becomes difficult to do so in the thinner dykes. The brown dykes are characterised by their brown weathering surfaces (as the name suggests) and also the tendency to spheroidal weathering (Fig. 5.22). The dykes often break down completely to a sandy gravel and can be mapped only as a distinct gully, easily identified on aerial photographs. (Fig. 5.23). The "onion" weathering of the dykes makes it difficult to obtain fresh specimens from the outcrop as the shells generally consist of a hard brittle serpentine(?) rich material. As noted by Wegmann these dykes often lack the chilled glassy margin that the black dykes possess but this is not a distinctive feature. Certainly the edges are fine grained with a typical blue black dolerite colour, whilst the centres especially in the thicker dykes are coarse grained and a dark blue grey colour in a fresh specimen. It appears to be unjustified to describe the two types separately as they have so much in common. Again it is a mistake to map these dykes as "black" or "brown" in the field for in many instances it is most difficult to differentiate them in this way. In most cases the dolerites show a strong chill against the granite the dyke often sending out apophyses into the granite and having large blocks of the country rock within the dyke. The width varies considerably, from less than half a metre to over one hundred metres. They have however similar characteristics no matter what the size, especially the fact that they thin and pinch out extremely quickly. The best example of this is seen in the eighty metre dyke which is first seen on the island of Mato in the west of the area (00/960850) and can be traced as a continuous body for 12 kilometres across the southern part of the peninsula. However within 100 metres of the eastern coast the dyke suddenly dies out and does not outcrop on the well exposed coast. (See Plate 3). The large dolerite dyke seen to the east on the island of Karramiut (10/130820) must be a continuation of this same dyke. Of similar nature is the small dyke seen on the east coast, north of Iterdlak (00/090845) (Fig. 5.24) which is a good example of a bayonet dyke injection.

Reports by geologists working in adjacent areas have described some of these dykes as "Step Dykes" because of the formation of steps along their length. These are formed by an arrangement of alternating flat and vertical joint faces which are at right angles to the strike of the dyke. These are texturally finer grained and have a greater resistance to weathering than the "brown" types and often have a thin brown skin rich in iron oxide no more than two to three millimetres thick. Only on one occasion has any type of banding been observed in these younger dolerites. This can be seen on the island of Karramiut where an eighty metre dyke striking 090° develops small scale banding locally. The banding is due mainly to concentrations of feldspar, the individual bands, being no greater than 4-5 cm. thick, dip into the centre of the dyke. (Fig. 5.25). This same dyke also has pegmatitic facies developed in which the individual feldspars and pyroxenes reach up to one centimetre.

Regarding the chronology of the dykes there are fairly numerous intersections which are much more conclusive than the intermediate dyke types mainly due to the excellence of the exposure. Apart from the very few examples of dykes which are older than the faults, most of the chronology is based on the dyke interesections.

One of the most important localities is on the island of Mato in the west of the area (Fig. 5.26). Here a thick dolerite striking 150° is cut by a much thinner dolerite striking 060. The younger dolerite has a chilled margin at each side against the older dyke which can be clearly seen. As on Karramiut the thick dolerite develops pegmatitic patches showing that its character has not changed over fifteen kilometres. The thinner dyke can probably be classed as a brown dyke as spheroidal weathering is prominent, but to the north a much thinner dyke, almost certainly of the same generation, also cuts the thicker dolerite, but in no way resembles a brown dyke. This is a good illustration of the deficiencies of the classification proposed by Wegmann.

Another informative crossing again involves this same pegmatitic dolerite just to the west of Taserssuaq (00/035850) where the dyke cuts across an olivine dolerite with a strike varying from E. - W. to E.S.E. - W.N.W. This intersection is repeated when the two dykes recross in the town of Julianehaab, at the south end of Taserssuaq. (Fig. 5.27).

The large pegmatitic dyke cuts across numerous thin dolerites striking N.W. - S.E. These dykes can be seen to cut the thinner E. - W. olivine dolerite already seen together with the thicker dyke in Julianehaab itself. From these intersections is derived the following sequence of dyke intrusion:-

N.E. - S.W. dolerites.
E. - W. dolerites.
N.W. - S.E. generally thin dolerites.
E.W. or E.S.E. - W.S.W. dolerites.

The older dolerites are encountered only occasionally, scattered throughout the greater part of the Julianehaab peninsula for the most part, less than 4 metres in width. In all cases they are affected by faulting, often carbonated with small vesicles filled with calcite. These weather out and produce a pitting on the surface. There is perhaps only one significant exposure of a crossing where one of these dykes after having been displaced by a N.W. - S.E. fault then cuts across one of the old trachytes. This occurs in the north east part of the peninsula. Further south a thin dyke of similar age is displaced sinistrally by a N.W. - S.E. (the Scarpen) Fault for about two hundred metres. This dyke is deeply iron stained and has the typical vesicular weathered surface. There must then have been a period of dolerite injection some time after the emplacement of the earliest trachytes but previous to movement in a north west - south east direction.

Some of the larger dykes create a space problem in their own right for many are close to 100 metres across and cannot be regarded as abnormal. The problem is whether the fluid came into place by stoping or by literally "pushing and shoving" its way along the lines of weakness. Granite blocks have been found within the dykes in several places but nowhere in great abundance. Assimilation in these blocks does not appear to have progressed to any great extent so that it seems likely that the latter explanation is more probable. In support of this is the regular margins to the dykes, normally sharp and straight, a feature suggesting the filling of a fracture.

Chapter 6

The Petrography of the Granites.

About one third of the specimens collected from the Julianehaab area (approximately six hundred in all) were of granite, so that it would be extremely difficult to give a description of these rocks which would cover all the granite types. In order to overcome this, three granite groups are described separately, namely the older granites containing phenocrysts of feldspar, the granites which have been "modified" by the intrusion of the Sanerutian granite and finally the Sanerutian "Aplitic" granite itself. These groups can be divided in space as well as time and the reader is referred to the section describing the field occurrences of these types.

"Older" Granites

The rock itself is a gneissose grey granite in which the white feldspar phenocrysts are prominent. Both microcline and plagioclase phenocrysts occur and they appear essentially similar. Frequently these phenocrysts exceed 3 cm. in length but only rarely do they display any consistent direction. The dark minerals are scattered irregularly throughout the rock, hornblende predominates but biotite is also conspicuous. Sphene can very often be seen in the hand specimen as small euhedral crystals which are much more abundant in thin section. Quartz is generally not conspicuous in the specimen because of the light colouring of the feldspars but it does occur interstitially and only rarely as larger segregations.

Many specimens contain xenoliths (or autoliths) of dark material, rich in biotite and amphibole and generally rounded due to absorption by the granite.

For the purposes of thin section description two specimens have been chosen. These are 23805 and 42888, both from the south coast of the Julianehaab peninsula. The former was collected from the road side quarries in the township itself (10/064824) and the latter about four km. west of the town-ship in Munkebugten (10/029819). These are taken as typical representatives of this group. The mineral constituents are (in order of abundance) plagioclase, microcline, quartz, biotite, and hornblende (sphene, epidote and opaque minerals).

Plagioclase

The most abundant mineral of the granite type, (see modal analysis data) it occurs as anhedral to subhedral grains often up to 5 mm. in length and 2 mm. across. Twinning although present is not universal, the minerals displaying mainly polysynthetic twinning. Generally the plagioclase has a light dusting of sericite which occasionally becomes intense in the centre of the grain blotting out the twinning. Composition has been determined by the Michel-Levy method, applying extinction onto nX on the sections normal to (010). Refractive indices have also been used to determine composition using the values given by Chayes (1952). These are shown below and provide a useful comparison.

	nY	Estimated %An	Extinction	Estimated %An
23805	1.547	30	9°	27
42888	1.547	30	10	28

The Michel-Levy method thus gives slightly less estimate of the anorthite molecule than the refractive indice method.

When in contact with quartz the plagioclase usually has a straight margin but against microcline there is frequently myrmekite development. Figs. 6.1 and 6.2 illustrate typical myrmekites developed in these rocks and attention is drawn to the plagioclase twinning being cut by the quartz blebs of the myrmekite.

Inclusions within the plagioclase are limited to small epidote granules, myrmekitic quartz and occasional blebs of irregular shaped quartz grains.

Microcline

Large grains of strongly twinned microcline are prominent in all sections of these rocks. Commonly individual grains reach a centimetre long but accumulations of several microclines can reach over 3 cm. Subhedral porphyroblastic * microclines are common, with the cross hatch pericline-albite combination twinning extremely well developed. Perthite lamellae are abundant throughout the mineral, especially vein perthite (Anderson 1928) (fig. 6.3) which is parallel to the optic axial plane and approximately parallel to (100). The veins appear as discontinuous lenses greater than 0.006 mm. across and up to 0.4 mm. long. Small amounts of film perthite also occur, which are parallel to the vein perthite

- The term porphyroblastic is to be preferred to "pseudo-porphyritic" used by Teall (1899) see Whitten (1957) for discussion of this point.

but much finer, and intersect the optic axial plane(fig.6.1)

The contact relationship with the plagioclase is generally obscured by the myrmekite along the margin but the contact with quartz is much more irregular. The quartz occurs as blebs of varying size as infillings between the larger grains but also as inclusions within the microcline often resembling micropegmatitic textures. (Photo 6.4). It is therefore quite probable that the alkali feldspar and quartz were crystallising simultaneously. Plagioclase is a frequent inclusion in the microcline, occasionally with myrmekitic margin, but normally the margin is smooth and the grain sericitised. Frequently an albitic rim occurs around the plagioclase (fig. 6.5) forming a barrier between the calcic plagioclase and the microcline.

A microcline separated from 23805 had the following optical characteristics:-

	nX'	nY	nZ'	$nZ-nX$	$2V_x$
23805	1.519	1.524	1.528	0.009	85°

Chemical analysis for K_2O and Na_2O are as follows:-

K_2O	Na_2O	% M/cline	% Albite
14.9%	1.27%	88.2	10.7

The table also includes the molecular microcline and albite calculated from these values.

A microcline separated from 42888 (whole rock) and also a phenocryst of microcline from the same rock have been analysed, the results together with the value for the optic axial angle are given below:-

	K_2O	Na_2O	% Microcline	% Albite	$2V_x$
42888	14.9	1.0	87.9	8.9	78°
42888 Phenocryst	13.5	2.0	80.0	16.6	-

It will be noted from these figures that the two feldspars are substantially different. The values so derived are supported by results derived by X-ray techniques (Chapter 10) so that there is little doubt that the large phenocrysts in the rock possess different characteristics to that in the general groundmass.

X-ray work on these feldspars (23805, 42888, 42888P*) shows that all are almost fully ordered and can be considered to be almost perfect in triclinicity. This suggests a long period of stable conditions which has allowed this total ordering to be achieved. The differences noted can not then be related to any inherent structural factor, and it would seem that the chemical difference noted must be due to large amounts of cryptoperthite in the phenocryst. There thus appears to be at least two generations of alkali feldspar, the large porphyroblastic phenocrysts and the interstitial microclines. Fig. 6(a) shows the contact of a microcline phenocryst against a plagioclase and also the inclusion of microcline in the phenocryst .

The microcline is normally free from alteration and develops good cleavage parallel to the optic axial plane (001), and a weaker cleavage parallel to the vein perthite.

Quartz

The mineral generally makes up over 20% of the rock section, an amount which does not appear justified from

* 42888P indicates the phenocryst of microcline from rock 42888.

examination of rock specimens. Clear, anhedral masses up to 2 mm. across are typical, developing in the pores between the feldspars. Mutual boundaries between quartz grains are irregular but not sutured and interlocking on a fine scale. Similarly the contact of quartz against microcline is generally simple often straight. Yet it is possible to find evidence of quartz replacement of microcline as shown in fig. 6.6 (c) (See explanation of the figure). The quartz also occurs intergrown with microcline fig. 6.4 so that small micropegmatitic patches are developed.

The quartz grains are unaffected by alteration, but do show strain extinction and extensive development of irregular fractures. Very small needle shaped colourless inclusions are prominent in the quartz with random orientation. The refractive index is higher than the quartz and the extinction masked by that of the quartz. The mineral is tentatively suggested as apatite.

Hornblende

Subhedral grains of hornblende up to 2 mm. long and 1 mm. across occur, generally associated with biotite and opaque material. The pleochroism and optical characteristics of hornblendes from these rocks are as follows:-

	nX'	nY	nZ'	$nZ-nX$	$2V_x$	$Z \wedge c$
23805	1.661	1.668	1.676	0.015	61	22°
42888	1.658	1.667	1.673	0.015	59	22°

nX: Yellow green
nY: Green
nZ: Blue green

The hornblendes are frequently twinned, these grains providing maximum birefringence, the c axis parallel to the twins, so that the twin planes must be normal to (010), and approximately parallel to (100).

Generally the hornblende is unaltered except for the concentrations of opaque granules which are normally associated. Biotite flecks are also a common mineral associated with the hornblende, occurring as isolated laths at varying orientations across the grain. Inclusions of quartz are also common. The hornblende is not visibly affected by quartz and the contacts are generally straight or only slightly irregular.

Biotite

The dominant dark mineral in these rocks, the biotite attains 2 mm. dimensions but is usually much smaller. Irregular flecks commonly with indented margins are scattered throughout the rock. The pleochroism is marked nX light yellow nZ brown green. The refractive index of nZ has been determined for the biotites from the two rocks and ranges from 1.622 (42888) to 1.631 (23805). Sphene granules are common inclusions within the biotite, accumulations of which occur as stringers across the mineral.

Occasionally biotite is altered to pennine which typically shows the anomalous blue colour .

Accessories

The common accessories are sphene as separate grains subhedral to anhedral in form and as granules in biotite. Opaque material is common as granules associated with hornblende and is probably pyrrhotite. Epidote is a rare accessory generally a sign of mechanical breakdown.

Table 6.1 lists the modal analyses of "typical" Porphyritic Granites.

Table 6.1 Modal Analysis of Porphyritic Granites.

	42888	42874
Plagioclase	37.0	41.1
Microcline	31.0	28.6
Quartz	19.0	20.0
Hornblende	4.0	2 2
Biotite	7.5	7.5
Accessories	1.5	0.4

42874 A quartz monzonite from the south coast of the Julianehaab peninsula, near Hvide Naes (10/052804)

Modal analyses based on combined rock and thin section counts.

Petrogenesis of the Older Granites

It is fairly certain, both from field and petrological evidence that very few of the original features of the roĉk are now preserved within these granites. It is also certain that they are polymetamorphic in origin and represent the end product of several phases of metasomatism. The writer however would not be confident in putting forward a detailed history of the rock in which the additions and subtractions of the various minerals are set out in time-table fashion (see King 1947, Cheng 1943). Nevertheless, there is little doubt that replacement textures do exist in these granite types, especially between the feldspars and quartz. Fig. 6.6 are drawings taken from these rocks. Fig.6.6(a) shows the inclusions of microcline lying within microcline phenocrysts and also the excessively indented border between the microcline and plagioclase. The chemical evidence also shows that the phenocrysts are radically different to the general microcline in the matrix and it is suggested that the higher percentage of the albite molecule in the phenocryst is the result of the replacement and absorption of plagioclase.

This supposition of the late origin of microcline phenocrysts (porphyroblasts) is by no means new and has been frequently described in the geological literature. (Whitten (1957), King (1947), Reynolds (1943), Krokstrom (1946) Anderson (1934) Spurr and Garry (1908)).

As well as microcline replacement textures there is some evidence for quartz replacing microcline as shown in fig. 6.6 (c). In cases of supposed replacement there is always the obvious objection that this is a three dimensional effect, but in this case it will be noted that there are two microclines of different orientations adjacent to quartz. Contained in the quartz are small portions of microcline optically continuous with the nearest large microcline. It is therefore difficult to imagine that this is a chance section. Within one of the microclines is a corroded plagioclase showing the younger age of the large phenocrysts. Fig. 6.6(b) again shows the nature of the contact between a microcline phenocryst and a plagioclase.

It is not the intention here to discuss the origin of the myrmekite and perthite in these rocks as this has been exhaustively discussed elsewhere (e.g. Oyawaye 1959). However, the occurrence of myrmekite is a good indication of the replacement by plagioclase of microcline which the writer considers as a late stage feature of the rock. In addition there is some evidence to show that some quartz and microcline crystallised simultaneously (fig. 6.4). These relations are summarised below:-

Mineral	Relationship to others
Microcline	Intergrown with early quartz
Microcline (phenocryst)	Replaces plagioclase, early microcline and ?quartz.
Plagioclase	Generally early, but replaces microcline (mymrekite) as a late feature.
Quartz	Replaces microcline, and?plagioclase.

It is thus easy to see why some writers have attempted to work out a time sequence for the various minerals developing in the granites.

The appearance of biotite probably is an indication of the potash metasomatism involved in the production in these rocks as it is considered that the hornblendes are relics of the early rock. If this is so, then it can be said that the environment was for the most part fairly dry as some amphiboles are known to break down under water pressure (Tuttle and Bowen 1958) and it can be fairly safely inferred that the hornblendes would not be an exception.

It is therefore suggested that throughout the evolution of the rock there is evidence to show an incoming of potash and silica at varying times, which has largely produced a rock of granodioritic composition. The potash metasomatism in particular producing the characteristic porphyroblasts. At a later stage, plagioclase replaced microcline, with the resultant production of myrmekite. Hornblende has remained fairly stable throughout these changes because of the lack of high water pressures, (this has also affected the perthites) and biotite is partially the result of potash metasomatism.

Granites Affected by the Sanerutian Metamorphism

The granites under this category are those which have been termed the Euhedral Phenocryst and Porphyritic Aplitic Granites. They appear characteristically associated with the main body of the Sanerutian granite (see Plate 1), and are linked genetically with it. No attempt will be made to separate these two granite types, for in thin section they are essentially similar, the Porphyritic Aplitic Granite having a finer matrix but the phenocrysts of plagioclase and microcline very similar to those seen in the Euhedral Phenocryst Granite.

In hand specimen the Porphyritic Aplitic Granite resembles the Sanerutian granite, because of the fine grained nature and the light colour. In detail however, small feldspar phenocrysts are developed which are easily distinguished and which the Sanerutian Granite rarely shows in any quantity. The Euhedral Phenocryst Granite is characterised by phenocrysts, often 2 cm. in length which are commonly zoned. In one specimen, (43064) large quartz nodes are prominent, the grains reaching 1 cm. across, this being an unusual occurrence in any of the granite types. The percentage of dark minerals is higher in this granite type, clots of hornblende and biotite are well spaced throughout the rock. Also in this type, well developed sphene can be seen with the naked eye, up to 3 mm. long.

Plagioclase

The percentage of this mineral is fairly constant throughout these rocks and generally exceeds that of microcline. The plagioclase phenocrysts are euhedral to subhedral invariably showing zoning effects with sericite bands picking out the zones. Typical phenocrysts are shown in fig. 6.7 with a narrow zone of alteration just inside the periphery. The perfect euhedral form in these grains is worthy of note. There are several examples of this type, and fig. 6.8 (43041) shows at least two of these bands picked out by the alteration. Fig. 6.9(a) is a drawing of the whole of this grain and it will be seen from this that there is probably a third zone. In fig. 6.10 (43062) three zones can be clearly seen with perhaps a fourth not fully developed. There can be little doubt that compositional zoning does exist in the phenocrysts with a more calcic centre and albitic margins. This can be shown in two ways, first from the extinction angle deviation and also by the intensity of the Becke line against quartz inclusions through the grain. It will be noted in fig. 6.10 that there is a large crack across the grain infilled by balsam. This is an effective test to note any change in composition of the zones, but apart from the progressive increase in refractive index toward the centre of the grain there does not appear to be any change across the zones.

Compositionally the plagioclases vary from acid andesine to albite. The majority of the grains are basic oligoclase (extinction angle and refractive indice measurements) but many have albitic margins and more calcic cores, with the result that the grains have often a sericitised core with a clear albite rim (Fig. 6.8).

Microcline

This alkali feldspar occurs in three ways in these rocks. The first and most common microcline occurs interstitially, but the mineral also occurs as euhedral grains and also as mantles around the plagioclase phenocrysts. By no means all the rocks examined possess these euhedral microclines and they are found nowhere else on the Julianehaab peninsula. The euhedral microclines are up to 1 mm. in length and 0.7 mm. across and are invariably twinned on the albite-pericline law. Fig. 6.11 shows this type of microcline crystal and also the zoning developed which is typical for this mineral in these rocks. This zoning is due to a combination of sericite and microcline in a different optical orientation . Fig. 6.12 shows a similar feature in a perthitic microcline. This zoning is sometimes due to quartz grains which are disposed in a particular zone which conforms to the crystal outline. Fig. 6.13 displays this feature.

Some microclines develop Carlsbad twinning as well as the typical cross-hatch twin, and it is interesting to note that the perthite lamellae respond to this by producing a herring-bone effect (Fig. 6.14).

Mantling of the plagioclases by the microcline is extremely common. Figs. 6.9(a & b) and fig. 6.15(a) are drawings of typical examples of this type of relationship. In all it is interesting to note that the actual contact is always extremely irregular (see Figs. 6.16, 6.15(b) and 6.17). Frequently, the perthite in the microcline is in optical continuity with the plagioclase of the core, showing that the influence of the central grain is strong. It can be argued that the albite lamellae are relics of the plagioclase left in the microcline, but this is unlikely as it is difficult to explain why the stringers should be left as parallel bands and not as isolated patches. However, this is not to say that there has been no replacement of the plagioclases, for as the margins show there is strong evidence to suggest that this has taken place locally.

Below are listed the Na_2O and K_2O contents of three of the microclines separated from these rocks together with the estimated potash and albite molecule percentages. Refractive indice measurements were not attempted as sufficient accuracy (better than ± 0.001) to obtain significant results could not be obtained without special equipment. (See Tuttle 1952). Optic axial angles were measured on the Universal Stage and are also given.

	K_2O	Na_2O	% Microcline	% Albite	$2V_{\bar{x}}$
43062	13.7	1.85	80.9	15.7	81
43063	13.6	1.96	80.3	16.5	78
43064	13.5	2.15	80.0	18.1	84

43062 Porphyritic Aplitic Granite (10/108957)
43063 Euhedral Phenocryst Granite (10/105954)
43064 Euhedral Phenocryst Granite (10/094948)

Unfortunately it was impossible to discriminate between the microcline rimming plagioclase, the euhedral and the interstitial microcline. The results obtained by chemical methods have however been confirmed by X-ray techniques.

Quartz

The mineral occurs in varying quantities in all the specimens examined. Generally the quartz is clear, free from alteration with prominent cracks. Large, single grains are common, often up to 2 mm. across in thin section. Interstitially the mineral makes up most of the matrix as anhedral blebs, cementing the larger grains together. Much of the quartz also occurs as inclusions within the feldspars but is rarely found within the biotite or hornblende.

Biotite

Only small quantities of dark minerals occur in these rocks and of these biotite is the most prominent. It is the sole dark mineral in the Porphyritic Aplitic granite as has been explained earlier. Flecks of subhedral biotite reach a maximum of 1 mm. across but more commonly they are less than 0.5 mm. Pleochroism is strong, nX straw yellow nZ brown green. Refractive indice measurements of nZ' on three biotites from these rocks all gave 1.622.

In several cases there has been chloritisation, but in others there are examples of biotite replacing hornblende. Biotite is normally associated with hornblende (where present) sphene and pyrrhotite commonly occurs as inclusions within the biotite.

Hornblende

This amphibole only occurs in limited quantities within the Euhedral Phenocryst granite, where it is normally associated with biotite. The mineral is anhedral and rarely exceeds 2 mm. in length. Pleochroism is as follows:-

nX - straw yellow
nY - green
nZ - blue green

The optical properties of one hornblende have been measured and are given below:-

	nX'	nY	nZ'	nZ-nX	$2V_x$	$Z \wedge c$
43064	1.657	1.666	1.672	0.015	63°	18°

43064 Euhedral Phenocryst Granite (10/094948).

Commonly, the hornblende is replaced by biotite.

Accessories.

Sphene is one of the most common accessories in these rocks, and is especially well developed in the Euhedral Phenocryst Granites. In these, perfect crystals are common, some almost 3 mm. in length (Fig. 6.18) but also the mineral occurs as inclusions in biotites. The opaque material is probably pyrite or pyrrhotite and occurs together with sphene and biotite. Epidote is not seen.

Table 6.2 lists modal analyses of some of the rock types described in this section.

Table 6.2: Modal analyses of Granites affected by Sanerutian metamorphism.

	43051	43053	43062	43064
Plagioclase	33.0	26.8	35.2	47.7
Microcline	31.8	41.0	26.9	29.0
Quartz	28.7	30.0	32.5	14.5
Hornblende	Abs.	Abs.	Abs.	1.8
Biotite	3.7	1.4	4.0*	5.0
Accessories	2.7	.9	1.3	2.0
	99.9	100.1	99.9	100.0

43051 Porphyritic Aplitic Granite (10/112946)
43053 Porphyritic Aplitic Granite (10/109944)
43062 Porphyritic Aplitic Granite (10/108957)
43064 Euhedral Phenocryst Granite (10/094948)

Petrogenesis of the Granites Affected by the Sanerutian Metamorphism.

These granites, affected by the Sanerutian metamorphism show textural features which make them more

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* This value includes chlorite.

interesting and informative than the Older Porphyritic types. These textures have been described in the preceding section, but a little more may be said in summary. The several plagioclases figured which show bands of alteration pose an important problem, for as was noted, there is a gradual change in composition from the calcic centre to the albitic rim, without any obvious sudden changes at the zones. If we are to believe that these bands represent compositional differences then it is to be expected that there would be sufficient refractive indice differences to be observed. This however is not the case, and the writer suggests that these alteration bands represent periods in which the growth of the crystal has been temporarily arrested during which time sericitisation took place. Alternatively, the zones of sericite represent more basic plagioclase which has been preferentially altered. The euhedral nature of many of the phenocrysts suggests that they were growing in a medium in which there was plenty of space and little competition from other minerals. These textures are particularly common in the Porphyritic Aplitic types and it suggested that the plagioclases of these rocks grew in a magmatic liquid. The plagioclase phenocrysts of the Euhedral Phenocryst granite however, generally have a marked albitic rim which gives the crystal its form.

One of the remarkable features of these granites is the sporadically developed euhedral microcline crystals. Again, zoning is present, either as zones of alteration and microcline of different orientation, or as lines of quartz grains. Here again the writer suggests that these crystals grew in a liquid in which the competition for space was not strong and in which there were periods of halted growth. The microclines of the Euhedral Phenocryst Granites do not show these features and occur as rims around plagioclases or interstitially.

Commonly, as in nearly all the granites, where small plagioclase grains occur as inclusions within microcline, a thin albitic rim develops. This feature has been observed by Ball (1908) Magnusson (1925) Ljunggren (1954) Whitten (1957) and Rogers (1961) all with varying interpretations. Ljunggren (1954) suggested that this clear rim of albite indicated a replacement texture with the microcline replacing the plagioclase. Whitten (1957) observed similar margins between adjacent grains of plagioclase and argued that this could not represent replacement. He suggested that the rim was the result of the circulation of late stage media which was able to penetrate inter-crystalline boundaries causing the alteration. Rogers suggested that the texture was an exsolution feature with the albite moving out from the microcline and accumulating around the plagioclase inclusion.

The present writer feels that this latter suggestion has more support than the "circulating media" of Whitten, even though not entirely satisfied with this explanation. If the rims do represent exsolved albite, then the lamellae now within the microcline presumably should be acting as feeders with an increase in the concentration as the inclusion is approached. It is remarkable that Rogers suggests that the majority of albite within granites is derived from a permeating fluid but makes an exception in the case of the rims now being discussed.

It is considered that in the case of the granites from the Julianehaab area, the albitic rim represents a reaction rim between the calcic plagioclase and the microcline. In many cases there is evidence to suggest that the microcline was not formed from a liquid, but even so, there must have been some interaction between the two. The consequent result would be albite, which would be in equilibrium with both the microcline and the plagioclase.

In connection with the dark minerals it has already been noted that hornblende is not developed in the Porphyritic Aplitic Granites as well as the prominence of sphene in the Euhedral Phenocryst Granite. In addition it will be seen from the modal analyses (Table 6.2) that this latter granite type is much richer in plagioclase than the Porphyritic Aplitic Granite.

The evidence therefore appears to suggest that the Porphyritic Aplitic Granites are Sanerutian in age and have been formed from a magmatic liquid, during which times the plagioclase grains (many of which represent partially assimilated Ketilidian plagioclases) together with microcline, have been allowed to grow in an environment in which there was ample space. It is probable that in these rocks the microcline is later in the crystallisation sequence (Bowen 1928) hence the rimming of the plagioclases. In the case of the Euhedral Phenocryst Granite, major portions of these rocks represent Ketilidian granites which have only been partially assimilated and in which the plagioclases have been centres for further crystallisation. There can be little doubt that potash was brought in, either by the media of solutions from the Sanerutian granites or emplaced in the solid state. In addition the presence of hornblende and the abundance of sphene lends support to the idea that the granite is strongly related to the Ketilidian granites.

The Sanerutian Aplitic Granite

The Sanerutian Aplitic Granite occurs principally on the islands to the east of Julianehaab and in the north around the Ivianguissat peak and Tartup Qaqa.

Mineralogically, it is distinguished by the abundance of the salic members and the suppression of the dark minerals. Typically in hand specimen the rock is fine grained, the individual minerals being of the same size and feldspar phenocrysts markedly absent. Frequently the rock shows a lineation of the dark minerals, which may develop into a weak foliation if the percentage of biotite is high. On the weathered surface the granite is characteristically white with only occasional dark clots of xenolithic material.

The mineral assemblage is principally plagioclase, microcline, quartz, biotite (opaque material, sphene, epidote). Texturally, the rock is granitoid.

Plagioclase

Anhedral interlocking grains, never greater than 2 mm. long. In the true Sanerutian granite, plagioclase phenocrysts are never developed, but this is rarely the case and in many of the rocks examined, there are small, zoned phenocrysts, with subhedral form. These represent the transition from the Porphyritic Aplitic Granite to the Sanerutian, the phenocrysts, actually being xenocrysts. Compositionally, the plagioclases are albite, but in some of the granites acid oligoclase is the primary feldspar. From 15 determinations on separate rocks, ten contained albitic feldspar, those containing oligoclase were those with a high percentage of xenocrystic phenocrysts. In many cases the rock contains two plagioclases, the oligoclase of the phenocrysts which may be more basic at the centre and the albite occurring as mantles or as primary material. In most cases the phenocrysts are extensively altered at the centres, with the development of sericite, but in many others it is saussuritisation, with abundant epidote granules displayed. Fine scale albite twinning is developed in most of the plagioclase in the "Aplitic" Granites.

Microcline

The mineral is invariably anhedral, clear and occurring interstitially or more rarely as mantles around the plagioclase phenocrysts. Albite-pericline combination twinning is extremely common together with string perthite. Only occasional replacement textures of the type described earlier are seen but these are by no means common.

The chemical composition of one microcline has been determined for this group, both by chemical and X-ray methods. These are given below:-

	K_2O	Na_2O	% Microcline	% Albite
23877	13.9	1.6	82.1	13.9

23877 Sanerutian Granite, Karrarmiut (10/125808)

The optic axial angle for this specimen was 80.0° about nX and the X-ray data showed that it was almost fully ordered. It is worthy of note that the microcline is similar in composition to those extracted from the Porphyritic Aplitic Granite and Euhedral Phenocryst Granites.

Quartz

Large amounts of this mineral occur in these granites, primarily as a clear, completely anhedral interstitial material. The quartz is extensively cracked and shows well developed strain extinction. Numerous minute inclusions are to be seen within the quartz but these cannot be identified specifically. The mineral only rarely appears as an inclusion within either microcline or plagioclase and from its relations within the rock, probably was very late in the crystallisation sequence.

Biotite

Biotite, rarely makes up more than 5% by volume of the rock. It occurs as small irregular flecks, about 0.5 mm. long at the most. Pleochroism is very intense with nX straw yellow and nZ deep nigger brown. Refractive indice measurements on the biotite from 23877 give a value of 1.642 for nZ', higher than those in the other granites, just described.

(Occasionally, some specimens of Sanerutian granite contain about 10% of biotite, which is much higher than that normally developed).

Commonly the biotite is altered to a chlorite with a pleochroism from yellow to strong green, the chlorite pseudomorphing the biotite.

Accessories

Epidote occurs as part of the alteration of plagioclase and also as the result of crush zones in some of the specimens. Small amounts of sphene granules occur associated with the biotite and opaque material but no well developed crystals. In some specimens small grains of orthite occur. Magnetite and pyrite are the principal opaque minerals. Hornblende is not found.

Modal analyses of eleven specimens of Sanerutian granite have been carried out. Two of these are given below, the remainder are given in the section dealing with modal analysis (Table 11.6).

	23430	23882
Plagioclase	36.5%	34.0%
Microcline	33.0	31.8
Quartz	26.5	31.1
Biotite	2.0	2.1
Accessories	2.0	0.9

23430	Sanerutian granite within Older Granite	(10/026889)
23822	Banded Sanerutian granite on Karramiut	(10/136821)

Petrogenesis of the Sanerutian Aplitic Granite

Much of the discussion on the Porphyritic Aplitic Granite applies equally well to the Sanerutian Aplitic Granite, for mineralogically they have much in common. The essential difference between the two, is the presence of the oscillatory zoned plagioclases which are found only in the Porphyritic Aplitic Granite. The albitic feldspar developed in the Sanerutian Granite is also found as rims around these zoned plagioclases.

Both the field and petrological evidence points to an intrusive, magmatic Sanerutian granite and the writer suggests that the Sanerutian and Porphyritic Aplitic Granites are essentially contempraneous. These granites represent the fused Ketilidian granites which have been injected into the Ketilidian basement rocks. The basic plagioclase phenocrysts having the highest melting point tended to resist this melting up whilst the quartz and microcline responded. Consequently, in some parts of the Sanerutian magma, remnant plagioclases provided nucleation centres for the crystallising magma, hence the albitic and microcline mantling. This resulted in the production of the Porphyritic Aplitic Granite, many of whose phenocrysts illustrate periodic times when crystal growth was halted and sericitisation took place. The Sanerutian Granite, contains only a few of these plagioclase xenocrysts the dominant type being albitic. Whether the xenocrysts were removed by a filter press mechanism or by gravitational settling is speculative. The filter-press mechanism was formulated in theory if not in name by Barrow (1892) and has been used by various workers since then to produce magmatic fluids of granitic aspect (Nockolds 1934, Eskola 1932). The actual mechanics of the process has been discussed by Mead (1925) in his study of dilatancy. He has shown that when the crystal mush has reached the state where the crystals form a close packing unit, any distortion by pressure will result in expansion of volume in the whole mass. Thus it is almost mechanically impossible to squeeze out fluids in such a consolidated mass without very great pressure and with the consequent production of cataclastic effects on the crystals. It is possible however to achieve this action if the pressure is exerted before the crystals attain sufficient numbers to form the consolidated mass. Thus in the case of the Sanerutian granite, the filtrate action, if it did take place occurred early in the evolution of the rock. The observed disorder in the lineations of the rock cannot therefore be attributed to this action.

It is shown in a later section (Chapter 11) that by using modal analysis techniques this postulated origin is supported by reliable quantitative data, and that the composition of the Sanerutian granites falls close to the low temperature trough described for the $NaAlSiO_4$-$KAlSiO_4$-SiO_2 system (Bowen 1937) and very close to the "ternary" isobaric minimum for quartz and feldspars (Tuttle and Bowen 1958).

CHAPTER 7

A Petrographical and Chemical Study of the Gneiss Band.

From the specimens collected along the length of this distinctive rock horizon it is extremely difficult to write a petrographic description which would take in all the various rock types. Homogeneity is rarely achieved by this rock, with the amount of introduced acid material varying considerably and the numerous tectonised specimens all contributing to the variation. Over all this there is a definite tendency for the rock to become lighter in colour and richer in quartz towards the north east extremity. In the central region, the northern margin to the granite is generally amphibolitic with few acid veins cutting it but toward the south west end, the amphibolites appear in the centre and southern margins, especially on the island of Mato. The description is therefore divided into two sections, the first describing an acid gneiss with acid veins cutting through it (specimen 43001) from the southern edge of the band, east of Eqalugarssuit tasiat (10/011871). The second is part of the northern margin of the band close to the acid gneiss to be described (10/009872) and is an amphibolitic gneiss (43004).

Acid Gneiss (43001)

In hand specimen the rock is a dark fine grained gneiss with an abundance of nearly parallel veins of granitic appearance.

In section the gneiss consists of plagioclase, hornblende, quartz, biotite (microcline, ilmenite-sphene), with veins consisting of plagioclase, microcline, quartz (biotite, sphene-ilmenite).

Plagioclase:

Subhedral, fresh, well twinned feldspars about 0.5mm. long make up, together with quartz the bulk of the matrix. Extinction $c \wedge X$ on sections normal to (olo) gives a composition of Ab_{65}. The mineral is unusually fresh, for normally plagioclases adjacent to acid veins are sericitised, as has been observed from other specimens. Frequently myrmekite is developed when in contact with microcline. Texturally the plagioclase appears to have been re-crystallised even though the twinning is so well developed.

Quartz.

The mineral occurs as anhedral grains which are generally equidimensional and of the same size as the plagioclase. Quartz is not abundant, probably less than 10% and occurs as isolated grains between the plagioclases and not as strings of vermicular shaped grains filling the interstices of the rock. For this reason it is suggested that they have not been introduced at the same time as the acid veins but have taken part in the general re-crystallisation of the rock, prior to the emplacement of the veins. The quartz is about the same relief as the plagioclase and untwinned feldspar can easily be mistaken for free quartz. Small cracks infrequently occur and there is only a minor development of strain extinction.

Amphibole.

Tabular subhedral to anhedral laths are prominent, with an orientation direction parallel to the long axes of the grains (generally sub-parallel about nZ). The grains rarely exceed 0.5mm. in size and have the following pleochroic scheme:

nX pale yellow-green
nY green
nZ blue green.

The optical characteristics for this amphibole and for two others from similar rock types are given below:

	nX'	nY	nZ'	nZ-nX	2V	Z c
42979	1.642	1.652	1.662	0.020	68	23
43001	1.642	1.652	1.661	0.021	68	23 °
43027	1.647	1.657	1.666	0.020	69½	22°

42979 Acid gneiss, south east of Nunarssuatsiaup Iterdla (10/046893)
43001 Acid gneiss, (10/011871)
43027 Acid gneiss (10/009863)

These values suggest that the hornblendes belong to the tremolite-actinolite series, although the extinction c Z appears to be higher than that given by Winchel (1945). The nZ colour of blue green is not typical of the tremolite sub-series but Layton (1959) suggests that there is solid solution series from the iron poor actinolite to common hornblende. Thus if iron is available, the tremolite minerals will take it up on increasing metamorphism. Tilley (1938) reported a nZ absorption colour of blue-green for actinolites from the Start District of Devon.

The hornblendes of the gneiss are free from alteration and are normally associated with biotite.

Biotite.

Subhedral laths of biotite with a strong orientation direction parallel to nZ, appears in equal quantities with the hornblende. Pleochroism and refractive indices are as follows:

nX pale yellow
nZ nigger brown

	nZ'
42979	1.627
43001	1.627
43027	1.633

Microcline.

Anhedral, clear grains with strong twinning appear interstially but are only abundant close to the acid veins. They are about 0.5mm. across. Away from the veins, only occasional grains are seen and it is suggested that the microcline has been introduced into the gneiss.

Accessories.

Commonly sphene appears either as mantles around ilmenite or as isolated granules within the matrix. Epidote has not been observed.

Amphibolitic Gneiss (43004)

In hand specimen the rock is dark, massive and crystalline, with biotite prominent on the fresh surface.

In section the gneiss consists of: Hornblende, biotite, plagioclase, quartz (microcline, opaque material).

Plagioclase.

Completely anhedral plagioclase at a maximum length of 1mm. forms an inconspicuous matrix into which is set the hornblende and biotite components of the rock. The feldspar shows well developed fine albite twinning, and extinction c X on a section normal to (010) gives a composition of Ab_{65-68}, very similar to that found within the acid gneiss. The feldspar is clear and fresh save for incipient sericite along small irregular cracks.

Quartz.

Small amounts of interstitial quartz occurs, the grains are anhedral and generally occur in minor pockets about 0.5mm.

across. In these quartz of varying orientations and irregular margins is intergrown, generally with small biotites associated. The quartz shows strong strain extinction but is only slightly cracked.

Amphibole.

The most abundant mineral in the rock, hornblende occurs as subhedral and occasionally euhedral tabular grains at a maximum of 2mm. long but the majority are less than 1mm. The colour in thin section is strong, the pleochroic scheme is as follows:

nX very pale yellow-green
nY green
nZ blue green.

Optical characteristics for specimen 43004 and also 43029 are given below:

	nX'	nY	nZ'	nZ-nX	2V	c Z
43004	1.630	1.646	1.653	0.023	74½	18°
43029	1.630	1.646	1.656	0.026	72½	17°

43004 amphibolitic gneiss (10/009872)
43029 amphibolitic gneiss (10/008864), slightly tectonised.

Characteristically, the hornblendes from both of these specimens have a heavy dusting of opaque material, composed of magnetite and perhaps ilmenite. This dusting may take on euhedral outlines as shown in Fig. 7.1. Normally the dusting is restricted to the central parts of the grain but there is no obvious compositional difference between the inner and outer parts of the hornblende. It appears that this is an exsolution of iron from parts of the grain, the euhedral nature developed on some of the hornblendes perhaps indicative of a previous iron rich core.

This is the only form of alteration developed in the amphiboles, some of the small grains show replacement by biotite but this is not seen in the larger hornblendes. The relationship of the biotite to the mineral can clearly be seen, for in numerous instances they wrap around the larger hornblende, giving the impression that there has been rotation about the central grain (Fig. 7.1. shows this feature). The writer suggests that this is due to the release in pressure at the ends of the stable hornblende allowing the new biotite to grow out of alignment and parallel to the principal stress direction. It is interesting to note that similar features are developed in specimen 43023, again amphibolitic, which has developed small folding accentuated by the strong biotite development. This rock occurs on the south side of the gneiss band, but the hornblende separated from it has optical properties closely resembling those already described for 43004 and 43029.

	nX'	nY	nZ'	nZ-nX	2V	c Z
43023	1.628	1.643	1.652	0.024	72	16°
43087	1.633	1.645	1.653	0.020	73	18°

43023 Small folded amphibolitic gneiss (10/005859)
southern margin of the gneiss band.
43087 Banded amphibolitic gneiss (00/958840)
south west end of Mato.

Details of 43087 an amphibolitic gneiss from Mato are also included for comparison. It will be noted that there is a remarkable similarity in properties in these 4 specimens, even though they occur at different places along the length of the gneiss band and in different places relative to the margins.

In specimen 43023, the growth of new biotite is almost complete with large hornblendes breaking down under stress. The process is complete in specimen 43087, for there are no large amphiboles left in the rock only small orientated laths parallel to the biotite (Fig. 7.2).

Biotite.

There is a conspicuous development of sub-parallel biotites throughout the rock. Individual grains rarely exceed 1mm. and typically have irregular outlines. The absorption is strong, nX pale yellow, nZ nigger brown. The mineral is fresh, having grown under conditions of stress and there is a tendency to wrap round the large hornblendes. nZ' measured on three different rock specimens is as follows:

Specimen	nZ'
43004	1.627
43023	1.617
43087	1.626

(Localities already given. Specimen 43029 did not contain biotite.)

Microcline.

In the specimen now being described (43004) small patches of clear twinned microcline occur. These are anhedral and are found in isolated groups, generally not as single grains. When in contact with plagioclase, myrmekite is developed and it would seem that the microcline, like quartz, is not a primary mineral in the rock assemblage.

Accessories.

The opaque minerals are for the most part limited to the dusting over the large hornblendes. These are largely composed of magnetite with a little ?ilmenite. Elsewhere, small amounts of ?pyrite are randomly scattered throughout the rock. No epidote has been observed in this or related specimens except 43029 where yellow epidote is found associated with small scale shears.

Modal analyses of some of these gneiss rocks has been carried out but most are considered either unreliable due to the very fine grain and the difficulty in determining untwinned plagioclase from quartz (the relief of the two minerals being very close), or the varying percentage of vein material in the section makes the analysis valueless. As an example of the inaccuracy is the analysis obtained for specimen 43087 which has proved unsatisfactory whereas 43028 with acid veining checks fairly well against the re-calculated chemical data.

Mineral Constituents		Volume %
	43028	43087
Plagioclase	53.2	15.5
Microcline	3.0	Abs.
Quartz	12.4	33.0
Biotite	12.0	23.9
Amphibole	16.0	27.6
Accessories	3.4	Tr.
	100.0	100.0

43028 Massive amphibole gneiss, veining well developed. Centre of the gneiss band (10/008863)

43087 Banded amphibolitic biotite gneiss. Southern margin of the gneiss band. Mato (00/958840)

In the recalculation, using weight percentages, 20% CaO is assumed to be in pure anorthite (Dana 1958) and 10% CaO in the hornblende (Layton 1959). Considering first 43028, the plagioclase contains 40% anothite, thus the % CaO in the plagioclase is 20 x 40/100 = 8%. As there is 53% modal plagioclase the percentage CaO in the rock contributed by the plagioclase = 8 x 53/100 = 4.24% CaO. By a similar calculation the hornblende can be shown to contain 1.2% CaO. The total 5.4% CaO is in good agreement with the value obtained by chemical analysis (5.37%). The estimated figure is probably high as some of the CaO has been contributed by sphene so it seems likely that the 10% CaO assumed for hornblende may be a little too high. Nevertheless this is convincing evidence to assume that the modal analysis is accurate.

Turning now to specimen 43087: the plagioclase is An_{40} and the modal value is 15.5%. This gives a CaO% = 1.24%; 23.9% modal hornblende gives 2.39% CaO, so the total is 3.63% which is much less than the CaO estimated from chemical analysis.

Petrography of the Acid Veins.

Specimen 23497 shows particularly well the development of smallfolding (ptygmatic) within the acid vein which is cutting a fine grained amphibolitic gneiss. The specimen comes from Singitsut, where some of the best ptygmatic folds can be seen (00/974848) (Fig. 3.11.).

The veins are composed essentially of quartz and microcline. Quartz grains with highly irregular outlines and a variety of shapes are common. The size does not exceed 0.5mm. but several quartz grains may accumulate into much larger areas. The contacts of quartz against quartz appear to be similar in character to those against microcline, generally lobate indentations link the two minerals (Fig. 7.3.). The microcline in the veins is fresh, with well developed twinning and exsolution lamellae are prominent. The albite lamellae are usually vein perthites which if coarse are often sericitised. Small amounts of myrmekite are also developed when a microcline abuts against a patch of sericitised plagioclase, the latter probably caught up from the gneiss. In some specimens (e.g. 43027) which have thin veins, microcline is absent and the vein is made up of plagioclase and quartz.

There is little evidence to show how the vein became deformed, for although the quartz shows some strain extinction there is no strong cataclastic textures to indicate forcible bending in the solid state. The lineation of the biotites in the gneiss host are parallel to the direction of the axes of the folds but at the axial culminations the picture is not quite so clear. There are many biotites which swing round to follow the vein but there are several others which retain the trend parallel to the main axis of the fold. The parallelism developed in the gneiss away from the vein is weak but still retains the general trend parallel to the axis of the ptygmas.

Some specimens of the gneiss show granite veins of a nebulous character, in which both biotite and amphibole occur. Specimen 43002 is a good example of this and below are given the optical characteristics of the amphibole and biotite found within the gneiss and also the granite vein.

		nX'	nY	nZ'	nZ-nX	C Z	2V	nZ' (Biotite)
43002	Gneiss	1.637	1.651	1.657	0.020	23°	73°	1.617
	Vein	1.646	1.657	1.665	0.019	21°	-	1.627

43002. Nebulitic amphibole gneiss. Taken from the centre of the gneiss band (10/009871).

Comparing these two values it is thus reasonable to assume that the amphibole and biotite found within the granite vein are of a different composition to those in the gneiss. If this is correct then it is also probable that these dark minerals have also been introduced together with quartz and microcline of the vein. There is thus some evidence to show that some of the veins found within the gneiss actually belong to the Ketilidian granite and have not been "sweated out" as a result of the activity of the granite. Unfortunately the matter is not as simple as this, for the optics of amphiboles contained in typical granites are higher than the values here quoted. It thus seems likely that there has been some contamination by the gneiss of the granite material, producing amphiboles with intermediate refractive indices. The argument can of course be presented that the hornblendes within the veins do belong to the gneiss but have been affected by the granitic material to the extent that the indices have been raised. Any such theory would have to take into account the greater size of the hornblendes found within the vein as well as the different textural relationships which would mean the recrystallisation of the mineral at the time of emplacement of the vein (Fig. 7.4.).

Discussion of the Optical Measurements on the Amphiboles.

Refractive index measurements have been made on twelve amphiboles from the gneiss band together with the coexisting biotites. The measurements have included the three refractive indices, optic axial angle and extinction on (010) sections.

Table 7.1.

Optical Data on Amphiboles and Biotites from the Gneiss Band.

	Amphiboles						Biotite
	nX'	nY	nZ'	2V	c Z	nZ-nX	nZ'
42979	1.642	1.652	1.662	68	23	0.020	1.627
43001	1.642	1.652	1.661	68	23	0.019	1.627
43002	1.637	1.651	1.657	73	19	0.020	1.617
43002'	1.646	1.657	1.665	--	21	0.019	1.627
43004	1.630	1.646	1.653	74½	18	0.023	1.627
43021	1.633	1.659	1.658	77	19	0.025	1.617
43022	1.636	1.650	1.658	71½	20	0.022	1.621
43023	1.628	1.643	1.652	72	20	0.024	1.617
43027	1.647	1.657	1.666	69½	22	0.019	1.633
43028	1.636	1.652	1.658	72	19	0.022	1.617
43029	1.630	1.646	1.656	72½	17	0.026	Absent
43087	1.633	1.645	1.653	73	18	0.020	1.626

42979 (10/046893).	Acid, leucocratic gneiss. Lineated dark clots.
43001 (10/011871).	Fissile migmatitic gneiss.
43002 (10/009871).	Massive migmatitic gneiss.
43002' .	As above, but specimen of granitic vein.
43004 (10/009872).	Massive dark, amphibolitic gneiss.
43021 (10/004864).	Massive dark gneiss with "nodes" of weathered hornblende.
43022 (10/004859).	Amphibole gneiss with parallel acid veins.
43023 (10/005859).	Amphibolitic gneiss with small scale folding.
43027 (10/009863).	Fine grained amphibole gneiss, thin acid veins.
43028 (10/008863).	Fine grained gneiss with prominent veins.
43029 (10/008864).	Slightly sheared, massive amphibolitic gneiss.
43087 (10/958840).	Banded and foliated amphobilitic gneiss.

Some of these values have already been given in the course of the rock description. For the sake of completeness these are included with the remainder in Table 7.1. together with the values derived for biotite.

Specimens were collected along the length of the band and also across the strike, the latter consisting of groups of three, taken from the northern and southern margins together with one from the centre. The following sets of specimens were taken from approximately the same area but across the strike:

General Locality	Specimen	Description
(10/010870)	43004	N. margin. Dark amphibolitic, no acid veins.
	43002	Centre. Nebulitic amphibolitic gneiss.
	43001	S. margin. Amphibole gneiss with veining.
(10/009864)	43029	N. margin. Dark amphibolitic, few veins.
	43028	Amphibole gneiss, well developed
	43027	S. margin. Fine grained amphibole gneiss w. veins.
(10/005860)	43021	N. margin. Amphibole gneiss.
	43022	Centre. Amphibole gneiss, parallel veins.
	43023	S. margin. Contorted amphibolitic gneiss.

In connection with the distribution of rock types it is worthy of note that the amphibolitic gneiss developed on the northern margin in specimens 43004 and 43029 is found on the southern margin in the case of 43023. In addition, it is generally found that the best development of veins is found toward the centre of the mass, a feature not altogether in agreement with the hypothesis of derivation from a granitic source.

The optical data (nZ against nY) have been plotted for all the hornblendes measured (Fig. 7.5A.) and also those values used in the text have been plotted separately to show the differences between those from the amphibolitic gneiss and those of the amphibole gneisses (Fig. 7.5B.). It is apparent from this graph that the refractive indices of those amphiboles from the amphibolitic gneisses (represented by solid dots) are consistently lower than their counterparts in the finer grained amphibole gneiss (represented by circles). Although all are probably tremolitic, this suggests that the amphibolitic types have less ferrous iron and therefore are nearer pure tremolite than the hornblendes from the amphibole gneiss. This compositional difference is also reflected in the extinction c Z on (olo) sections which is lower for the tremolitic types. This is illustrated in Fig. 7.6C. where the relationship of c Z to the optical axial angle is illustrated. When all values available for extinction and optic axial angle are plotted there is a definite trend to a decrease in extinction angle with increasing axial angle. (Fig. 7.6B. and Fig. 7.6A. shows the trend of increasing extinction angle with increasing nZ.)

Considering the values of nZ' for hornblende for those sets of specimens taken across the strike, it is soon obvious that the apparent diachronous nature of the amphibolitic gneiss will rule out any definite trend. The values of nZ' for these amphiboles have been plotted against their position relative to the margin (Fig. 7.7) for each separate set. Fig. 7.7b and c show a definite increase in nZ' across strike with the lowest value on the northern side. This is reversed however in the case of the most westerly set of specimens, as Fig. 7.7a shows. If the values are re-plotted so that specimens from the northern margins are all shown together and the same repeated for the central and southern margin specimens it is again apparent that the amphibolitic facies is affecting the general picture. What is interesting is the apparent stability of the hornblendes in the centre of the gneiss band, even though the specimens have acid veins cutting them. These results are shown in Fig. 7.7d,e,f.

From the twelve rocks in which hornblende has been separated and its optical constants measured, only one did not contain biotite. The nZ' refractive index has been measured for all of these biotites, with a view to ascertaining if there was any relationship between them and the amphiboles. (Similar attempts have been made by Wiseman (1934) with amphibole and chlorite and Tsuboi (1933) with amphibole and biotite.) Fig. 7.5C is a plot of nZ' of hornblende against nZ' of biotite and it will be noted that but for two exceptions there is a definite relationship. The two exceptions are both of the amphibolitic gneiss type (43004 and 43087), but the specimen 43023, also amphibolitic gneiss does not conform to this deviation.

The suggestion is therefore that with increasing refractive index of the hornblende the biotite index also increases, suggesting, as does the petrographic evidence that the two minerals are closely linked.

Chemical Data on the Gneiss Band.

Ten specimens from this gneiss horizon were selected for partial analysis, these included two groups of three specimens across the strike of the band,and a specimen from an acid vein. Two other specimens come from opposite ends of the gneiss band, one a banded amphibolitic gneiss, the other a quartz rich leucocratic gneiss. Table 7.2 gives the specimens used, their type, locality and results of the chemical analysis.

The specimens were analysed for K_2O, Na_2O and CaO, the techniques used are described in the appendix. Results of this analysis are given in Table 7.2.

Table 7.2. Chemical Analysis Results of Specimens from the Gneiss Band.

	Av. K_2O	Av. Na_2O	Av. CaO
42979	3.1	4.9	4.4
43001	2.5	4.4	6.2
43002	2.6	5.0	6.7
43002'	4.6	3.3	4.7
43004	2.7	3.0	7.2
43027	1.9	4.0	6.4
43027'	2.1	4.1	6.3
43028	3.2	3.9	5.4
43029	2.0	3.1	7.3
43087	3.4	2.4	6.1
Average difference two determinations.	0.06	0.06	0.2%

Specimen	Locality	Type used for analysis	Position
42979	(10/046893)	Acid gneiss.	E. end S.margin
43001	(10/011871)	Gneiss with acid streaks.	S. margin
43002	(10/009871)	Gneiss without vein material.	Centre
43002'	(10/009871)	Acid vein.	Centre
43004	(10/009872)	Amphibolitic gneiss.	N. margin.
43027	(10/009863)	Gneiss without veining.	S. margin
43027'	(10/009863)	Gneiss with acid veins.	S. margin
43028	(10/008863)	Gneiss with parallel acid veins.	Centre
43029	(10/008864)	Amphibolitic gneiss	N. margin
43087	(00/968840)	Banded amphibolitic gneiss.	W.end S.margin

The position of the specimens are given relative to the margin and to the extremities of the band. Where the latter is not given the specimens occur in the central part of the length, about Eqalugarssuit tasiat.

Chemical Approach to the Origin of the Veins.

There are two opposed ideas on the origin of acid veins in basic bodies. The first is that they were injected and the second that they were exuded or "sweated" out of the rock. These are in fact the "arterites" of Sederholm and the "venites" of Holmquist respectively. It is however very probable that as in many geological problems, there are several roads leading to the same place and no one theory gives the complete answer.

Obviously the origin of the veins within the gneiss band cannot be firmly established from partial analyses on small fragments from this large body. It is possible however, that the results will give some indication which interpretation is correct and it was with this in mind that the analyses were carried out.

Specimen 43027 was analysed twice, the first specimen contained several acid veins and the second, without veins, appeared homogeneous in hand specimen. The specimen occurs on the southern margin of the band and has an irregular distribution of thin acid veins so that it was possible to select a specimen without any observable veins through it. It will be noted from Table 7.2 that the differences in the three oxides in the two specimens of 43027 are very slight, probably insignificant in the case of CaO and Na_2O and only 0.2% in K_2O. As the mean difference between two determinations on the same specimen for K_2O calculated for all the gneiss specimens (10 in all) is 0.06%, there is obviously a significant although small difference in the samples in the case of K_2O. Unfortunately the veins within the specimen were too fine to extract for analysis, and it is not permissible to use the analysis of specimen 43002 (where the differences between gneiss and vein are substantial) because the veins differ mineralogically.

Assuming that granitic veins penetrating the gneiss body were formed by the exudation of the more fusible elements due to metamorphism, it would then be expected that the gneiss containing veins should have the same bulk composition as gneiss without, (unless it is argued that the material of the veins is drawn from the whole body and not only from the immediately adjacent gneiss). This is to some extent true for specimen 43027, except in the case of K_2O which is higher in the gneiss containing the veins. If this specimen is examined petrographically, it is immediately noticeable that microcline is absent from the mineral assemblage, with only quartz, plagioclase (whose composition is the same as that in the gneiss), large poikolitic hornblendes and biotite. This type of assemblage can hardly be called an "exudate", for the absence of microcline excludes this possibility. Yet the analysis shows that K_2O is greater in the gneiss plus vein specimen, which cannot be accounted for by microcline or biotite (which is better developed in the gneiss than vein). There is a possibility that the plagioclase in the vein contains K_2O in excess of that found in the gneiss specimens, but it is thought more likely that the answer lies in the gneiss immediately adjacent to the vein and not in the vein itself. There is ample evidence of biotite replacing hornblende in these areas, and it is suggested that the veins were formed by the introduction of silica and potash, the latter, not being able to combine with alumina to form microcline, reacted with the hornblende in the adjacent gneiss and produced biotite. In larger veins, for example those found in specimen 43002, microcline, together with quartz, is abundant, the plagioclase again of the same composition as the plagioclase in the gneiss. It therefore seems likely that there may have been more than one mechanism producing the veins, but the principal factor in setting off the reaction has been the emplacement of the granite. Using the terminology of Sederholm (1926) this means that the "revolutionary" forces of the country invaded, and the "invading van-guard" both owe their origin to the granitic masses which are coming into being all around. Perhaps Read (1944) is also hinting at this when he states: "In felspathisation, material for the formation of feldspar may be contributed both by country rock and by the induced solutions, magmatic or otherwise".

Chemical Trends in the Gneiss Band.

Fig. 7.8a is a plot of the total alkalis against the position of the specimen in the gneiss band. Only those specimens across the strike of the horizon are used, and in these two groups the amphibolitic gneiss is found on the northern margin. From this figure there is a definite increase in total Na_2O plus K_2O toward the centre of the band, and a corresponding drop toward the margins, the northern margin specimens (amphibolitic gneiss) being lower than the southern margin specimens. This correspondence may be purely fortuitous for there is by no means this correspondence if the individual oxides are plotted.

Considering the amphibolitic facies, there are available three analyses of the type, two from the northern margin (43004, 43029) and one from the southern margin at the far western end (43087). Fig. 7.8b is a plot of K_2O against Na_2O and shows that the amphibolitic gneiss types are well separated from the other gneiss rocks, mainly due to the lower Na_2O values. This can be explained by the relatively lower plagioclase content, which is more basic than in the other gneisses and the higher percentage of amphibole. This division is maintained on a triangular diagram when Na_2O, K_2O and CaO are recalculated to give a total of 100% (Fig. 7.9).

These factors indicate that the amphibolitic gneiss is a distinct chemical type, which behaves in a different way to that of the gneisses. For example, microcline rarely enters the rock and acid veins in any great quantity are not developed. Field observations show that it is not conformable to the strike of the gneiss band and mineralogically the hornblendes are also distinctive.

Comparison of the Gneiss Band with Other Rock Types.

Mineralogically the gneiss band is fairly straight forward assemblage but chemically it is difficult to place it into any rock assemblage bearing in mind the chemical composition. It must also be noted that available analyses on the gneiss are far from complete, so that no definite comparisons can be made with certainty. Table 7.3. lists "typical" analysis of CaO, K_2O, Na_2O for the common sedimentary and igneous rocks. The nearest approach to the typical composition developed within the gneisses is the Tonalite described by Nockolds (1934) from Loch Awe.

Table 7.3. Typical Analysis of Common Rocks.

	K_2O	Na_2O	CaO	
Arkose	5.6	2.0	1.6	Pettijohn (1949)
Graywacke	2.0	3.4	3.5	Pettijohn (1949)
Olivine Basalt	0.6	2.4	10.3	Macdonald (1949)
Diabase Dykes	2.2	4.0	7.2	Brögger (1933) after Barth
Trachybasalt	4.1	2.5	18.4	Holmes & Harwood 1937
Tuff	4.0	3.6	2.0	Oliver 1954
Tonalite	2.6	4.4	6.1	Nockolds 1934
Diorite	2.5	3.8	8.4	Reynolds 1934
Epidiorite	2.3	3.2	9.4	Mem. Geol. Surv. 1931

The mineralogical description given by Nockolds however does not fit at all closely with the gneiss. If metamorphic rocks are considered, the epidiorites bear some resemblance to the gneiss as do the petrographic descriptions (for example the epidiorites described in the Geological Survey Memoir on Chemical Analyses (1931). In all comparisons, the K_2O value proves to be the anomalous reading, the gneiss rocks, due to the high percentage of biotite, having a larger value. Thus in specimen 43029, without biotite the K_2O value drops appreciably below the average for the gneisses.

In consideration of the original nature of the gneiss band the basic problem must again be faced as has already been discussed, namely the nature of the metamorphism. If it is considered that the metamorphism was isochemical then there is a definite restriction to the number of rocks which can be chosen as possibilities. Barth (1952) however states "Isochemical regional metamorphism senso stricto .... does not exist", for he considers that regional metamorphic rocks must have suffered a change of composition, as the processes of change (transportation and transfer of chemical matter and heat) are inherent parts of the process

Experience of the metamorphic rocks developed on the Julianehaab Peninsula suggests that Barth is probably correct in this matter. The gneiss band, although presenting an effective resister to the granite has not remained unchanged and it is considered that there has been introduction of potash and silica resulting in the production of quartz and biotite and in other cases microcline, minerals probably alien to the original assemblage.

In consideration of the amphibolitic gneiss which transgresses so freely about the band, it would be tempting to correlate the closeness of its composition to that of some diabase body (see Table 7.3.) and conclude that it was originally an intrusive rock. It is then difficult to explain why the dyke should remain so closely attached to the gneiss horizon for at least half its length and shift its position relative to the margins. On the other hand there is a good deal of evidence to suggest that it was originally intrusive into the gneiss as is well seen on Mato (00/958843).

Summary and Conclusions.

Mineralogically, the gneiss is made up of a plagioclase hornblende (tremolitic), quartz, biotite assemblage with subsidiary microcline occasionally present. Refractive index, extinction angle and optic axial angle measurements show that those hornblendes in the amphibolitic gneiss are distinct from those developed within the normal amphibole gneiss, but the details of the hornblendes of the acid veins are inconclusive. Optical determinations on the biotites, show that with a few exceptions there is a tendency for nZ' of the amphibole to vary with nZ' of the biotite. This suggests that the composition of the biotite is controlled by the hornblende, a fact supported by the petrographic observations. Chemically the gneiss proves to be unusual, fitting most closely types described as epidiorites from north-west Scotland. The high potash values are indicative of the introduction of the potassium ion and the vein material is thought to have been the result of a similar process, the potassium ion accompanied by silica. The diachronous nature of the amphibolitic gneiss makes it difficult to define any trends across the strike of the gneiss but there is evidence to suggest that the composition of the central part of the band remains, at least in part, constant.

Evans and Leake (1960) point out that one of the basic fallacies in assessing chemical work on amphibolites, has been the assumption that the banding indicates a sedimentary origin (see Poldervaart 1953). Metamorphic segregation, they claim, can produce exactly the same result by movement along schistosity planes. It would appear from the work on the Julianehaab Peninsula, that composition plays a very strong part in this segregation, for although it is well developed in the amphibolitic gneisses, it is nowhere seen in the more common type of veined gneiss.

Compositionally the gneiss appears to have been basaltic to andesitic in composition, possibly intrusive or extrusive (tuff or lava) in origin with later modifications producing the high K_2O values, and consequently a dioritic composition.

The actual nature of the original rock remains in doubt. Mapping to the south east by Windley (1960), has shown that this particular horizon is no longer unique in the area, the gneiss horizons described maintaining the same strike direction as on the Julianehaab Peninsula. The possibility that these represent mylonitic zones of pre-granite age still remains, although this idea is not favoured by the writer.

Structurally the gneiss band again presents a problem for it is little short of amazing that it should maintain such a constant strike direction when it is obviously of pre-granitic age and therefore must have been affected by Ketilidian folding. Small scale folding is seen in isolated areas which indicate that the gneiss is folded isoclinally with the axial plane parallel to the strike of the gneiss band and this has also been suggested by Windley (1960). Unfortunately no major closures indicating isoclinal folding have yet been observed, but further mapping in the surrounding areas may shed more light on the problem.

Chapter 8

Petrography of the Basic and "Dioritic" Plutons.

Petrography of the Basic Intrusion and the Associated Amphibolites

The description of these types has been put into a single section because it is thought that the associated amphibolites are a consequence of the breakdown of the essentially basic igneous rocks, found as patches within them. In hand specimen, the rocks are similar, dark coarsely crystalline and heavy, with a low percentage of leucocratic minerals.

For the purpose of thin section description, the rocks are divided into three groups, the basic igneous rocks, those basic rocks with a high degree of alteration and finally the true amphibolites commonly developed within the region.

Basic Igneous Rocks

Compositionally the rocks vary from very basic rocks with a prominent development of olivine to those types rich in pyroxene. The dominant mineral however is always plagioclase with the mineral assemblage as follows: Plagioclase clinopyroxene, orthopyroxene, olivine, biotite (apatite, magnetite and amphibole). The rocks show a typical "igneous" texture with primary olivine and pyroxenes and interprecipitate feldspar.

Plagioclase.

The mineral occurs as anhedral plates frequently greater than 4 x 4 mm. enclosing the olivines and pyroxenes.

Strong zoning has not been observed in any of the sections examined. The twinning developed is predominantly of albite type, the lamellae being very fine and continuous along the length of the grain. Occasionally combined albite-carlsbad twins are present and more rarely albite-pericline.

In one specimen (23373) extinction onto nX on sections normal to (010) gives a composition of Ab_{10} but in other specimens the plagioclase is not so basic. Alteration of the feldspars is not common, but in places there is intense schillerisation, the opaque needles causing this can often be distinguished under high power. In plane polarised light these opaque needles produce a brown clouding effect. Frequently this clouding clears away around the olivine and occasionally around the pyroxene. (Fig. 8.1). In one specimen (23373) albitic feldspar has been observed, coexisting with basic plagioclase.

Parts of the plagioclase, especially when not affected by the schillerisation, contain numerous apatite needles, which are frequently very dense, forming an interlocking network within the feldspar. (fig. 8.2).

<u>Pyroxene</u>

Both orthopyroxene and monoclinic pyroxene occur within the rock. In those specimens with a high percentage of olivine (about 12%) the pyroxenes rarely exceed 1 mm. in length. The grains are subhedral to anhedral, frequently moulded around the olivine and enclosed by the plagioclase. Specimens poor in olivine contain pyroxene in plates approaching 3 mm. long and 1 mm. across, but still are weakly subhedral.

<u>Monoclinic Pyroxene</u>: In specimens 23373 and 23834, the dominant pyroxene is monoclinic, colourless to faint green in thin section and of moderate birefringence. Extinction $nZ \wedge c$ is almost symmetrical these sections showing maximum birefringence in second order blue. The optical characteristics of one pyroxene are listed below:-

	nX'	nY	nZ'	$2V_z$	nZ-nX
23373	1.677	1.688	1.702	54	0.025

23373 Olivine Gabbro (10/066865)

This data gives a composition of Ca_{44} $Mg_{40}Fe_{16}$ using the determinative chart of Hess (1949), which indicates that the clino-pyroxene is a diopsidic augite. Frequently augite occurs as rims around the hyperstene. The alteration of the pyroxene is dealt with elsewhere.

<u>Orthorhombic Pyroxene</u>: In specimen 42951, the orthopyroxene is the dominant pyroxene, with only small quantities of augite and olivine developed. The subhedral-anhedral plates reach 3 cm. in length and show the characteristic faint pink pleochroism of nY. Extinction is parallel but often not to the strong cleavage direction (110), and the birefringence is low, generally first order yellow. Optic interference figures on a section normal to an optic axis indicates that the mineral is negative with an optic axial close to 90°, which is confirmed by Universal Stage measurements which give a value of 84° about nX. This indicates a composition of MgO_{75} FeO_{25} (Poldervaart 1950)

Hypersthene in these rocks is frequently mantled by clinopyroxene and includes small grains of olivine. In one case hypersthene grains were observed to be mantled by granular aggregates of augite (fig. 8.3). Early stages of exsolution of augite within the hypersthene are occasionally seen, this having the form of irregular blebs with a sub-parallel disposition. Alteration around the margins and in the form of cracks across the mineral is common, these being filled with granular magnetite and a green amphibole.

Olivine

Olivine occurs in varying quantities throughout the basic rocks. In all, the mineral is colourless anhedral and invariably associated with a magnetite dusting. The maximum size observed for olivine is 2 mm. long and 0.7 mm. wide. Extinction where it can be measured is straight but in many cases the grains are rounded with irregular fractures, so that extinction cannot be determined. The optic axial angle is very large, probably close to 80° and the mineral is negative. This indicates an olivine of intermediate composition about Fa_{30} (Poldervaart 1950)

An interesting feature connected with the olivine is the double reaction rim invariably associated with the mineral (Specimen 23373). The olivine core is usually surrounded by an irregular magnetite mantle outside which is a regular mantle about 0.05 mm. wide of a colourless mineral with a low birefringence and straight extinction. This is, in all probability, orthopyroxene. The outer margin of the pyroxene rim is fairly regular and abuts directly onto the outer rim which is normally wider and may approach 0.1 mm. in width. The outer mantle consists again of a colourless mineral, with a lower relief than the orthopyroxene but a higher one than the plagioclase surrounding it. The mineral has a slight pleochroism colourless to yellow green maximum absorption being approximately parallel to length of the grain. Birefringence is moderately strong, reaching second order blues and extinction angle is very small to parallel. Most of the individual laths are arranged at right angles to the margin of the rim, the outer margin being irregular as the grains penetrate into the plagioclase. It is thought that this mineral is the amphibole, actinolite but normally in this association a green spinel occurs. This has not been observed in these rocks. In some sections the first mantle is absent and the amphibole rests directly on the olivine. In these cases the mineral of the mantle develops a strong colour more typical of actinolite. Modal analysis of the rock 23373 shows that 9% by volume is made up of the reaction rims and 10% by volume of olivine.

Biotite

Biotite is a common feature of all the basic igneous rocks collected from the region. It occurs as interstitial anhedral plates, rarely exceeding 1 mm. in length and normally about 0.5 mm. The pleochroism is a striking red-brown (nZ) to colourless or pale yellow (nX), a pleochroism reminiscent of the biotites of the alkaline dyke rocks. This resemblance has also been noted by Ichimura (1931) for biotites of a noritic inclusion in Japanese lavas. A biotite from specimen 23373 has a nZ value of 1.627, surprisingly low when the colour is considered. Typically the mineral occurs around the olivines and pyroxenes obviously late in the crystallisation sequence, and may represent the final acidic fraction.

The biotite is in most cases fresh and free from inclusions. Rarely, symplectite outgrowths mantle the biotite and protrude, myrmekite fashion, into the plagioclase. The vermicular colourless mineral has a higher relief than the plagioclase and the biotite and has very low birefringence.

Accessories

Most of the accessory minerals have already been described together with the major minerals with which they occur. Apatite occurs primarily in the plagioclase and can be seen to transgress from this mineral into the olivines and pyroxenes. Amphibole is developed as a reaction mineral around olivine. It is probably actinolite.
Magnetite is universally present with olivine as part of the break-down of this mineral.

Modal analysis of specimen 23373 has been carried out, the results are given below:-

Constituents

Mineral		Volume %
Plagioclase	....	54.0
Clinopyroxene	....	12.5
Orthopyroxene	....	6.8
Olivine	....	10.0
Reaction Rims	....	9.4
Biotite	....	5.2
Opaque	....	2.0
		99.9

Altered Basic Igneous Rocks

For the purpose of description it is intended to describe the minerals in order of increasing susceptibility to alteration. This means that they will be described in the following sequence: olivine, orthopyroxene, clinopyroxene plagioclase.

Olivine

As has already been described, the olivine developed in these rocks is typically anhedral and always associated with magnetite. Whether the anhedral nature is an original feature is doubtful, resorption and the effect of the reaction rims was probably a more active agent in this connection. With increasing metamorphism, the dusting of opaque material increases until the whole crystal is entirely obliterated. The final product of alteration is a colourless serpentine mineral with magnetite, only occasional olivine remaining in the centre of the grain. In specimen 42960, from the north of the intrusion, the reaction rims around the olivine are preserved, so that the colourless serpentine mineral is mantled by a green actinolite.

Hypersthene

Specimen 42951 is the only rock in which orthopyroxene is really fresh and as already noted, in this specimen granular magnetite and colourless amphibole fill cracks across the grain. The magnetite becomes more prominent with increasing alteration as do the number of fractures, so that the hypersthene is left as a series of irregular patches between veins of magnetite. In these specimens, rims of green uralitic amphibole occur, these often penetrating into the plagioclase along irregular fractures and cleavage planes. (Fig. 8.4). This feature has been noted by Harker (1956) in his description of the thermal metamorphism of basic rocks and from Belhelvie, by Stewart (1946). In one specimen, low in iron, the hypersthene is entirely pseudomorphed by uralitic amphibole, the cracks along which the alteration proceeded being prominent. Identification of these as orthopyroxene is due to the occasional remnants which are unaltered (fig. 8.4).

Clinopyroxene

The clinopyroxene observed in these rocks resists alteration much more than the hypersthene with which it co-exists. In specimens in which orthopyroxene is completely pseudomorphed the clinopyroxene remains fresh. Some specimens of olivine gabbro show the first stage of breakdown of the pyroxene with green mantles developing around the augite and also subhedral laths of amphibole appear in the rock. The process is completed only in the amphibolites, where what may be relics of pyroxene have been observed in one specimen only (42949) at the south end of the mass. In these, colourless cores about 0.25 mm. across, associated with magnetite grade into a dusty amphibolitic mantle about the same width across. These have a faint green pleochroism at the outer margin.

Plagioclase

The development of a brown dusty appearance due to opaque needles has already been mentioned in connection with the plagioclases. The principal alteration however occurs after the alteration of the olivine and hypersthene before the breakdown of pyroxene, but continues long after the final alteration of the pyroxene. Sericitisation of the cores of the plagioclases gradually spreads so that finally in the amphibolitic types most of the mineral is altered.

Much of the alteration products of olivine and hypersthene also affect the plagioclase as veins of serpentine and uralitic amphibole penetrate in fractures across the mineral.

Petrogenesis of the Metamorphosed Basic Igneous Intrusion

There can be little doubt that the material collected and described here gives only a sketchy and tantalising picture of the basic body. It is therefore very dangerous to generalise on the mineralogical evolution of the rocks without more collecting and thin section examination. However, from the several specimens examined there can be little doubt that the order of crystallisation is as is shown in fig. 8.5A. The evidence for this has been described in the preceding sections. Principally textural evidence has been used, the rimming of olivine by pyroxene and the rimming of hypersthene by augite are examples.

This series agrees fairly well with the reaction series of Bowen (1928) with the possible exception of the absence of amphibole between the pyroxenes and the biotite. It would appear that in fact the primary crystallisation of the rock stopped soon after the monoclinic pyroxene and plagioclase were precipitated and that the biotite is a later addition or a pseudomorph of amphibole. The result has been the development of a series of differentiated gabbros, ranging from olivine-gabbro with augite and hypersthene to olivine norites with hypersthene as the dominant pyroxene. This mineral differentiation conforms with the field evidence of small scale layering, which unfortunately is only preserved in a few localities.

From the available evidence it appears that the pyroxenes give the clearest indication of the evolution of the mass, for both orthorhombic and monoclinic types occur in varying proportions. Poldervaart and Hess (1951) Brown (1957) and McDougall (1961) all give accounts of the differentiation trends within pyroxenes crystallising from a magma of basaltic composition. The general trend suggested by Hess (1941, p.586) was drawn using the published accounts of layered bodies throughout the world.

Comparison of the Julianehaab Basic Intrusion with other Types.

There are many examples of this type of intrusion already described in detail of which Skaergaard, Bushveld, Stillwater and Duluth are probably the best known. The course of crystallisation in these bodies is summarised in fig. 8.5.B.

Hess (1941) states that igneous rocks of basaltic composition which show crystallisation of lime-poor pyroxene before augite are exceedingly rare, for a magnesium olivine would be expected. In less basic magmas (andesitic) this pyroxene sequence is common, for example in Japan and the Lesser Antilles. There can be little doubt that this has in fact happened in the case of the Julianehaab intrusion, which in this aspect is similar to the border facies of the Stillwater, and to a lesser extent the main part of that intrusion, for the orthopyroxene is accompanied in this example by chrome endiopside in small amounts. It is also interesting to note from fig. 8.5.B. that the Stillwater has a similar crystallisation sequence (olivine-orthopyroxene-clinopyroxene) to the Julianehaab intrusion. The hypersthene of the border facies of Stillwater show roughly oriented inclusions of augite as do the Triassic diabases of New Jersey. Hess (1941) describes these as roughly oriented plates or rows of globules of exsolved augite, the hypersthene having a composition here of $MgO_{70}\ FeO_{30}$. Similar inclusions have already been described from specimens of Olivine Gabbro rich in clinopyroxene, from Julianehaab. The composition of the Julianehaab clinopyroxene at this stage is $CaO_{44}MgO_{40}FeO_{16}$. and that of the hypersthene about MgO_{80-90}. It would thus seem that the differentiation of the clinopyroxene and or the pyroxene from this intrusion had not proceeded very far toward the iron rich composition.

As was stated earlier, it is difficult to give an accurate picture of the mass from a series of exposures set in an amphibolitic mass. It is possible however to set out the range of mineral assemblages found within the body, as is done below.

Hypersthene-Olivine Gabbro: Augite-Olivine-Hypersthene-anorthite. (biotite)
Olivine Norite: Hypersthene-augite-olivine-labradorite. (biotite)
Norite: Hypersthene-augite-labradorite(biotite)
Olivine Gabbro: Augite-olivine-labradorite(hypersthene-biotite).

The association of hypersthene and augite without any olivine is difficult to explain without some type of crystal sorting, for in other localities the three are found together. The norites, as far as is known are restricted to the central and northern parts of the mass, as is shown in Fig. 3.16, whilst the gabbros are concentrated in the south.

Petrography of the Amphibolites

It is intended to give only a brief description of the amphibolites associated with the basic intrusion as a further illustration of the breakdown of the igneous rock.

Plagioclase

The plagioclase in these rocks occurs typically as ragged anhedral grains, the size decreasing from 2 mm. in the south to less than 0.5 mm. in the north. This is perhaps the most striking feature of the plagioclases. It has also been observed that the percentage of feldspar is also greater in the south. Compositionally, there is little variation from Ab_{55}- Ab_{65}, but some specimens collected from the central region contain free quartz and the plagioclases are less basic (about Ab_{75-70}.)

The alteration of the plagioclase results in the formation of sericite; degree of alteration increases from south to north. Twinning, especially in the north is obliterated or not developed, the plagioclases in these northern amphibolites are generally engulfed by small colourless "shredded" amphibole grains and green biotite masses which are also composed of small ragged flecks.

Amphiboles

The dominant amphibole develops from the aggregates of colourless small grains which replace the dark minerals of the gabbros and norites. Typically, the amphibole shows a pleochroism from colourless to a delicate pale blue green, which is frequently difficult to detect. The amphibole has a characteristic twinning on a multiple scale which in a general way resembles the pericline twinning of microcline when cut parallel to the albite twins (fig.8.6). The individual twins are lenticular and of varying length so that the amphibole has a shredded appearance along its whole length which may reach 2 mm. This complex twinning produces zigzag extinction across the width of the grain.

The breakdown of the pyroxenes and olivines produces the dense aggregates of small colourless amphiboles which frequently, especially in the south of the mass are associated with a dusting of magnetite which is seen nowhere else in the rock section. This magnetite represents the last remnants of the gabbros and norites and the amphibolites to the north are lacking in any quantity of opaque material.

The development of the larger amphibole from the aggregates can be clearly seen in many of the specimens beginning first as isolated patches in optical continuity throughout the mass (which represents in two dimensions the outgrowths of a large poikoblastic amphibole. There is then a progressive incorporation of the smaller grains into the growing amphibole, until the new, faintly pleochroic amphibole dominates the whole mass. It is likely that the magnetite derived from the breakdown of the gabbro and norite is absorbed by this new mineral.

The optical characteristics of three amphiboles from this region are given below:-

	nX'	nY	nZ'	$nX-nZ$	$c \wedge Z$	$2V_x$
23802	1.619	1.635	1.645	0.026	20°	73°
23841	1.627	1.639	1.652	0.025	18°	77°
42950	1.625	1.637	1.647	0.022	20°	70°

23802	Biotite amphibolite (10/068868)
23841	Biotite amphibolite. Colourless amphibole(10/065863)
42950	Biotite amphibolite,pyroxene pseudomorphs(10/071870)

The optical properties (low nZ' and high optic axial angle) suggests that the amphiboles are members of the Hornblende series and belong to the Tremolite-actinolite, sub-series, with a low ferrous iron content. Biotites from the same rocks gave the following nZ' values:-

	nZ'	
23802	1.612	Green biotite
23841	1.622	Red brown biotite
42950	1.622	Red brown biotite

Biotite

This mineral also reflects the change brought about in the igneous rock. In the gabbro and norite, the biotite is red-brown and strongly pleochroic, and where the amphibolite contains relics and pseudomorphs of these rocks the biotite still retains the characteristic colour. In many however, there are numerous examples of the change in colour from red-brown to green and in the amphibolites without relics the change is complete. Consequently, the red-brown biotites are restricted to the amphibolites of the south and centre together with those amphibolites which still possess some features of the igneous rock.

The brown biotite occurs as anhedral plates up to 2 mm. in size with small fragments flaking off around the margins. Green biotite replaces the red-brown gradually, first around the margins and along the cleavage planes and eventually the grain appears as a mass of smaller green flecks without any specific orientation, a feature typical of the biotites from the northern amphibolites.

It is worthy of note that the end stage rocks of the Belhelvie intrusion described by Stewart (1946) resemble in a remarkable way the Julianehaab intrusion. The description of the uralitisation of the olivine hypersthene gabbros (p.477-478) could well be accounts of the olivine norites from the north of the body. Stewart suggests that the late stage fluids or vapours from the basic magma produced these alterations which occupy a stretch of intrusion about 6 km. long and 1.5 km. across an area much larger than the whole mass on the Julianehaab Peninsula.

Metamorphism of the Basic Intrusion

The changes brought about by metamorphism have been discussed in a preceding section, the main purpose here is to show that field and petrographic evidence supports the contention that the amphibolites are direct derivatives from the gabbros and norites. The process can be followed clearly in the early stages, the alteration of olivine and hypersthene in particular is well displayed. Unfortunately, only in one section of amphibolite is relic pyroxene preserved and in this case it is mantled by a green hornblende. The plagioclase alteration begins shortly after that of hypersthene but is not completed except in the higher grades of amphibolite and long after the breakdown of clinopyroxene. Biotite is somewhat of a problem, for it persists into the amphibolites yet shows alteration to a green biotite, a feature entirely absent in the gabbros and norites which are partially altered. Texturally it is obviously a late mineral in the crystallisation sequence, but it is difficult to say if it belongs to the same period as the pyroxenes and olivines. Ichimura (1931) contends that the red-brown colouration is due to oxidation consequent upon thermal metamorphism and MacGregor (1931) that the clouding within the basic plagioclases is also due to this type of metamorphism. If the biotite was a product of the emplacement of the Ketilidian granites then the thermal metamorphism must be due to the Sanerutian period. We are thus left with the problem of the cause of the alteration of the red brown biotite in the amphibolites. The real problem is to ascertain the age relationships between the Ketilidian granites and the gabbros and norites, as well as the relative effects of the Ketilidian and Sanerutian granites. It is also possible that the emplacement of the Illimausaq and Igaliko batholiths produced changes within the rocks under discussion. J. Stewart (personal communication) reports a fairly narrow alteration zone of about 4 km. in basalts around the Ilimaussaq batholith, but nothing is known of the sub-surface geology.

Reaction Rims

Reaction rims around the olivines are interesting in that they lend support to the hypothesis of Shand (1945). On the one hand it can be argued that they were formed as a natural consequence of the reaction between a solid (olivine) and a liquid phase (e.g. rich in the anorthite molecule), producing coronas at the time of crystallisation. Shand argues that mineralogical composition is not the sole factor in corona formation and that thermal metamorphism triggered off the reaction. The "Becke Equation" explaining the molecule for molecule reaction is only "chemical book-keeping" giving a false idea of the actual process. Shand's argument involves the reaction of the two solid minerals separated by films of water vapour containing "wandering ions" of Mg, Fe, Ca, Al and SiO_4. These ions are supplied by the plagioclase and olivine which themselves are insoluble in the water vapour, and whose relative proportions by weight had no influence on the course of the reaction.

The instability of olivine on metamorphism causes the release of iron and magnesium ions which attack the plagioclase resulting in the production of the coronas (in the case of the Julianehaab rocks, a "two-ply" corona). The idea of metamorphism causing the production of the coronas fits the facts as observed from the Julianehaab gabbros. The development of clouding within the plagioclases thought by MacGregor (1931) to be the result of thermal metamorphism producing small opaque inclusions, also has some bearing on the problem for there is a marked absence of inclusions about the coronas (fig. 8.1) MacGregor (1931) suggests that the more basic plagioclases contain a greater percentage of iron oxide and therefore are more liable to produce the opaque inclusions. It would appear from this that the absence of the inclusions about the coronas is due to the participation of the iron in the formation of the rimming. It is likely that the reaction rims were formed first, producing a deficiency in iron in certain regions of the plagioclase, hence the clear zones about the coronas. In the highly altered basic rocks the reaction rims are preserved as relics about pseudomorphs of olivine.

In summary, it is suggested that the coronas were not formed at the time of primary crystallisation of the gabbros, but were a consequence of their thermal metamorphism which acted as a triggering mechanism in setting off the reactions.

Summary and Conclusions

It is not known definitely whether the relics of the basic mass just described are part of a fairly large body now in part converted to amphibolite or are inclusions within a rock which has been completely converted to amphibolite. The present work suggests that the former suggestion is the true one.

The mineralogical evidence suggests that the rocks exposed represent the early differentiates, olivine gabbros and norites, from a basic magma. The evolution of the later part of this body is not revealed in the material available for study, as the clinopyroxenes are still calcic, the hypersthene magnesium rich and the exsolution of augite lamellae from the hypersthene is only in its earliest stages.

The crystallisation sequence in the magma commenced with olivine and was followed later by hypersthene, the olivine ceasing to crystallise shortly afterwards. Later, calcic augite was precipitated and the two pyroxenes crystallised together with the exsolved augite appearing in the hypersthene. There is no evidence of pigeonite or iron rich clinopyroxenes to suggest that any higher stages in the intrusion were reached.

Thermal and regional metamorphism produced reaction rims around the olivines and a clouding within the basic plagioclases. The olivine and hypersthene were progressively broken down into serpentine and amphibole while plagioclase and clinopyroxene resisted alteration to a greater extent, the augite being replaced by amphibole after the alteration of the rest of the rock. Emplacement of the Ketilidian granites caused the introduction of potash which may have given rise to the biotite but on the other hand the evidence is not conclusive about the relative ages of gabbro and granite. The red colouration of the biotite may be due to oxidation consequent to thermal metamorphism but the colouration is lost or only partially retained in the amphibolites.

There is little doubt that there was a metamorphism after the introduction of the red-brown biotite into the gabbros and norites which converted a large area into biotite amphibolite. The degree of alteration appears to increase going from south to north this being due to the difference in mineralogy of the igneous rocks, the norites being particularly susceptible to alteration. As a consequence of this, relic textures within the amphibolites are found only in the south and central region, these being characterised by pyroxene pseudomorphs and red brown biotite which shows alteration to a green biotite. The amphiboles (tremolites) found within the amphibolites are characteristically low in iron a feature which supports the conclusions about the state of differentiation reached in the igneous body.

The Petrography of the Dioritic Rocks.

Introduction.

The major dioritic masses occur on Arpatsivik, Karrarmiut and to the north east of Taserssuaq and mineralogically the Karrarmiut diorite differs from the others in the development of appreciable quantities of quartz. The naming of the rocks is beset by the subjective observations of the individual, and although the classification advanced for the granitoid rocks can be applied directly to these dioritic types the writer feels that the essentially "igneous" character of the classification makes this undesirable.

The mineral assemblages encountered in these rocks are principally, plagioclase, hornblende and biotite with subsidiary quartz and microcline. The rocks however are of undoubted metamorphic origin although of dioritic composition in the mineralogical sense of the definition. It is therefore suggested that the term dioritic amphibolite be used to describe these rocks.

The description of these rock types is based to a large extent on the material collected from the body exposed in the centre of Arpatsivik (10/125880), which displays a type of mineralogical variation akin to igneous layering. This variation is mainly due to the different proportions of plagioclase to total dark minerals, a feature better appreciated in hand specimen.

Plagioclase

Subhedral tight packed grains of plagioclase which are normally fresh are typical of these rocks. They are often of appreciable size, in some instances up to 1 cm. in length. Normally the feldspar is about 2 mm. long and only slightly less in width so that the grains are stubby, not unlike those developed in the granites on the main peninsula. Twinning, where developed is always of albite type and extinction c:nX gives compositions from Ab_{70-80}. There appears to be no systematic change in composition of the feldspar in relation to its height in the body, nor with the relative proportions of plagioclase to amphibole. Texturally the plagioclase shows mutually interfering boundaries as in granites, but the shape of the amphiboles and biotites do not appear to be influenced by the feldspar.

Zoning developed in some of the feldspars is in many cases due to mechanical distortion of the grain as well as compositional changes, for in several instances, the twin lamellae have been observed to be dislocated and bent. With progressive deformation, the feldspar breaks down into sericite which gives way to flecks of colourless muscovite in random orientation. Epidote is often associated with the sericite indicating the acidification of the feldspar, although sericitisation is more common.

Amphibole

The dominant mafic mineral in all these rock types is a green subhedral to anhedral amphibole. The mineral occurs as laths, which may reach a length of circa 4 mm. long and as equidimensional grains about 1 mm. across. The pleochroism is as follows: nX: pale straw yellow, nY: pale green nZ: pale blue green. Optical characteristics for a series of amphiboles taken from different heights in the Arpatsivik body are given below:-

	Metres above S.L.	nX'	nY	nZ'	nZ-nX	$2V_x$	$c\,\hat{}\,Z$
42842	250	1.645	1.660	1.665	0.020	67	18°
42840	200	1.625	1.640	1.650	0.025	76	20
42848	190	1.638	1.659	1.664	0.026	72	22
42823	40	1.620	1.638	1.650	0.030	73	22
42822	30	1.644	1.657	1.662	0.018	61	27

In all probability, specimen 42822, which was originally thought to be part of the pluton is not related at all. The values for birefringence, optic axial angle and extinction all differ markedly from the rest of the amphiboles. The field evidence is not conclusive on this point as there is much unexposed ground in the lower levels of the area. It is considered therefore that the values derived for the amphibole of this specimen suggests that it is alien to the main pluton.

Birefringence and optic axial angle data suggest that these amphiboles are of the subseries tremolite-actinolite of the hornblende group. (Layton 1959)

Biotite

Biotite is developed in almost all of the dioritic amphibolites after hornblende. The mineral occurs as anhedral flecks normally associated with the amphibole and in many cases completely overlying the latter mineral. There can be little doubt from the frequency and constant nature of the association that in the majority of cases the biotite is primarily the result of the breakdown and replacement of amphibole.

Pleochroism of the biotite nX:pale straw yellow nY and nZ:deep nigger brown, is also fairly constant throughout these rocks. nZ' measured on three biotites from the Arpatsivik pluton all gave 1.622.

Quartz

Quartz is developed only in quantity in the Karrarmiut rocks. Elsewhere it occurs as small irregular interstitial blebs or accumulations of small grains, with sutured margins and strain extinction. In the Karrarmiut rocks it is present in greater quantity but in a similar fashion. Modal analysis of these rocks indicates about 9% quartz by volume.

Microcline

Microcline is only occasionally seen either as small interstitial grains which appear to be associated with vein material or as replacement of the plagioclase. In the latter case the development has not progressed far, fringing microclines only are developed.

Accessories

Opaque material is conspicuously lacking in these rocks, a feature noted in many of the Kuanitic dyke rocks. It is thought that to a large extent the iron is assimilated by the amphibole on metamorphism. Ilmenite with sphene mantles are developed in the Karrarmiut rocks but are absent from the Arpatsivik pluton. Opaque material developed in 42822 again indicates that this rock is not typical of the material developed in the Arpatsivik body. Similarly, large amounts of apatite occur which is not developed in quantity elsewhere in the dioritic rocks.

Modal analyses of the dioritic amphibolites are given below which demonstrate the limited mineralogical assemblages found.

Constituents	23868	23837	23891
	%	%	%
Plagioclase	25	88.0	62.0
Quartz	-	-	9.8
Biotite	37.5	-	17.0
Amphibole	35.0	12.0	9.2
Accessories	2.5	-	2.0
	100.0	100.0	100.0

23837	Dioritic amphibolite block in gabbro (10/065864)
23868	Part of amphibolitic raft on Karrarmiut (10/130810)
23891	Dioritic amphibolite, Karrarmiut (10/125803)

Petrogenesis of the Dioritic Amphibolites

Little need be said on the metamorphism of these rocks for much of the discussion on the Kuanitic dykes is directly applicable to this topic. There can be little doubt that there has been metamorphism of an originally igneous rock producing the simple plagioclase-amphibole assemblage, with subsidiary biotite. The original nature of the rock can be limited to a fairly narrow field enclosing the gabbro-diorite clan.

The plagioclase-hornblende assemblage of these rocks indicates that they belong to the Amphibolite Facies (Eskola 1915). Barth (1952) states that the facies is widely distributed in the Pre-Cambrian gneisses especially in Synkinematic intrusive-like rocks (p.341) Similar rocks are described by Harker (1956) and Elett & Hill (1912). The absence of epidote, except in unusual cases, is significant, for the assemblage appears to be of higher grade than the Epidote Amphibolite facies and Barth (1952) states that the upper boundary of this facies is 400°C where the stability relationship :

$$\text{Epidote} \rightleftharpoons \text{Oligoclase}$$

defines the boundary. This corresponds very well to the 400°-500°C value obtained from the distribution of sodium in the plagioclase and microcline for the older Porphyritic Granites and Sanerutian Granite. (op.cit.) It can thus be stated that the metamorphism of the igneous plutons resulting in the production of hornblende and more acid plagioclase was due to the emplacement of the Porphyritic Granites and was probably repeated on the intrusion of the Sanerutian Granite.

The epidote developed on the surface of some of the plagioclases is due to retrograde metamorphism consequent upon tectonism.

CHAPTER 9

The Petrography of the Minor Intrusives.

Kuanitic and Earlier Dykes.

As has been described in the section of the field relations, there has been displayed in these rocks a great variety of structure, texture, thickness and degree of metamorphism. The significant fact remains however that the variation within the types is remarkably small being limited to plagioclase, amphibole (hornblende) biotite quartz, with subsidiary epidote, opaques, sphene and microline.

The group can be broadly divided into two, those types which are older and much richer in amphibole and the younger dykes in which some of the original texture may be preserved. The actual age considerations have already been discussed.

Early Kuanitic Dykes.

This group occurs principally to the north-east and south-west of Taserssuaq (10/050830) with a general N.E. - S.W. strike direction. Most of the specimens have been collected from the large body in the Munkebugt area, (10/030825) and the smaller bodies on the high ground to the east of the lake.

Petrography.

The mineral assemblage of this rock type is (in order of abundance) amphibole-plagioclase-biotite (quartz).

Plagioclase.

This mineral makes up the general matrix of the rock. Grains of .5mm. diameter anhedral, interlocking, are common but larger grains do occur with a subhedral form, displaying corroded margins. Such crystals are over 2mm. long, with sericitisation partially obscuring the albite twin lamellae. Around the margins is a clear rim (Fig. 9.1.) without twinning, which is more albitic in composition. The general absence of twinning in the smaller feldspars together with the texture suggests that this is not original, only the larger phenocrysts being preserved. One specimen (23865) has retained the general plagioclase texture, but is in the process of being broken up into the anhedral mass already described from other specimens. Sericitic shreds and scaly biotite penetrate into the zoned plagioclase grains. The outlines of the feldspars become extremely ragged, with sericitic cores and penetrating biotites at the margins.

Quartz.

Quartz is often absent from the mineral assemblage. When developed it occurs as anhedral interstitial masses, generally difficult to differentiate from the untwinned, recrystallised plagioclase feldspar. The mineral is free from any alteration, with few inclusions and only a slight suggestion of any "shadow" extinction.

Microline.

Rarely developed, generally as pods of clear unaltered material, which is probably vein material.

Amphibole.

Anhedral masses which is abundant in all the specimens examined. In some, the poikolitic grains are up to 2mm. long but normally they are only .5mm. long. Pleochroism is strong and is as follows:

nX colourless to pale yellow
nY green
nZ blue green.

Birefringence is moderate. The optical properties of amphiboles from three specimens are as follows:

	nX'	nY	nZ'	nZ-nX	2v	z c
23337	1.623	1.635	1.644	0.021	78°	18°
23355	1.619	1.635	1.644	0.025	79°	17°
23865	1.619	1.633	1.644	0.025	-	17°

23337 (10/052853) Amphibolite, wast of Taserssuaq.
23355 (10/027825) Amphibolite, west of Taserssuaq.
23865 (10/854847) Amphibolite, east of Taserssuaq.

The similarity of the optical properties shows that the amphiboles from these rocks must be compositionally similar. One specimen (23382) shows a type of zoning, especially noticeable in plane polarised light, with a green or colourless core moving out into a darker green margin. Except for specimen 23382, all the amphibole is intimately intergrown with biotite.

<u>Biotite</u>.

Occurs in all but one specimen. In those specimens which are not foliated or lineated, the biotites occur in sheaves of intergrown lathes (Fig. 9.2.) in which minor amounts of amphibole are found. Individual grains are about 0.5mm. long. Pleochroism nX colourless, nZ brown-green. Refractive index of biotites on nZ' range from 1.612-1.615. The relationship of the biotite to the hornblende is one of mutual intergrowth, with occasional textures showing the replacement of hornblende by biotite.

Accessories.

Minor amounts of epidote and sphene occur but opaque minerals are generally absent.

Kuanitic Dykes.

At least two generations exist within this younger group of dyke rocks. As has been discussed earlier, there is good field evidence to show this relationship, with chilling and inclusions of older in younger. The dykes can be divided into several groups on a mineralogical basis rather than on an age one and it is thought more satisfactory to describe them in this way. The scarcity of field evidence makes any subdivision on time extremely broad, but if it had been possible this would have been preferable to the one now attempted. Set out below are the major types (Table 9.1.); it is to be noted that the last group are questioned for there is no definite proof that the material is Kuanitic in age. The specimens all occur in the south of the island of Arpatsivik, and although they can be traced as bands through the granite, they could be interpreted as relic horizons. The presence of relic zoned plagioclases in them however suggests that they may possibly be of Kuanitic age.

Table 9.1. Mineralogical Types of Kuanitic Dykes.

Amphibolitic, dark, strong lineation at edges, segregations in centre.
Light coloured, coarse grained, mafic clots, feldspar phenocrysts.
Very leucocratic, especially weathered surface, mafic streaks.
Fine grained, very dark, in centre, coarser, with mafic spots.
Medium to dark in colour, crystalline with feldspar phenocrysts.

Several of the specimens collected do not fit easily into the divisions given above, but this is understandable, for several factors are in operation, especially the degree of metamorphism, original composition and also the proximity to fracture zones. It is emphasised again that these subdivisions are purely arbitrary, and represent only a general outline of the major rock types of the Kuanitic period.

Petrography.

Lineated, amphibolitic coarse grained types.

Several specimens have been collected of this type, which is most abundant on the south coast of the peninsula, to the west of Julianehaab. Most of these show a "chilled" marginal zone.

The mineral assemblage (in order of abundance) plagioclase, amphibole, biotite, quartz, with subsidiary epidote and magnetite which is in many instances absent. (There being no other opaque mineral present.)

Plagioclase.

No remnant textures observed, the whole mass appears to be recrystallised into an interlocking mass of equidimensional grains, about 1mm. in diameter. Twinning is extremely weak or absent, and the composition is only determined with difficulty as Ab_{70}. Alteration products are rare so that the plagioclase grains are clear and resemble quartz. Small needles of ? apatite are well developed as inclusions within the feldspar.

Quartz.

This mineral is extremely difficult to differentiate from plagioclase, only difference in relief gives any indication of its presence. Quartz is not abundant, making up less than 5% of the rock slice.

Amphibole.

Anhedral to subhedral strongly pleochroic grains which in some specimens show elongation parallel to the length of the crystal (i.e. parallel to "c" crystallographic axis). The mineral occurs in clots together with biotite with a maximum length of 2mm. and also as discreet grains scattered throughout the matrix, generally 0.2mm. Pleochroic scheme is as follows:

nX	colourless to straw yellow
nY	green
nZ	blue green.

The colours are more intense than those described from the Early Kuanitic dykes.

The optical characteristics of three of the amphiboles from these dykes are listed below. These fit the amphiboles into the hornblende group and probably the Tremolite Sub-Series.

	nX'	nY	nZ'	$2V_x$	nZ-nX	$Z \wedge c$
42869	1.637	1.653	1.662	-	0.025	17°
42878	1.656	1.668	1.674	57	0.018	27°
42906	1.648	1.665	1.672	57½	0.024	18°

42869	Biotite rich, pronounced lineation, 1km. south-west of Julianehaab (10/059810)
42878	Specimen in contact with a granite block, 2km. south-west of Julianehaab (10/049805) Hvidenaes.
42906	"Spotted dyke", 7km. west of Julianehaab (00/990826).

Biotite.

Discreet laths of short biotites from 0.2mm. to 1mm. in length, generally subhedral, and often replacing amphiboles, especially in specimens 42878 where streaks of amphibole occur along the cleavages of the biotite. The quantities vary from dyke to dyke, and in specimen 42878 the proportion increases toward the granite block. Pleochroism very strong, nX straw yellow, nZ nigger brown.

nZ' measured on biotites from 42869, 42878, 42906 has a range of 1.612 - 1.615.

Biotite is strongly lineated in most specimens, even when the amphibole is not, suggesting that the growth of biotite took place during a period when a strong shearing stress existed, which was unable in many cases to influence the amphibole.

Accessories.

Opaque minerals are conspicuously rare, less than 0.5% in most specimens. Epidote is present in varying quantities, often prominent next to acid veins which cut through these dykes. In specimen 42886 biotite clots are almost completely converted to chlorite, with shredding of the ends of the biotites and interdigitation of the chlorite. Within these biotite-chlorite clots, discreet epidote grains also occur.

Coarse grained leucocratic type.

All the specimens of this type collected come from the southern end of the island of Arpatsivik, with the exception of 43038, which occurs north of Iterslek on the east coast of the Julianehaab peninsula, (10/085883). It is more than likely that these are all of the same age, and their close proximity suggests an even stronger relationship.

The mineral assemblage (in order of abundance) plagioclase, quartz, amphibole, biotite microcline ilmenite-sphene, (epidote).

Plagioclase.

This mineral is distinctive in all the sections. In the matrix, small anhedral interlocking plagioclase occurs, about 0.2mm. long, infrequently twinned. Larger relic grains are conspicuous throughout the section, which to a large extent give the rock its character. Subhedral grains which may reach up to 6mm. long are common, generally with an elongate habit. Compositionally they vary from albite to Ab_{70}. In many cases, the grains show the development of a more albite rich rim which is separated from the main grain by a period of corrosion and fracture. Specimen 43038 displays these features very well. Fig. 9.3. illustrates the textures observed within the phenocrysts of plagioclase, (a) and (b) both show this later marginal rim, whilst (a) has an infilling of plagioclase of different orientation across a fracture which has been later sealed by the albitic rim (Fig. 9.4.). In Fig. 9.5. (c) and (d) are typical examples of the phenocrysts, to show the corroded margins. Fig. 9.3(b) also shows this, as well as small traces of microcline occurring in the pits of the plagioclase. Fig. 9.6. is a photomicrograph of the grain shown as Fig. 9.5(d). Also shown in Fig. 9.3(a) and 9.5(c) is what the writer has termed skeletal zoning. Irregular shaped portions within the plagioclases, extending from centre to border extinguish together, whilst retaining the same twin planes as the rest of the grain. It is difficult to explain this phenomenon other than a type of compositional zoning, and it can hardly be imagined to have been caused by any metamorphic process. Perhaps this skeletal network is the remnants of a corroded crystal, around which later plagioclase has been deposited. Later this was fractured, with an infilling of plagioclase, and then a marginal rim of albite was deposited sealing the fracture. This polygenetic history of a single plagioclase grain mirrors in a minor way, the history of the rock and it is quite probable that this in its turn is even more complicated.

The "history" of the grain illustrated in Fig. 9.3(a) and shown in Fig. 9.4 is set out in tabular form below.

Albitic rim
Plagioclase infilling fracture
Fracturing of plagioclase
Deposition of new plagioclase
Corrosion of plagioclase
Crystallisation of plagioclase.

↑ Time

Such grains as these, already described, show that the phenocrysts are actually relics of an earlier rock, which in all probability was of igneous origin.

Quartz.

Anhedral, clear grains making up to 30% of the matrix, the rest being of plagioclase and microcline. Typical metamorphic texture, with the grain boundaries of the several minerals interlocking tightly.

Microcline.

This mineral occurs as several forms throughout the dyke type. Principally, as interstitial, small grains forming part of the matrix. There are several good examples of the replacement mode of this mineral. For example in specimen 42851, pseudomorphs of microcline after plagioclase are developed, with a strong development of epidote, which is due to the excess CaO, Al_2O_3 and can be imagined as the replacement of calcium by potassium. Fig. 9.7. shows an occurrence of this type.

As figured in Fig. 9.3(b) microcline also occurs around the corroded plagioclase grains, infilling the pits. Microcline grains also are seen without any evidence of replacement origin from plagioclase. One such example is seen in specimen 23376, where prominent phenocrysts of both plagioclase and microcline are developed. In Fig. 9.8. a microcline is illustrated which has a thick rim of albite. The core of the grain is about 3mm. across and the rim .8mm. wide, the whole crystal having an almost euhedral form. The albite-microcline contact is irregular and perthitic lamellae within the microcline are in optical continuation with the albite rim. Within the outer portions of the rim especially, are regular concentrations of pear shaped quartz blebs. Each quartz grain has a common orientation, but each seems to be separate from its neighbour. The size of the quartz blebs does not vary a great deal, about 0.02mm. in length.

It would appear that this grain must also be treated as a relic feature of the dyke rock. It is undoubtedly a good example of what is termed a rapikivi texture (in the modern sense), but the actual method of formation still presents a problem. It is possible that the grain represents an intermediate stage in the expulsion of albite from the microcline lattice, hence the lamellae in optical continuity, but this feature could, of course, be also imposed by the rim on the exsolved material. If this is so, then the microcline must have suddenly been changed from an environment at a temperature above 700°C to avoid the exsolution of the albite into one in which it acted as a nucleus for the precipitation of albite. The consolidated grain was then cooled, and the crystallographic directions within the albite which was exsolving was pre-determined by that of the albitic rim.

The quartz blebs are more difficult to explain. It is a characteristic of myrmekite that quartz is thrown out as plagioclase replaces potash feldspar, but these can in no way be likened to myrmekitic quartz grains. Perhaps they can be explained by imagining an excess of SiO_2 in the magma which deposited the albite around the microcline, for there is an excess of free silica in the groundmass. Acidification of a former calcic plagioclase on metamorphism would also cause the expulsion of free quartz.

<u>Amphibole</u>.

The amount of amphibole varies considerably from specimen to specimen. When abundant, the mineral occurs in clots (together with biotite) which may reach over 4mm. in length. The crystals are anhedral, slightly poikolitic and without any preferred orientation. Optical characteristics of one such amphibole are given below:

	nX'	nY	nZ'	nZ-nX	$Z^{\wedge}c$
42851	1.647	1.658	1.663	0.016	20°

42851: West side of the southern half of Arpatsivik, at about 200 metres level (10/114880). The pleochroic scheme is similar to that already described for hornblendes from the coarse grained, amphibolitic types.

nX colourless to straw yellow,
nY green,
nZ strong blue green.

Biotite.

Varies antipathetically with hornblende, normally associated with this mineral in the basic clots characteristic of the dyke types.

Pleochroism is as follows:

nX Yellow
nZ Deep brown
nZ' = 1.627 (specimen 42851).

Anhedral plates occur with a crude lineation, but the folia direction of the flat biotites is not developed. They rarely exceed 1mm. in length and occasionally occurs as a mass of tiny interlocking flecks less than 0.1mm. long.

It is noticeable that the prominence of biotite is generally matched by the presence of significant quantities of microcline, rimming plagioclases and occurring interstitially, although in the cases where it appears that the alkali feldspar is original this is not true.

Ilmenite-sphene.

These two minerals are grouped together because in this dyke set they are common partners. Invariably they are found associated with the clots of dark minerals, thesphene forming rims or mentles around the ilmenite. The largest ilmenite-sphene growth observed is about 0.5mm. across, the mantle generally not greater than 0.03mm. thick.

Accessories.

Epidote is not common, generally as a secondary product after plagioclase and some long apatite crystals cutting through all grains.

Fine grained, Leucocratic, (younger) Dykes.

This group is in a way enigmatical, for the field evidence, already described, suggests that this rock type is younger than the more basic types, yet the general texture is one of total recrystallisation. This is probably due to the ease in which leucocratic rocks recrystallise.

The mineral assemblage is: plagioclase, quartz, biotite amphibole microcline, (epidote) (opaques).

Plagioclase.

Anhedral, interlocking grains about 0.2mm. across. Twinning rare, so that a tentative composition of Ab_{70} is suggested from insufficient determinations. The grains are slightly dusted, so that they can with difficulty be distinguished from quartz which has similar shape and size. Occasionally sericitised anhedral masses of plagioclase are seen, about 1mm. across.

Microcline.

In some, this mineral is particularly well developed as an intimate part of the matrix. The mineral has similar dimensions to the quartz and plagioclase so that the whole groundmass can well be described as even grained. The cross hatch twinning is well developed and makes the mineral conspicuous.

Quartz.

This is the most abundant mineral in some specimens. Occurs as integral part of the interlocking fine grained matrix and in some specimens show a crude elongation parallel to the lineation of the biotites.

Biotite.

In most examples the mineral occurs as strongly lineated laths of pleochroic material. It is often converted to chlorite, which retains the lineation pattern. nZ' on one of these biotites: 1.641, the highest recorded on the biotites from Kuanitic dykes (Specimen 23814).

Amphibole.

Not well developed as in the other types. Can occur as anhedral, small grains (0.3mm.) with random orientation, in long streaks, together with biotite and chlorite. In other cases, the mineral is well scattered throughout the rock with a crude lineation. The optical characteristics of one such amphibole are listed below:

	nX'	nY	nZ'	nZ'-nX'	$2V_x$	$Z\hat{}c$
23814	1.657	1.671	1.678	0.021	54½	20°

Specimen 23814 is a strongly lineated, leucocratic rock, from north of Iterdlak (10/089858).

Pleochroic scheme for most hornblendes of this group is as follows:

nX	yellow
nY	olive green
nZ	green blue.

Accessories.

Epidote, conspicuous in most specimens, occurring as accumulations of small grains, without any apparent connection with the dark minerals.

Opaque minerals are not well developed, usually as ?ilmenite with rims of hematite, indicating oxidation conditions.

Dark, fine grained, type.

This group of dyke rocks is extremely broad and includes a wide assortment of dyke rocks which fit into none of the other divisions. It is, in fact, an assortment of dykes which have been subjected to varying degrees of metamorphism acting on different compositions. The one thing in common is the fine grained dark nature of the rock. Consequently, nothing will be gained by giving detailed descriptions of the group so that the more important features of the rocks will be described briefly.

Plagioclase, in many instances, especially in the centre of the dyke, retains its original form, although severely corroded and sericitised. At the edges of the dykes, it is invariably recrystallised and the size diminished in order to accommodate the strong lineation direction imposed upon the rock. Amphibole is the dominant mafic mineral in nearly all cases, this too being oriented into linear streaks except for the occasional knot of amphibole and biotite. One such lineated amphibole has been examined and its optical characteristics are as follows:

	nX'	nY	nZ'	nZ'-nX'	$2V_x$	$Z^\wedge c$
23339	1.657	1.670	1.676	0.019	$57\frac{1}{2}$	23°

Specimen 23339 is taken from the edge of a Kuanitic dyke on the north west slopes of Sarqarssuaq (10/055852).

Pleochroic scheme is as follows:

nX	pale yellow
nY	pale green
nZ	green-blue.

The amphiboles, taken from two dyke rocks which have remnant plagioclase phenocrysts which show later rimming, have also been examined and their optical constants determined:

	nX'	nY	nZ'	nZ'-nX'	$Z^\wedge c$	nZ' biotite
23336	1.647	1.660	1.667	0.020	20°	not present
23351	1.635	1.646	1.657	0.022	19	1.622

Specimen 23336, about 1km. west of Taserssuaq (10/027833).
Specimen 23331, about 1km. south west of Julianehaab (10/057809).

Both of these specimens contain significant quantities of microcline, either as part of cross cutting acid veins or as part of the groundmass, often replacing the plagioclase.

The biotites of this group vary in quantity, and normally never reach over 0.5mm. long. Specimen 23346 contains biotites with a large number of inclusions, probably of zircon. The rock itself is cut across by acid and epidote veins.

This varied group can be best described as most typical of the metamorphosed Kuanitic dykes, for not only do they vary from dyke to dyke but also along their length.

Medium to Fine grained dykes with Remnant Plagioclase Phenocrysts.

As mentioned in the introduction to this section, these dykes all come from the south end of the island of Arpatsivik and cannot definitely be proved to be Kuanitic dykes, even though they can be followed as strips of basic rock through the granite. Examples of this rock type are specimens 42830, 42832 and 42834. The preservation of relic textures, suggests that the metamorphism to which they have been subjected has not been as strong as to suggest that the rocks are Ketilidian in age.

Petrographically they do not represent any major differences from the types already described. The plagioclase phenocrysts are remarkably well preserved in many cases and often reach 2mm. in length. The euhedral form is often preserved and the rimming by ? albite improves the crystal shape. Frequently zones of sericitisation occur which conform to the grain boundaries, showing that the plagioclase are zoned, perhaps indicating some reverse zoning. Twinning is not common in the phenocrysts, so that compositional determinations are difficult, but they appear to be more basic than plagioclase from the other groups, about Ab_{62}. Zoning however undoubtedly reaches more albite rich margins and some phenocrysts appear to have acted as a nucleus for deposition of albite.

The plagioclase of the groundmass is completely anhedral but not completely recrystallised. Occasional twinning can be observed but this is not common.

Interstitial microcline occurs in varying quantities, never as large masses, but as discreet grains about 0.2mm. across.

Biotite and amphibole are prominent, usually biotite is more abundant, without any linear pattern. Optically, the amphibole appears to be similar to the other hornblendes already described.

One of the most characteristic features of this rock type is the abundance of anhedral stringers of sphene. The mineral although very often associated with ilmenite, also occurs by itself, scattered throughout the rock without any obvious relationship to any other mineral. The familiar mantling by sphene of ilmenite, seen in the leucocratic types with remnant phenocrysts is common in this group also.

Table 9.2 Modal Analysis Values for Four Amphibolitised (Kuanitic) Dykes.

	a.	b.*	c.	d.
Plagioclase	37.7	48.8	37.5	50.9
Microcline	-	5.2	10.1	7.9
Quartz	-	21.5	36.2	21.1
Amphibole	29.9	9.5	-	3.5
Biotite	31.4	11.2	12.4	11.4
Epidote	1.0	Tr.	Tr.	Tr.
Sphene	-	{3.8	3.8	5.2
Ilmenite	-			Tr.

a. 23337. Early Kuanitic dyke. (10/052853).

b. 43038. Leucocratic, with feldspar phenocrysts. (10/086883).
* Probably quartz over estimated as feldspar untwinned.

c. 23822. Leucocratic, fine grained dyke. (10/089863).

d. 42830. Dark, fine grained with remnant phenocrysts. (10/127866).

The Metamorphism of the Kuanitic Dykes.

In approaching the problem of the metamorphism of these dyke rocks the ultimate object is to determine the original compositional nature of the rocks. To a large extent, this determination has to be largely based on the observers own ideas on metamorphism and the forces in operation at the time. The literature affords an abundant supply of data and subjective observations on the topic and these can be subdivided into two groupings. The first, attempts to produce the typical metamorphic assemblages by a reorganisation of the chemical elements within the rock itself. This isochemical viewpoint means that the chemical composition of the rock does not change during metamorphism even though a radical change is brought about in the mineralogy. Harker (1956) and Wiseman (1934) advocated this type of metamorphism whilst the second group have described rocks in which there has been an incoming of particular elements and the consequent expulsion of others. Potash particularly is the element which is thought to have been introduced into the igneous rocks during metamorphism (see Cheng 1943). It is quite likely that both groups are correct in the observations of their own metamorphic terrain and, as in the granite problem, there are several ways of producing the same end product.

The metamorphism of igneous rocks, especially dykes, has been given special attention, by several geologists. One of the earliest descriptions of this was given by Teall (1885) and in this are given several references to earlier accounts. Wiseman's (1934) published account of the progressive metamorphism of a series of sills is a classic one and the petrographic and chemical detail makes it a standard reference text in metamorphic petrology.

Sutton and Watson (1950) describe the metamorphism of dolerite dykes which were injected between the Scourian and Laxfordian metamorphisms. In this account, the authors outline the progressive changes in mineralogy of the dolerite as the metamorphism increases. More recently, Roddick and Armstrong (1959) have described relic dykes in the Coast Mountains near Vancouver, an area which Phemister (1945) had already described. Field and petrographic evidence are used to show that the dykes were metamorphosed almost as soon as they were injected as the plutonic rocks were evolving by granitisation contemporaneously with the injection of the dykes.

This account of previous descriptions of metamorphosed igneous rocks would not be complete without mention of the pioneer work of Sederholm, who in a series of publications on migmatites (1923, 1927, 1934) showed the value of metamorphosed dykes in evaluating the evolution of the metamorphic rocks. The detailed descriptions of the field localities are formidable and the illustrations of the morphology of single dykes shows the extent to which he was prepared to go in order to elucidate the history of these rocks.

In considering the mineralogical transformations brought about by the metamorphism of these dykes, it seems to the present writer that in this particular case the isochemical viewpoint cannot be strictly adhered to. The abundance of biotite and microcline, together with the ubiquity of quartz in the dykes can be explained in two ways. The first is to assume that the rocks were originally doleritic in composition, in which case K_2O has been introduced in large quantities to produce the microcline and biotite or else the dykes must be considered to have been more acid in composition, say trachy-andesitic or andesitic. The composition of the relic plagioclase (An_{20-30}) would perhaps give a support to this assumption. However the field evidence points to the metamorphism of the dykes at a time when there was a large scale anatexis of Ketilidian granites which eventually produced the Sanerutian granite. It would be indeed surprising if there were no manifestations of this in the shape of microclinisation in the rocks immediately adjacent

The development of hornblende in metamorphosed igneous rocks is universally regarded by mineralogists as due to the conversion of pyroxene and Harker points out that this is the reverse of that expected from the Reaction Series. This is explained as a delayed or suspended reaction, which had been previously prevented by the drop in temperature and which is continued when metamorphism raises the temperature to moderate levels. As pointed out by Laxcroix (1917), Harker (1956), and Wiseman (1934), it is very probable that plagioclase is also involved in the production of hornblende, as well as augite. This means that the calcic part of the anorthite molecule is required to produce hornblende. Hence on metamorphism the plagioclase suddenly loses part of its anorthite molecule and consequently becomes more albitic. The augite is entirely replaced by the calciferous hornblende, and in no case have remnant pyroxenes been found in the Kuanitic dykes.

Wisemann suggested for the sills which he described that in the low zones, the plagioclase plus augite combination produces chlorite as well as hornblende. The chlorite presumably taking up the extra Al_2O_3 from the anorthite molecule. In the Kuanitic rocks there is very little evidence to suggest that chlorite is a primary metamorphic mineral so it seems likely that the Al_2O_3 combined with the excess CaO which the hornblende could not absorb, to form epidote. The presence of epidote in nearly all the rocks has already been noted. It must also be noted that the break down of the plagioclase anorthite molecule would also release SiO_2 which would appear as excess quartz in the rock.

Before leaving the reactions involving the CaO molecule it is worth noting the presence of the sphene mantles around the ilmenite in the coarse grained leucocratic dykes. This is also a manifestation of the release of CaO by the plagioclase for the ilmenite takes up the CaO and SiO_2 of the anorthite with the consequent production of sphene. The excess Al_2O_3 and FeO is probably absorbed by the hornblendes and biotites with which the ilmenite-sphene are always associated and the remaining SiO_2 appears as quartz.

$$\underbrace{(CaO + SiO_2 + Al_2O_3)}_{\text{Anorthite}} + \underbrace{(FeO \quad TiO_2)}_{\text{Ilmenite}} \longrightarrow \underbrace{(CaO + SiO_2 + TiO_2)}_{\text{Sphene}} + FeO, Al_2O_3 + SiO_2$$

It is also of passing interest to note that the TiO_2 is not taken up into the hornblendes to any great extent. In many of the dykes where magnetite is the only opaque mineral, most of this is absorbed by the hornblende yet this does not appear to be true for ilmenite. The fact that titanium is not found in any great quantity in these hornblendes is suggested by the absence of any brown colouration (Deer 1938).

The plagioclase thus appears to be one of the minerals which is controlling the metamorphic assemblages and it is worth studying in a little more detail. The typical xenomorphic texture noted throughout the dykes of this mineral is due to the total recrystallisation with very few twin lamella being seen. Compositionally they vary only slightly from Ab_{70}. Some dykes, characteristically contain relic plagioclase phenocrysts, which show typical ragged margins often with a more albitic rim around them. Wiseman (1934) and Harker (1939) state that after the initial increase in the albite molecule on metamorphism of the plagioclase (due to the expulsion of the anorthite molecule) the mineral becomes progressively more basic with increasing metamorphism due to resorption of epidote. Sutton and Watson (1950) state however that increasing metamorphism results in a progressive decrease in the anorthite molecule. They also describe rimmed oligoclases with indented margins. Cheng (1943) suggested that such features were due to a potash metasomatism, the displaced soda causing the ragged edges. It is thus hard to avoid the fact that in the Kuanitic dykes there has been introduction of potash and this is reinforced by the pseudomorphs of microcline after plagioclase (Fig. 9.7.) seen in one of the dykes (42851). Consequent upon this is the production of epidote which is scattered throughout the phenocrysts.

The introduction of potash would have been in some ways compensated for by the hornblende which would absorb the large molecule, but there is a saturation point (probably no more than 3% K_2O) after which further potash produces the breakdown of the hornblende lattice with the production of biotite, and probably epidote. It is also probable that granitic solutions of microcline and quartz were also active and this would account for the incipient development of microcline as an integral part of the matrix of some of the dykes. Microcline also occurs rimming plagioclase phenocrysts and infilling the pits at the margins (Fig. 9.3(b)).

The metamorphism of these dykes however, cannot be represented satisfactorily as a series of chemical formulae, for their evolution was much more complex than set out in this account. It is quite probable that the plagioclases underwent several periods in which they were corroded and later added to by resorption from other minerals and the addition of potash. The final metamorphism however did not reach any stage higher than the amphibolite facies, for there is no evidence for the development of new pyroxenes which would be expected with increase in temperature. It is suggested that the majority of the dykes here described can be placed in the biotite-hornblende-plagioclase-microcline-quartz subfacies of the amphibolite facies (Turner and Verhoogen 1951) and owe their present mineralogical setting to a metamorphism consequent upon the evolution and emplacement of the Sanerutian granites and the introduction of potash (and quartz) from the same source.

The Kuanitic dykes were probably doleritic to andesitic in composition, the present differences in texture and colour index due to the original percentage of plagioclase and pyroxene (olivine), the degree of metamorphism and the amount of introduced material.

The pronounced lineation developed in some dykes is due to stress conditions at the time of the crystallisation of the minerals and in some cases it would appear that this has actually caused the recrystallisation of hornblende and biotite. This factor means that the relationship of biotite to hornblende is often masked by the later recrystallisation of the two minerals.

The appearance of the lineation, especially at the margins of the dykes again suggests that it is a metamorphic rather than original feature. The principal stress factor at that time appears to have been from the north-west and south-east (Fig. 3.8. shows boudins of aplite in the amphibolitic gneiss and this is a good indication of the pressure direction) and the dominant dyke direction is approximately at right angles to this. This is apparently conflicting evidence, for Anderson (1951) suggests that dykes are intruded at right angles to the minimum stress field. However, if the granite country rock was sufficiently plastic at the time of dyke intrusion, then it would be the foliation directions of the granite which would control the dyke injection. The lineations of the dark minerals as well as the lineation in the biotite-hornblende schlerion all suggest that the strong N.W. - S.E. stress field later became more effective producing this shear lineation at the edges of the dykes. The coarser grained central parts of the dykes were more resistant to this shearing movement, hence lineation was not strongly developed.

The hornblende-biotite clots found in several of the dykes are due to metamorphic segregation, the hornblende having formed first, often without any lineation, is later replaced by biotite which responds to the strong shearing stress.

If it is assumed that the dykes were injected at right angles to the minimum stress, then the fact that the lineations (which are thought to have formed at right angles to the maximum stress) are parellel to the strike of the dyke is anomalous. One would have to postulate a swing of maximum stress field to a position exactly at right angles to the strike of the dykes, after the injection of the dykes. The coincidence is difficult to imagine, for there must be a more fundamental reason for the lineations being approximately parallel to the strike of the dyke other than chance.

The Petrology of the Metamorphic Changes in the Older Dykes.

The mineralogy of these older Kuanitic dykes is similar to those younger types, except for the greater proportion of amphibole. It would seem that these dyke rocks have been subjected to a greater period of metamorphism which at times was of a high grade. It will be noticed that the refractive indices are much lower in these older dykes than in the hornblendes of the younger Kuanitic dykes. This is the opposite to what was found by Harker (1939) and Wiseman (1934) who state that with increasing grade the indices increase. The factors which effect the rise in indices have been dealt with by numerous writers, but the consensus of opinion seems to indicate that the MgO/FeO ratio is an important one. Deer (1938) states that with increasing ferrous iron the refractive indices increase. Increasing alumina is also stated to affect the optical properties in the same way. It therefore seems that there is an inherent difference in chemical composition in the two groups, probably with low ferrous iron and less alumina in the older types. This means that in composition the pyroxene of the older types contained less FeO and consequently on metamorphism a hornblende with low refractive indices was produced. The statement by Wiseman (1934) that refractive indices increase with increasing grade was made after observations on sills of the same age and composition and is probably due to the breakdown of the opaque minerals with increasing metamorphism and the absorption of FeO by the hornblende.

Summary and Conclusions on the Kuanitic Dykes.

The Kuanitic dykes on the Julianehaab peninsula are of two generations and perhaps more. There is also evidence to suggest a group of metamorphosed dykes which are either early Kuanitic or pre-Julianehaab granite. The field work has shown that the main set of Kuanitic dykes cut the Julianehaab Granite but are extensively cut and metamorphosed by the intrusion of the Sanerutian Granite.

Petrographically, most of the dykes are completely recrystallised with the development of hornblende from augite and plagioclase and a later development of biotite and microcline due to potash metasomatism. It is also shown that the main mineralogical changes agree with that expected with the metamorphism of doleritic or andesitic dykes, the microcline being of external origin as is most of the quartz.

Remnant plagioclase phenocrysts still remain in certain groups and these often display the long and varied history through which the rocks must have passed. Optical studies on the hornblendes from the major groups indicates that the ? early Kuanitic dykes have hornblendes with low refractive indices suggesting that the pyroxenes from which they are derived contained less ferrous iron and more magnesia.

Finally the dykes are used to demonstrate the stress field in existence at the time of injection and consequent metamorphism. It is concluded that the Kuanitic dyke rocks were injected into an already plastic granite which was unable to transmit the maximum stress so that the foliation within the granites controlled the direction of the dykes. The remobilisation of parts of the country rock to produce a palingenetic magma also caused the metamorphism of the Kuanitic dykes. Very soon after, a strong shearing stress was developed with the maximum stress from the north-west and south-east. This shearing was the cause of the lineation of biotite and occasionally hornblende especially at the margins of the dykes. Hence the metamorphism and lineation found in the Kuanitic dykes took place early in the Sanerutian period of the geological history of the area.

The Petrography of the Alkaline Dyke Rocks and Related Types.

The dyke types described by Ussing (1912) from the adjoining area of Igaliko has formed the basis for the description and nomenclature of the dyke types found within the region for many years. Terms such as hedrumite (Brøgger) tinguaite (Rosenbusch), monzonite porphyry, augite syenite porphyry and nepheline porphyry were applied by Ussing to the dyke rocks found. In the opinion of the present writer these terms are of only historical value for they are needless additions to an extensive assemblage of rock names covering this range of composition. Fig. 9.9. is a diagrammatic summary of the suggested terms used by the writer for these rocks and has been compiled mainly from Johannsen (1931) and Hatch, Wells and Wells (1952). Ussing's terminology has also been included to give an indication of the range of rocks covered in his descriptions.

The classification is based mainly on the percentage of alkali feldspar to plagioclase and composition of the plagioclase. A subdivision according to grain size has also been suggested, this being common petrographic practise. The undersaturated types described by Ussing (nepheline porphyry and hedrumite) are distinguished in this scheme by the prefix of the feldspathoid mineral, thus nepheline microsyenite and nepheline trachyte can be derived although Phonolite can be used as a synonym for this. Hedrumite is more difficult to fit in, for Ussing's description only suggests the presence of nepheline, but also states that there are no porphyries and that a sodic orthoclase and acid plagioclase co-exist within the matrix. The rock may then be described as a (nepheline) sodic trachyte. In the field, the hedrumite is very distinctive in that Ussing's description of the silky lustre and the tendency to split into thin slabs parallel to the flow structure is quite accurate. Hence it is unfortunate that the term cannot be retained, for there are sodic trachytes which do not possess these characteristics, and it is suggested that the name may still have some use as a field term.

The types identified from the Julianehaab Peninsula range from microsyenites, trachytes and their undersaturated equivalents, sodic trachytes (including the hedrumitic types), trachyandesites and trachybasalts.

Microsyenites, Trachytes, and Nepheline Varieties.

The microsyenites and trachytes can be subdivided into two groupings according to the nature of the pyroxene and amphibole constituents. Accordingly for this description those dykes containing sodic rich dark minerals will be grouped under the heading of sodic microsyenites and sodic trachytes in contradistinction to those with augitic pyroxenes. Invariably, those rocks containing nepheline belong to the sodic group in which both aegerine-augite and sodic amphibole are well developed.

Sodic Rich Types.

Mineralogically, the rocks are composed of perthitic orthoclase, pyroxene, alkali amphibole, biotite, (nepheline) (olivine).

Feldspars

Texturally the feldspars show a wide variety of forms ranging from the typical "trachytic" texture to porphyritic, and radiating microlites to phenocrysts set among stubby laths without any orientation. The microsyenites generally occupy the latter section and the trachytes show all variations.

In those specimens with a strong alignment (Fig. 9.10) the elongate laths up to 2 mm. long are packed close together. The alkali feldspar makes up all the feldspar in these rocks with Carlsbad twinning and a strong perthitic development. This makes the determination of the host difficult because interference figures are generally unsatisfactory, but appear to give consistent positive optic signs indicating that it is albite. This is supported by X-ray work which although the material did not homogenise after 10 hrs. at 800°C indicated, that the albite molecule was predominant. Extinction on (010) $a \wedge nX$ is close to 10° which further supports the albitic composition. The optic axial angle is large, a feature not characteristic of Common orthoclase or sanidine, whereas albite does have a large positive axial angle.

The conclusion is that the majority of the sodic trachytes and microsyenites have an antiperthitic feldspar, with albitic feldspar being the host. The percentage of anorthite is fairly small as the refractive index of the albite, as estimated from the Becke line, is lower than the balsam.

Measurements of the phenocrysts of alkali feldspar against balsam indicate an albitic composition and one of these is shown in fig. 9.11 with a type of hour glass twinning structure.

On alteration, especially within fault zones the feldspar takes on a strong iron dusting, which gives the rock a brick red appearance. In these cases the dark minerals are reduced to chloritic aggregates. Normally however, the alkali feldspar is fresh with only a thin covering of alteration which appears as a faint dusting and does not interfere with the optical properties of the mineral.

Amphibole

Typically the amphibole of these types is a sodic rich type of the riebeckite series and in the micresyenites the pyroxene is completely subordinate. Examples of this type of dyke are specimens 43044 and 43046, the former probably carrying interstitial nepheline.

Subhedral to anhedral grains of sodic amphibole occur as wedges between the well developed laths of perthitic feldspar. The variation in size is small, the maximum size being about 0.8 mm. long. Two types occur within the dyke, the first is rare and has a red-brown to deep red brown pleochroism. The second is by far the most prominent and has the following pleochroic scheme:-

nZ - dull yellow
nY - green
nX - deep green blue

The absorption of nX is very strong so that in some cases the mineral appears to be opaque. It is worthwhile noting that the optical orientation is difficult to determine in thin section, for although Winchel (1946) states that the majority of alkali amphiboles are length fast the colours of the mineral coupled with the low birefringence makes this almost impossible to confirm. In the present case, powdered grains were used in a refractive index liquid of 1.700, which showed that nX had the greatest absorption and was also parallel to the length of the mineral. Optical characteristics, for two of the riebeckites are given below:-

	nX'	nY	nZ'	nZ-nX	$c \wedge X$
43050	1.698	---	1.707	0.009	8°
43046	1.698	---	1.707	0.009	ca 15°
42974	1.698	---	1.707	0.009	10°

43046 Riebeckite microsyenite, (10/103939)
43050 Riebeckite microsyenite, (10/121952)
42974 Sodic Trachyte (10/065886)

This blue variety of amphibole occurs as rims around the red-brown type when it is present and the situation is probably analogous to the rimming by aegerine of augite which is far more common.

Occasionally the riebeckite is moulded around a colourless to faint green pyroxene which has a high birefringence. Alteration in most dykes does not affect the riebeckite and it is only in fault zones that it is reduced to chlorite.

Pyroxene

For the most part, pyroxene occurs in minor quantities often as the nucleus of a riebeckite grain. In the finer grained dykes more properly termed trachytes the pyroxene becomes dominant. In one dyke ofmicrosyenitic aspect however, the pyroxene occurs in equal quantities with the riebeckite and in this case the riebeckite develops a brown absorption colour in the nY direction (specimen 23474).

Pyroxene resembles the amphibole in form and size as it occurs as wedges between the alkali feldspar grains. Typically the mineral has a colourless core with a narrow mantling zone of green pyroxene. (Fig. 9.10). Generally there is no sharp dividing line between the two and the faint green colour seen with difficulty in the centre of the grain gradually intensified outwards. The distribution of the sodic portions of such grains is by no means regular and may be concentrated at the ends of the grains or along one side. Also within the slide, aegerine augite occurs without the colourless pyroxene, but even these show a slight zonation from edge to centre with the delicate green colouration intensifying outwards. Some of the sodic poor cores have a slight purplish tinge indicating a titaniferous augite. Refractive indice measurements carried out on the pyroxenes in these rocks are not reproduced here because the ambiguous results and the high birefringence values obtained was obviously the result of measuring nX for the calcic pyroxene and nZ for a more sodic type which being a thin grain did not show the strong green colouration. The value of nZ for an aegerine augite indicated a composition of about 66% aegerine molecule (Winchel 1951) with nZ being 1.790 and extinction c^X being close to 0°, the strong colouration preventing accurate measurement. The zoning within the pyroxenes also produced a wide range in optic axial angle, the values of 66°-76° were recorded in specimen 23496(00/966868) nY values for colourless pyroxenes range from 1.697 to 1.713 and optic axial angles of about 56° havebeen recorded for specimen 23496, but strong zoning even in the colourless cores makes accurate measurement difficult. This data indicates that the pyroxenes are close to ferro-angites (Hess 1949).

Biotite

Biotite is almost always developed in the sodic microsyenites and trachytes although there are certain exceptions to this. It would seem from the available material that biotite is characteristically absent from certain of the dykes, although mineralogically they do not appear to differ from the rest of the sodic trachytes and microsyenites. Perhaps this feature may provide a useful correlation factor in later work.

Typically the irregular biotite flecks reach no more than 0.5 mm. across and show a bright orange red absorption colour in the nX direction and a deep brown in the nZ. This absorption colour makes the mineral almost opaque. Biotite occurs principally as ragged grains surrounded by riebeckite or pyroxene and appears to be in the process of being assimilated. nZ' measured on two biotites from sodic trachytes is as follows:-

Specimen	nZ'
42974	1.672
43046	1.687

42974	Sodic Microsyenite	(10/065886)
43046	Microsyenite	(10/121952)

Olivine

Olivine is developed in a few cases, generally in the sodic trachytes but there is one case of the mineral occurring within a porphyritic trachyandesite (on the northern coast of the main peninsula at Nunarssuatsiaup Nua.) Anhedral grains with a tendency to roundness are generally fresh in the centre, with a rim of brown opaque material which may have acted as an armour against assimilation. Normally the grains are small about 0.2 mm. across but exceptionally larger grains over 0.5 mm. are found. The mineral is optically negative with an optic axial angle of $2v_x = 54^\circ$ (43110) indicating a composition close to fayalite (Poldervaart 1950). Birefringence is moderate, with second order blue being the highest colour. Occasionally the pyroxenes and amphibole are moulded around the olivine but this is far from common in many of the specimens.

Alteration within the olivine is restricted to the expision of iron, many of the sodic trachytes having irregular patches of opaque material with only slight traces of olivine remaining in the centre.

Nepheline

Nepheline appears to be restricted to the sodic types, more especially the microsyenites where it appears as euhedral platy crystals reaching over 3 cm. in hand specimen. Frequently a zonal structure can be seen in the mineral (fig. 9.12) which is conformable to the outlines of the grains. No fresh nepheline has been observed in the dyke rocks the alteration being to a dusty brown coating of sericite.

The "nepheline porphyry" of Ussing (Ussing 1912 p.272) is accompanied by comparatively fresh phenocrysts of euhedral alkali feldspar. Frequently around the nepheline phenocrysts a rim of green material is developed which is probably chlorite after pyroxene or amphibole.

Interstitially, nepheline is difficult to detect due to its alteration to a fine grained sericitic mass although in several of the dykes there is a strong suggestion that it is present even though there are no large phenocrysts.

The major nepheline bearing dyke occurs on the south side of Iviangiussat and is seen again on Nugatsiaq to the south west from which locality it can be traced almost as far as Kangerdluarssuk.

Accessories

The most prominent accessory is magnetite which occurs primarily in the trachytes but which is conspicuously absent from the riebeckitic microsyenites. It occurs as irregular shaped small grains associated with the dark minerals, particularly olivine and pyroxene. Chlorite and iron oxide are the frequent results of the breakdown of pyroxene-amphibole and biotite respectively.

Modal analysis of a microsyenite and sodic trachyte are presented below. The dominance of riebeckite in the microsyenites is a feature in this area whilst the position is reversed in the finer grained rocks. The low percentage of biotite within the trachyte is perhaps not typical, for it normally exceeds that of olivine. Both rocks, as in all these alkaline dykes, have a high percentage of feldspar and this together with the riebeckite and aegerine-augite means that the rocks must have an extremely high percentage of Na_2O. Ussing (1912) records from 8 - 10% Na_2O for hedrumites and nepheline porphyries (sodic trachytes and nepheline sodic microsyenites respectively).

Constituents	Volume Percentages	
	23474	42941
Feldspar	60.5	74.2
Amphibole	17.9	6.0
Aegerine-augite	(6.8	6.3
Augite	(	5.9
Olivine	N.Present	2.1
Biotite	6.9	1.5
Opaque, accessories & alteration products.	7.9	4.0
	100.0	10.0

23474 Sodic microsyenite (10/036879)
42941 Olivine sodic trachyte (10/069889)

Inclusions Within the Sodic Microsyenites

In several of the dykes, especially on clean coastal sections, irregular dark inclusions of varying size are found. Petrologically these are of trachytic composition, invariably fine grained and of a less sodic character. The feldspar component of the rock is no longer monopolised by alkali feldspar but owing to the fineness of the grain nothing definite can be said about the varying proportions. Titaniferous augite is the dominant dark mineral, with only a faint rim of aegerine augite, or more commonly chlorite. Riebeckite is not present and biotite forms a more prominent part of the mineral assemblage. This does not hold true however for specimen 43044, the nepheline microsyenite on the southern slopes of Iviangiussat which contains small inclusions of riebeckite trachyte together with alkali feldspar phenocrysts.

The Potassic Microsyenites and Trachytes

These dykes are less numerous than the sodic types and many are already rich in Na_2O, with aegerine rims, although thin, developed on the margins of the titaniferous augites. The riebeckite however is not so prominent and in many is absent or appears as a trace. One specimen, 43103, from the west coast of Akuliarutsip Nuna (10/974907) is unusual in that an amphibole is developed, which resembles that occasionally seen in the cores of the riebeckites (e.g.23474) The pleochroism is as follows:-

nX - red-brown
nY - olive-green
nZ - light brown yellow

Optical characteristics:-

	nX'	nY	nZ'	$nZ-nX$	$c \wedge nX$	$2V_x$
43103	1.678	1.687	1.690	0.012	18	Small

Orientation of the amphibole is b=Z and negative elongation (i.e. nX approximately parallel to the tabular length). This amphibole is frequently mantled by a thin riebeckite veneer indicating its alkaline nature.

Using the data compiled by Layton (1959) it is suggested that this mineral is close to the Arfvedsonite group, characterised by a very high $c\hat{}Z$ extinction angle, together with a moderate to low optic axial angle ($2v_x$ = c.50^o) Birefringence which is greater than that of riebeckite also agrees with the published data on arfvedsonite.

In many cases, it is difficult to differentiate a specimen into either of the two groups because of the good development of aegerine rims. There can be little doubt that a series of intermediate stages does exist between the two groups and that the subdivision into sodic or potassic trachytes is not a field but a laboratory classification. Having said this it should be said that the hedrumitic types identified as such in the field by their weathering and general appearance, are invariably rich in aegerine or riebeckite so that the previous statement is not entirely true in all respects.

One of the best examples of a potassic trachyte is found on the peninsula of Arpatsivik (specimen 43082 (10/008947). In this trachyte, the texture is not well developed, with the alkali feldspar tablets randomly oriented. Again the feldspar appears to be albitic in nature, but only simple Carlsbad twinning is developed. The prominent pyroxene development shows little or no sign of aegerine rims and occurs as small colourless to faint pink anhedral grains associated with a brown biotite and minor quantities of chlorite.

nY measured on the pyroxene was 1.697 with a moderate optic axial angle (c. 54°) about nZ, indicating ferro-augite. nZ′ measured for biotite is 1.672.

It is worthy of note that the refractive indices of biotites within these alkaline rocks are much higher than normally recorded for biotites. For example Kerr (1959) 1.638, Larsen (1937) 1.72, Dana (1958) 1.68. These values quoted are maximum nZ refractive indices, the highest being that of Dana. In specimen 43046, a riebeckite microsyenite, nZ′ for biotite is 1.687, and other values, already quoted range from 1.672 to 1.676. High refractive indices are thought by Hall (1941) to be due to a high TiO_2 content and it seems that the colour is not a reliable means of estimating the indices for as is noted in the gabbros and norites, red-brown biotites in these rocks have much lower nZ values.

Porphyritic Trachy-andesites and Trachy-andesites.

The trachyandesites (termed Monzonite Porphyries by Ussing) are a distinctive set of dyke rocks within the area. Their best development is seen on the north coast of the main peninsula around Eqalugarssuit Kangigdlit where dykes containing both plagioclase and alkali feldspar phenocrysts are exposed. Specimen 23409, although from close to a fault zone is a good example of this type of dyke rock, the percentage of alkali feldspar phenocrysts being slightly greater than the plagioclases.

Feldspars.

Both types of feldspar occur as phenocrysts and within the groundmass. The Alkali feldspar phenocrysts are euhedral, fresh and reach up to 2 cm. in hand specimen. The composition of the phenocrysts, as determined by X-ray methods after homogenisation is Or_{37} Ab_{63}. More detail on this mineral will be found in the section dealing with the alkali feldspars but it is worthy of note that the rate of homogenisation was very rapid and required temperatures less than 1000° C. This may have been partly due to the nature of the perthite which is faintly detectable in thin section (cryptoperthite) but the mineral became monoclinic also indicating a very low initial triclinicity. The optic axial angle is variable, a feature typical of alkali feldspars of this composition and state of ordering (see for example Bondam 1955) and ranges from 44° to 58° about nX. Plotting the optic axial angle against composition on the diagram of Tuttle (1952) indicates the mineral is midway between the low sanidine- high albite line and the orthoclase-low albite line (fig.10.14 based on the diagram of Emeleus and Smith 1960). In the broadest sense, the feldspar can be termed a sodic orthoclase, assuming that the expression "common orthoclase" covers the whole temperature range from sanidine to maximum microcline.

A feature typical of both types of phenocryst is the narrow zone of?chilled dyke around their margins. Normally this is less than 0.01 mm. across and characterised by the development of needles of opaque material at right angles to the margin. Throughout this grid of material small colourless pyroxenes can be recognised as well as fine grained feldspar. (Fig. 9.13) The orthoclase develops a patchy dusting of brown iron oxide which is not well developed.

Plagioclase phenocrysts are completely altered to sericitic masses with saussurite also developed. Due to this, the composition cannot be ascertained, for only in rare instances is any twinning preserved. This is unfortunate, for in other localities, close to the region being described, xenocrysts of anorthite-rich plagioclase have been described occurring as extremely large porphyritic aggregates. Such rocks are more properly termed trachy-basalts.

In rare cases, alkali feldspar rims, reaching 2 mm. across mantle the altered plagioclase which may be up to 2.5 mm. across. The whole phenocryst has a euhedral margin, indicating that its formation pre-dates the consolidation of the bulk of the dyke.

In specimen 23440 (10/010887), the proportion of alkali feldspar to plagioclase is greatly increased, but there is the unusual case of the preservation of a fresh plagioclase in which the twin lamellae can be observed. Extinction angle measurements on the Universal stage on a section normal to (olo) gives 18°. Unfortunately, neither the relation of the refractive indice to balsam or an optic axis figure can be obtained. The possibility remains therefore that the composition, using the charts of Michel-Levy, is Ab_{97} or Ab_{66}, the same mineral having a rim of new untwinned feldspar, probably of albitic composition around it.

Pyroxenes

Subhedral colourless augitic pyroxenes are the dominant dark mineral in these dyke types. In size, the pyroxene reaches 0.5 mm. and more commonly it is 0.2 mm. in length. Most show a thin veneer of aegerine-augite. The pyroxene is frequently associated with magnetite granules which often show their cubic form. The percentage of opaque material is greater than that in the trachytes and more alkaline types. Pyroxene in specimen 23409 had the following refractive indices:

nX' - 1.701
nY - 1.713
nZ' - 1.722

This pyroxene does not show a strong development of the green sodic rim, so that the indices just given are probably very close to the actual values of the colourless pyroxene. Certainly the birefringence, (0.021) is of the right magnitude. The optic axial angle $2v_z$ was not obtainable owing to the lack of suitable material. However, a value of over 50° is likely, indicative of a ferro-augite.

Olivine

Olivine is found only occasionally in these dykes and has a similar habit to those in the trachytes. The fresh, colourless cores are surrounded by the thin opaque mantle, the composite grain tending to be rounded and bearing no relationship to the general texture of the dyke.

Biotite

The mineral is found only in minor quantities, red-brown in colour with a strong pleochroism, from this colour in the nX position to almost opaque-brown in nZ direction. Biotite is frequently moulded around the olivine with the opaque mantle intervening and it appears to be later than pyroxene in the crystallisation sequence.

Accessories

Magnetite is the dominant accessory mineral, normally associated with pyroxene and acicular apatite crystals are prominent in the alkali feldspars.

Petrogenesis of the Alkali Dyke Rocks in the Julianehaab District

It would be a great presumption on the part of the writer if he were to formulate the evolution of these dyke types from the material available from the Julianehaab District. This task is better left to those working in and around the syenite complexes of Ilimaussaq and Igaliko.

The actual source of the material has already been discussed during the field descriptions and it is thought that the majority of the dykes are closely related to the Igaliko batholith although some of the dykes close to Skovfjord have affinities linking them to the Ilimaussaq complex.

The dominant characters of the rocks is the high percentage of alkali feldspar which is rich in sodium together with the development of aegerine andriebeckite both minerals, repositories of unusual quantities of sodium. Many of the dykes show their undersaturated nature in the development of nepheline, the resultant rocks being nepheline microsyenites and nepheline trachytes (phonolites, tinguaites). This feature is also emphasised by the presence of olivine in several of the dykes, especially the trachytes. Overall the dykes appear to be either undersaturated or just saturated but none have been observed to contain free silica. This feature is also true for the lamprophyric sill, which is most probably genetically related to these dyke types.

The sequence of differentiation appears to be fairly simple and can be formulated both by field and petrographic evidence. The earliest types are trachyandesites with calcium rich pyroxenes and these are followed by trachytes with iron rich olivines, and ferroaugites. Associated with, but slightly later, are the sodic types, together with microsyenites, the nepheline bearing varieties of which are one of the latest dykes of this type in the area.

Individually, the pyroxene shows the greatest amount of chemical change with the familiar colourless cores passing outwards into the sodium rich mantles and the rocks developing aegerine as a direct precipitate and not only as mantles around older pyroxenes. In a similar way, although not by any means so well developed, the red-brown arfvedsonites are mantled by the prominent deep green blue riebeckite, this again demonstrating the differentiation of the minerals toward their sodic rich varieties.

Biotite, which is in process of absorption in the sodic trachytes is much later in the crystallisation sequence in the trachyandesites, so that there is an indication that biotite crystallised before the extreme sodic varieties of pyroxene and amphibole.

Summary

A set of alkali dykes, ranging in composition from porphyritic trachyandesites to nepheline microsyenites (phonolites) are described from the area around Julianehaab. The dykes show a differentiation toward increasing sodium content both in time and within the individual dyke. In time, because of the sequence trachyandesites- trachytes- sodic trachytes and microsyenites- nepheline microsyenites and within the dyke itself because of the zoning within the pyroxenes and the amphiboles.

Optical data is produced to show that the dominant pyroxene is a colourless ferro-augite (often titaniferous), which grades into aegerine-augite with up to 60% aegerine molecule, whilst arfvedsonite gives way to riebeckite with its characteristic pleochroism. The feldspars are shown to be sodic orthoclases and this is confirmed by both optic and X-ray data. Heating experiments on one of the feldspars illustrates its high temperature origin because of the rapidity in which it becomes monoclinic.

Biotite present in these rocks has nZ values greater than those normal for the mineral and higher than most published refractive indice measurements. Olivine present in a few of the trachytes and trachyandesites is iron rich, close to fayalite in composition. The nature of this mineral illustrates the extreme differentiation to which the series has progressed as does the character of the pyroxenes and amphiboles.

It is suggested both from field and petrographic evidence that the dykes are related to the Igaliko batholith.

The Petrography of the Lamprophyric Sill

The field characters of the sill together with the age relationships have shown (see Chapter 5) it to be post alkali dykes and pre-the majority of the dolerites. The Sill is not found in a faulted condition so that it must be late in the stratigraphical sequence. In thin section, the rock is dominated by the striking brown-red colour of the amphiboles but there is a high percentage of feldspar and some pyroxene.

Feldspar

The feldspar consists of plagioclase which together with the amphibole forms the major part of the rock. In length the plagioclase rarely exceeds 1 mm. into which project the euhedral amphiboles. Twinning in the plagioclase is poor with strong zoning developed. Extinction on sections normal to (olo) indicates a labradorite composition and the feldspar contains numerous elongate apatite needles which also penetrate into the amphiboles indicating their primary nature.

Alteration in the plagioclase is restricted to a very slight sericite dusting which is only detected with difficulty.

Amphibole

The amphibole as already mentioned is characteristic of the rock because of the striking red-brown colouration. It occurs as euhedral crystals frequently with simple prisms at both end of the stumpy grains. The mineral is on average 0.5 mm. long and about 0.3 mm. across. Occasionally elongate grains occur but these are uncommon. The mineral has the following optical characteristics:-

	nX'	nY	nZ'	$nZ-nX$	$Z\hat{}c$	$2V_x$
23804	1.673	1.683	1.687	0.014	15°	73°

Pleochroism is as follows:-

nX - very light brown
nY - red brown
nZ - intense red brown

23804 Lamprophyric sill (10/o76885)

The fact that in the absorption scheme nZ is greater than nX suggests that the mineral is not one of the major alkali amphiboles (e.g. arfvedsonite which is close to this in colour but has negative elongation). The large negative optic axial angle precludes the possibility of ferro-hastingsite so that the writer suggests that the mineral is barkevikite. Unfortunately, no complete data on this mineral has been found in the literature. Winchel (1951) and Wilkinson (1961) list some of the properties, but the size of the optic axial angle is not given. Barkevikite is considered by some writers (e.g. Hallimond 1943, Sundius 1946) to belong to the calciferous amphibole sequence although it possesses strong alkaline affinities. There is also the possibility that the amphibole is lamprobolite (Rogers 1940) but the birefringence quoted is greater than the amphibole under discussion although the other properties fit fairly closely.

The mineral is always very fresh and generally associated with magnetite grains, which tend to be euhedral in shape. Very frequently pyroxene grains occur in the centre of the amphibole (fig. 9.14) and apart from this and apatite, other inclusions are rare and difficult to identify owing to the intense absorption. On the outer margin the amphibole grades into a thin faintly green zone, which may be a sodic amphibole (? riebeckite).

Pyroxene

Colourless to faint pink-purple anhedral pyroxene rarely occurs without a mantle of amphibole. The size varies from small grains 0.1 mm. or less across to grains 0.5 mm. long in which the amphibole is only a thin veneer around it. Normally however, the amphibole is the dominant partner and may often be found without the pyroxene core. Fig. 9.14 shows the general texture of the rock and also illustrates the rimmed pyroxenes.

The pyroxene appears to be titaniferous from the faint purplish cast developed in some, it also has a positive optic axial angle which is about 44° (The exact value cannot be determined as nY is unknown). Zoning in the pyroxene cores is common and the purplish cast is also noticeably stronger in the centre of the grains.

In chilled portions of the sill, pseudomorphs of carbonate occur after amphibole(?) Plagioclase laths occur together with these pseudomorphs and the feldspar is perfectly fresh. A typical section of the chilled sill shows calcite, pyroxene and plagioclase phenocrysts set in a microcrystalline ground mass of amphibole and feldspar. The plagioclase phenocrysts have a composition of about Ab_{40} which is more basic than those in the centre of the sill. This is what is expected in the circumstances, because of the zoning found within the feldspars of the central part of the sill. No doubt these zoned feldspars are of this composition near the middle of the grains representing the first precipitates of the original magma. Thus if the chilled sill is accepted as being fairly close to the original magma in composition, then the feldspar fraction, (labradorite) indicates a liquid of Ab_{80} composition using the Ab-An Phase diagram of Bowen (1912).

Accessories

Euhedra of magnetite are associated with the amphibole, generally in clusters of small opaque grains. Small amounts of chlorite occur interstially which is probably of deuteric origin.

The carbonate found in the chilled margins is not obvious in the coarser central parts of the dyke. These pseudomorphs are thought to be after amphibole phenocrysts but there is a possibility that they were originally olivine. Apatite occurs as prominent needles especially in the feldspar.

Petrogenesis of the Lamprophyric Sill

Using the classification of Rosenbusch (1887), the best terminology for this rock type is Camptonite, which has mineralogical affinities to the deep-seated alkaline rocks such as the sodic syenites. (Rosenbusch and Hatch, Wells and Wells), although Turner and Veerhoogen (1951) cast doubt on such a generalisation. Mineralogically the rock is basic with the development of andesine-labradorite, titanaugite and barkevikitic amphibole. Apatite and deuteric products such as chlorite, together with the carbonate pseudomorphs are almost identical to the standard descriptions of these rocks (see Turner and Verhoogen 1951, Hatch Wells and Wells 1952, Harker 1954). The panidiomorphic texture applied by Rosenbusch to these rocks is also very typical of the sill as is the lack of feldspar phenocrysts (except in the case of the chilled margin) noted by Harker. The pyroxene cores inside the barkevikitic amphiboles seem peculier to the Greenland rock for this feature is not mentioned in any of the standard descriptions.

The mode of origin of these rock types is in as much doubt as that of the trachyte and related dyke types. Bowen (1928) suggested that the rocks were due to the assimilation of biotite and amphibole by olivine basalt magma ensuing crystallisation and fractionation under varying conditions providing the various types. Another suggestion is that they originate in the differentiation of granitic magma (Tyrrell 1926) and others by the selective fusion of granitic rocks by olivine basalt (Turner and Verhoogen 1951). Camptonite was first named by Rosenbusch (1887) from Campton in New Hampshire. Other examples have been described from Central Ross, Warwickshire and Orkaey. A more recent detailed description of a camptonite is given by Campbell and Schenk (1950) from Arizona and the general problem of petrogenesis has been dealt with by Smith (1946).

The evidence of the chilled margin is probably the most reliable in formulating the evolution of the rock. In the chilled margins, the amphibole and pyroxene (the latter very difficult to identify) are microcrystalline together with the feldspar. However, there are large numbers of porphyritic plagioclase laths together with fewer pyroxene phenocrysts. The carbonate pseudomorphs may be after amphibole, but there is the possibility that they represent olivine.

The zoning developed within all themajor minerals together with the transition from titanaugite to barkevikite to a sodic rim lends strong support to the idea of differentiation. This latter fact especially, suggests that this differentiation sequence followed the established trend of pyroxene followed by amphibole, noted by Bowen (1928) for basaltic magma. The rock then crystallised essentially in place from a magma of unusual composition and there must have been a fairly quiet period to allow the differentiation sequence to take place. At the same time the cooling must have been rapid enough to prevent complete equilibrium to be reached, hence the zoning in the feldspars and amphibole.

Texturally, the feldspars appear to be later than the pyroxene-amphibole grains which are completely euhedral. The feldspars are however not anhedral and it seems that the major minerals were crystallising simultaneously with the crystallisation of amphiboles being completed first, the last residual liquid being feldspathic and acting as a final cement.

It is very difficult to evade the conclusion that the camptonitic sill is in some way related to the syenitic complexes in the adjoining regions. The field evidence suggests that the source area was to the south-west although this can hardly be proved conclusively. The sill has been shown to cut the oldest set of dolerite dykes which are older than many of the alkali dykes. Only one satisfactory exposure has been found in which the sill cuts a "hedrumitic" type and nowhere has it been seen to be faulted. The inference is therefore that the sill was intruded soon after or late in the alkali dyke sequence and presumably related to a similar source. The large dolerites in the south of the area all are younger than the lamprophyre and there are many localities in which this is well shown (see fig. 5.8).

Summary

A Camptonitic lamprophyre occurs in the region as a sill like body. Petrographically it is an andesine-titanaugite-barkevikite rock with a distinct zoning developed within the pyroxenes amphiboles and plagioclases. The pyroxenes are nearly always mantled by the amphiboles whose crystallisation was completed before that of the plagioclase. The initial composition of the plagioclase was Ab_{40} but the albite molecule increased as crystallisation progressed. The rock is shown to be close to the alkali dyke suite in age and it is suggested that it came from the same source material. Consolidation of a magma of unusual composition, involving the crystallisation of pyroxene-amphibole and plagioclase (in that order of final consolidation) took place under quiet conditions but fairly quickly so that zoning was preserved. The source magma, it is suggested, was of secondary origin itself due to the differentiation of a basic magma type.

The Petrography of the Dolerite Dykes

In general the dolerites are mineralogically simple, being composed of plagioclase, pyroxene and olivine. In some cases, olivine is absent, but this is apparently not consistent within a particular set of dykes having the same direction. Alteration of the dykes is common, particularly in the feldspars and olivines but the specimens from the large east-west dyke found within the township of Julianehaab and traceable across the peninsula are remarkably fresh. For this reason, the description of the rock type is based to a large extent on this particular dyke. The freshness is attributable to the fact that the specimens were collected from the debris of blasting operations within the township, the dykes themselves having a weathering zone which is wide and extremely difficult to penetrate.

In hand specimen the fresh rock (23358) is coarse grained holocrystalline and dark. Plates of black pyroxene up to 0.5 cm. across are easily seen but olivine is less conspicuous.

Plagioclase

Euhedral elongate laths of feldspar occasionally over 4 mm. in length dominates the matrix of the rock. In width, the grains reach about 0.5 mm. which is fairly constant irrespective of the length. The crystals are arranged randomly and together with the pyroxene make up a typical ophitic texture (fig. 9.15). Zoning although present is not strong except in isolated cases, where a normal type is developed. Twinning on combined Albite and Carlsbad laws is common and the composition estimated from sections normal to (010) is Ab_{46}(as measured on Universal stage). The crystallisation sequence appears to be clear, for euhedral plagioclase laths project into olivine clusters and pyroxene grains,and the pyroxene is invariably moulded around olivines, the latter frequently are found within the pyroxene grain (Fig. 9.16).

Alteration of the plagioclase is common, especially on the weathered surfaces of the dykes. In many of the dykes the feldspar is reduced to small muscovite flecks and sericite alteration, the twinning being obliterated.

Olivine

Completely anhedral, clear grains of olivine are prominent in these rocks. Individual grains rarely exceed 1 mm. across but there are larger masses composed of several smaller grains. In the freshest specimens (23400 from a blast site on the south-east outskirts of Julianehaab) the olivine is colourless with only small amounts of opaque material along cracks. Optic axial angle about nX is 73 - 78° (specimen 23358) depending on nY which was not obtained. The data of Poldervaart (1950) indicates that this has a composition of about Fa_{40-50} which is rather iron rich for an olivine from a dolerite. The uncorrected value for the optic axial angle is 79° and this would indicate a composition of Fa_{35}, which is still basic. Walker and Poldervaart (1949) found this composition in dolerites from the Karroo but in this particular case there was a variation from Fa_{30-50}.

The olivine and plagioclase appear to have crystallised almost contemporaneously for although occasional feldspars project into clusters of olivines none have been seen to penetrate olivine grains. The olivines tend to group together and isolated grains are rare.

The alteration of the olivine is complete in some of the dykes examined. The result is a secondary material in which at least three minerals can be distinguished. (Specimen 23310 is good example of this). In the centre of the irregular shaped masses a colourless to faint green mineral occurs. The birefringence is moderate, about second order blue, and the mineral consists of a large number of sub-parallel length slow elongate fibre which as a consequence do not extinguish uniformly. Occasionally around this colourless mineral a material with a light red brown to green pleochroism occurs which resembles biotite in many ways. The absorption direction parallel to the only cleavage is blue-green and at right angles to this is pale red brown. Extinction is straight and the birefringence moderate. No good interference figures could be obtained on this mineral.

The most prominent mineral of the three, normally rims the colourless type. It is strongly coloured in greens and is probably related to the pale brown type just described, although the birefringence is very low resembling that of chlorite. The mineral is almost uniaxial with a very small optic axial angle which is negative. Hence basal sections appear to be isotropic. Fig. 9.17 shows the typical development of the mineral aggregates, the individual units measuring less than 0.3 mm. across and closely packed together.

Pyroxene

Anhedral plates of clinopyroxene make up the dominant dark mineral in these rocks. Plagioclase and olivine project into the plates making up a typical poikolitic texture. The pyroxene, pale brown in thin section, is occasionally zoned (Fig. 9.18) and in the coarser portions of the dyke occurs in plates of over 16 sq.mm.

Specimen	nY	$2V_Z$
23358	1.697	48°
23333	--	45°

Specimen 23358 Dolerite from Julianehaab Township (10/066820)
Specimen 23333 Dolerite from west of Taserssuaq (10/032832)

Using the data of Hess (1949) this gives an estimate of the composition as Wo_{39} En_{38} Fs_{23} indicating a diopsidic augite.

In all the specimens, pyroxene remains fresh, a characteristic noted in the gabbros and norites further to the north.

Accessories

The dominant accessory is an opaque mineral which is probably ilmenite. This mineral occurs as a primary precipitate in unusual shaped skeletal grains (Fig. 9.19) which are up to 4 mm. across (Larger ones have been reported from adjacent areas). Around this ilmenite are flecks of red brown biotite which may have formed as the result of the reaction of the ilmenite with late stage acidic fractions. The reaction in which ilmenite and plagioclase produce biotite as a reaction rim has been noted by Brogger and also Tornebohm, the latter in connection with hyperites (norites).(Both reported in Shand 1945).

Modal analysis of dyke material from Julianehaab township is presented below. It can be seen that plagioclase is the dominant mineral, although the amount varies within the same dyke. Another interesting feature is the high percentage (by volume) of primary opaque material and the relationship of the biotite to it. In 23400 the percentage of biotite is 0.7% but in 23358, where the percentage of opaque material is lower there is also a significant drop in the biotite percentage. The ratio of pyroxene to olivine is fairly constant in the specimens examined, 1.4: 1 (23400) and 1.7:1(23358), the exsolved magnetite of the olivine is included within the olivine percentage.

Constituents	Volume Percentage	
	23358	23400
Plagioclase	53.3	65.9
Pyroxene	24.8	15.3
Olivine	14.7	10.9
Primary Ilmenite	4.5	7.0
Biotite	0.3	0.7
Alteration products	2.4	Tr.
	100.0	100.0

23358	Olivine dolerite, Julianehaab township (10/066820)
23400	Olivine dolerite, Julianehaab township (10/074816)

Petrogenesis of the Dolerite Dykes

Little need be said about these rock types for they have been described in great detail by numerous writers from all parts of the world. Most geologists are now agreed that they are the result of crystallisation of basaltic magma. The mineral assemblage, of basic plagioclase olivine and pyroxene indicates the "normal" crystallisation sequence expected from such a magma, and the banding observed in the largest of the dykes further supports crystallisation in place from a magma body. Zoning observed within the plagioclase and pyroxene is indicative of the conditions prevailing within the body at the time for although not strong there must have been a sufficient cooling rate or extraction rate to preserve the zoning. Optical values on the pyroxenes show that they are magnesium rich with a low iron content, but the olivines appear to be richer in iron.

The direction of the major dykes is consistently in an east-west direction, and it would appear to be a fair assumption that the dykes originated from the same source being injected into the country rock along a series of fractures which opened to accommodate the magma.

CHAPTER 10

The Alkali Feldspars.

Introduction.

The alkali feldspars have for some time been the topic of debate among mineralogists who were interested in their structure and phase relations from the standpoint of pure mineralogy, and petrologists who sought information on the thermal and chemical history of the rocks. Essentially they can be regarded as a solid solution series of the compounds $KAlSi_3O_8$ and $NaAlSi_3O_8$ here designated potash and soda feldspar respectively.

For the purpose of this account it is intended to give a review of the work done on the structure of the minerals identified as sanidine, orthoclase, adularia and microcline. In a later section, the varying theories of the phase relations of the minerals to the soda varieties will be discussed. This work commenced with the diagrams of Dittler early this century and more recently Bowen and Tuttle (1950) and Laves (1952) have contributed to the problem. The earlier reports will be dealt with briefly as most are purely speculative, but since 1950 data published from experimental work on artificial and natural glasses is more reliable. Structure and phase relations are dependent on each other and much of the information given in the first section applies directly to the understanding of the second.

The problems of composition determination are dealt with, especially from an X-ray point of view and such methods are shown to be reliable.

In the final section heating effects on the triclinicity of specimens is discussed together with the use of the minerals as geothermometers.

Polymorphism of the Potash Feldspars.[*1]

The debate about the structure of the minerals is principally concerned with the existence of several polymorphic forms, which although possessing the same chemical composition have varying physical characteristics, which Alling (1921, 1923, 1926) and Spencer (1937, 1938) have discussed in detail.

The polymorphic forms have been classified by Spencer (1937) and fig. 10.1 is his graphical presentation. It is remarkable that not only can these forms be subdivided on a physical basis but environmentally they are also distinct. Table 10.1 lists the varying characteristics of the types.

Table 10.1

Type.	Environment.
Sanidine	Volcanic tuffs and lava flows.
Orthoclase	Igneous and metamorphic rocks. *2
Adularia	Low temperature hydrothermal veins.
Microcline	Igneous and metamorphic rocks. *2

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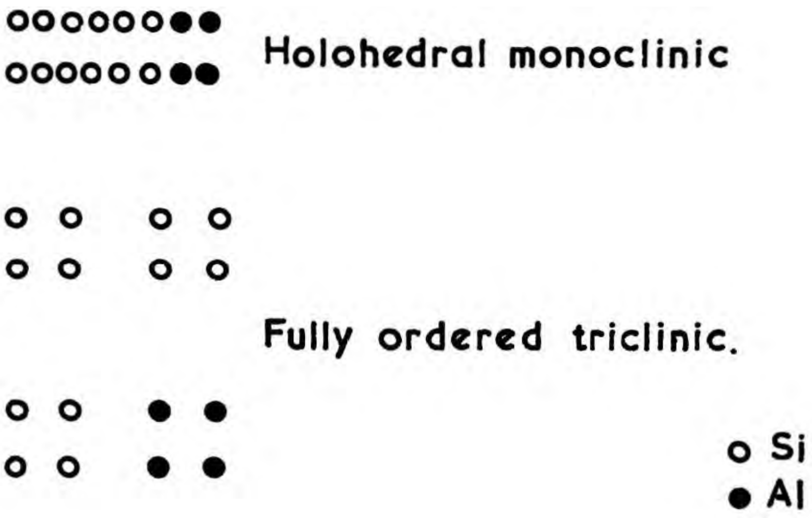
*1 A polymorph is a chemical compound with more than one crystalline form, or structure.

*2 The significance of microcline or orthoclase in these rocks is discussed later.

The real problem however hinges on whether all potash feldspars are triclinic or whether some are monoclinic. Fig. 10.2 illustrates the classical concept of the monoclinic orthoclase family and the triclinic microcline. Mallard (1876) believed that the feldspars under discussion were not polymorphous and suggested that the basic structure was triclinic. He explained the apparent monoclinicity of orthoclase and sanidine by suggesting that they consisted of regularly repeated triclinic individuals twinned on a submicroscopic scale. As a result of this they appeared optically homogeneous and of a higher symmetry. Mallard's hypothesis was immediately adopted by Michel Levy (1879) and recently has been used by Goldsmith and Laves (1954a) to explain orthoclase.

Alling's and Spencer's work however have shown that even though the idea is feasible, the variation in physical characteristics between microcline and sanidine suggests a fundamental difference. Spencer (1937, 1938) carried out experiments on a number of specimens in which the thermal reactions of monoclinic and triclinic forms were noted as well as differences in specific gravity and refractive indices. Taylor, Derbyshire and Strunz (1934) claimed that X-ray techniques showed that orthoclase was untwinned.

Taylor (1933) demonstrated for the first time the structure of the feldspars and pointed out that the monoclinic holohedral symmetry demanded by sanidine requires two eight-fold sets containing 16(Al and Si) atoms in the unit cell. In the potash feldspars there are 3 molecules of $KAlSi_3O_8$ per unit cell suggesting that instead of two eight-fold there are four four-fold sets, in which three contain 4 Si each and one with 4Al. He then pointed out that such an arrangement could only be triclinic or monoclinic hemihedral. This suggestion seemed to give added support to Mallard's hypothesis.



The relationship was explained by Barth (1934) who suggested that the four Al and twelve Si atoms are distributed randomly in orthoclase forming a monoclinic structure (with disorder) and in microcline the Al-Si atoms were fully ordered with the Al atoms segregated in a groups of four. This has come to be known as the "order-disorder" relationship which is related to the temperature of formation and cooling rate. We have here a fundamental principle which is of importance to the petrologist investigating the thermal history of acid and intermediate rocks.

Perhaps the best recent description of this order-disorder relationship is that by Barth (1959) who describes three end members of the potash structure. The first is the disordered monoclinic in which Al is distributed among the four-fold sets as 25, 25, 25, 25, (i.e. statistically 25% aluminium atoms in each set of atomic sites). Partly ordered monoclinic is second with a distribution pattern: 50, 50, 0, 0, and the third is the triclinic ordered member whose pattern is 0, 100, 0, 0.

The next step followed directly from this order-disorder concept and Goldsmith and Laves (1954a) showed that intermediate stages existed between fully ordered microcline and disordered sanidine. Orthoclase they considered could be regarded as one of the intermediate stages and perhaps was triclinic with apparent monoclinic symmetry due to the Mallard effect. Their views are summarised in fig. 10.3 (1954b).

Positive proof of order and disorder however was not forthcoming until a detailed investigation was carried out by Bailey and Taylor (1955). These workers used a microcline from Spencer's (1937) collection (specimen U) and demonstrated that it was partially ordered with respect to Al-Si over the tetrahedral sites whilst sanidine was fully disordered. Taylor and Bailey state that the evidence provides definite proof "... that the polymorphism of these two minerals is a result of an order-disorder relationship between Si and Al."

More recently Jones and Taylor (1960) have demonstrated that orthoclase shows partially ordered Si and Al and is very close to monoclinic symmetry, perhaps showing a slight deviation from it. This is in some measure support for the claim of Goldsmith and Laves (1954b) that orthoclase can be triclinic. Similarly Chaisson (1950) has shown that monoclinic and triclinic adularia can be distinguished optically. The evidence derived from this work suggests that adularia crystallises in the monoclinic form but in time gradually becomes triclinic the change taking place at the edges of the crystal and working inwards.

With these considerations in mind, namely that the polymorphism of the potash feldspars is a fact, that the differences in symmetry between sanidine and microcline are due to the different arrangement of Si and Al atoms in the lattice and that there exists a series of intermediate unstable states between the ordered and disordered minerals, we can proceed to discuss the phase differences within the alkali feldspars. Before doing so however it is of interest to note the work of Laves (1950). Laves demonstrated through work on the twin relations of the microclines that such a complex arrangement could only be explained by an initial crystallisation of a monoclinic crystal with a later transition to triclinic symmetry. Stated summarily by Goldsmith and Laves (1954b) "The great majority of microclines show the combination albite-pericline cross hatching with geometric relations such that twinning can be accounted for by inversion but not by growth" (p. 111). This additional evidence for the existence of the two end members (microcline and sanidine) with all the intermediate relations is a good introduction to the study of the phase relations within the alkali feldspars.

Phase Relations of the Alkali Feldspars.

As has been summarised in the preceeding section the existence of several polymorphic states within the potash feldspars is now generally acknowledged by mineralogists.

The varieties containing sodium are also of interest in this respect. Experimental work by Schairer and Bowen (1935), Bowen and Tuttle (1950) showed that at high temperatures there was complete miscibility between the two end members $KAlSi_3O_8$ and $NaAlSi_3O_8$. This solid solution series could be preserved in artificial glass mixtures by rapid cooling. In most natural feldspar crystals it appears that this miscibility does not exist within the general range of $Or_{80}\,Ab_{20}$- Or_5Ab_{95}, for within this range perthites are formed. Optically homogeneous feldspars within this range have been shown, using X-rays, to be cryptoperthites, i.e. submicroscopic albite lamellae in a potash host. We have here the basis for phase diagrams of the alkali feldspars series. Early workers, limited by the absence of experimental facilities were forced to use intuition together with obervational data. Dittler (1912) suggested that miscibility existed at high temperatures but was obviously unaware of the immiscibility at lower temperatures. Fig. 10.4 is a compendium of phase diagrams suggested for the system. Makinen (1917) has published a diagram in which the solvus is represented at a temperature of about 700°C. Winchel (1925, 1951) suggests that the solvus is higher and Oftedahl (1948) shows a solvus at a maximum of 800°C. It was not until the work of Bowen and Tuttle (1950) that reliable quantitative experimental results were published together with a proposed phase diagram. This diagram is reproduced as part of fig. 10.4. The work was carried out on artificial glass using the X-ray ($\bar{2}01$) technique to determine the composition of the two unmixed phases. They demonstrated that at normal pressure the top of the solvus occurs at about 650°C for a composition of $Ab_{55}Or_{45}$. By holding the crystals at progressively lower temperatures they were able to obtain the composition of the two phases and hence draw in the solvus. Here was experimental proof of a possible origin for perthites. Bowen and Tuttle (1950) also demonstrated that with increasing water pressure the solidus and liquidus curve became lower. Yoder et al (1957) demonstrated that at 5000 bars water pressure the solidus intersects the solvus. Fig. 10.5 which shows this phenonenon, is of great petrological importance for this indicates that two feldspars can crystallise out simultaneously.

Symmetry Change in the Solid Solution Series.

The acknowledgement that sanidine is monoclinic was witheld by many because of the necessity of a symmetry change from monoclinic to triclinic when approaching the albite end of the series. Bowen and Tuttle's (1950) straight line graph of the shift in $d(\bar{2}01)$ with composition (fig. 10.6) shows no obvious breaks which would indicate where the change had occurred. As Laves (1952) rightly points out this can be easily explained as $d(\bar{2}01)$ is governed by the "a" and "c" axes and the angle β. Any change in the α or γ (those angles which deviate from 90° in a triclinic mineral) do not affect this spacing. Laves (1952) described the transition from monoclinic to triclinic and stated that it was a function of temperature. At 0°C the transition occurred at $Or_{40}Ab_{60}$ whilst at 16°C the composition was $Or_{35}Ab_{65}$. This was primarily accomplished using crystals of known composition and progressively plotting the extinction angles as the temperature increased (see fig. 10.7). On reaching the monoclinic state the extinction against (010) on the (001) face becomes 0°. Laves found on extrapolation, that this line met the pure albite composition before reaching the solidus, which meant that there was a monoclinic variety of albite. Since no monoclinic albite had been reported (except the discredited Barbierite) he suggested the line must curve and meet the solidus first. Fig. 10.8 demonstrates the type of phase change involved. This was obviously a case of making the facts fit the ideas, for in the same year MacKenzie (1952) demonstrated the existence of a monoclinic albite, which was metastable and which could not be preserved even by rapid quenching. (Schneider and Laves (1957) have proposed the name of Monalbite for this monoclinic modification of albite). MacKenzie (1952) using synthetic materials produced a curve similar to that of Laves. It is interesting to note that MacKenzie used diffractometer charts and optical methods which utilised the disappearance of albite twinning, whilst Laves obtained similar results with single crystal ray photographs and extinction angles.

Discussion of the Proposed Phase Diagrams.

The problem of phase relations was enlarged by Bowen and Tuttle (1950b) who demonstrated the existence of High albite which although triclinic possessed different X-ray and optical properties to albite. Having produced the material from synthetic glasses it was soon apparent that the discrepancies in the optics of the plagioclase feldspars which had been mentioned several times in the literature was due to a natural high temperature plagioclase. Kohler (1941) and Oftedahl (1948) had already previously suggested the existence of high-low feldspar relationships.

As a further complication Laves (1952) named the high albite, analbite, thus reviving an old name. The suggested divisions within the group are demonstrated in fig. 10.8 (from Laves p.561). This diagram summarises Laves views on the phase relations within the alkali feldspar group. An interesting feature of the diagram is the suggestion that near the inversion point complete solid solution exists between microcline and albite.

The phase transition microcline sanidine has now been placed at 500°C by Goldsmith and Laves (1954a). This value was derived by hydrothermal experiments on a microcline to determine when the triclinicity reached 0. From this it would appear that Laves has modified his original phase diagram so that the transition line, instead of being horizontal now rises from about 500°C at the potash end to 700°C at the albite end.

Part of the solvus has been redetermined by Smith and MacKenzie (1958) using single crystal X-ray methods on a natural sodium rich cryptoperthite. This is reproduced as fig. 10.9.

The most recent phase diagram for this region is that published by Rao (1959). Where Laves' (1952) diagram is reproduced but with the analbite field moved across the transition line into the field of monoclinic symmetry (in contradistinction to Laves own definition of that mineral), whilst in his own diagram he replaces it as a triclinic modification. Fig. 10.10 is the Laves diagram after Rao and fig. 10.11 is the phase diagram of Rao.

Rao who heated various mixtures of natural microcline and albite found that mixtures between $Or_{70}Ab_{30}$ to $Ab_{90}Or_{10}$ could not be fully homogenised, even after periods longer than 96 hours at 1o25°C (unspecified time). He therefore proposed that there was a reaction barrier for these compositional limits which prevented homogenisation. This barrier he suggested was the order-disorder potential barrier with respect to Al and Si, the ordered albite-microcline could not pass into a homogeneous mixture with appreciable disorder.

The observational fact that non-perthitic feldspars with Or_{50} Ab_{50} are rare or absent is reaffirmed by Rao. Laves' diagram suggests that it is possible to have a micfocline with such a composition (however it would be an intermediate microcline) but the geological environment to produce it would be extremely rare. It may be with the increasing realisation of the importance of the minerals that the scanty evidence will be supplemented. Of the twelve feldspars investigated in the present study, only two were found to be within the Ab_{30-90} region, and this only after homogenisation. It is significant however that they did homogenise and also crossed the phase boundary into the monoclinic field. The specimens are discussed elsewhere in detail, but suffice to say here that they do occur in the field in which Rao claims that the reaction barrier exists. It thus appears that the problem is not as straight-forward as Rao envisaged. Moreover the petrologist would consider that the subject has been tackled from the wrong end of the temperature scale. The information as to whether artificial mixtures of natural minerals will homogenise at 1050°C is not directly relevant to the genesis of the rock. The important point is that alkali feldspars of bulk composition Ab_{30-90} do exist, are fairly common and can be homogenised.

In an effort to determine why these mixtures had not homogenised at the temperature and time stated, the present writer has attempted to estimate the composition of the various phases produced by Rao from the $d(\bar{2}01)$ spacings given by him. (The technique used is described in a following Section). Table 10.2 gives the 2θ values for the $d(\bar{2}01)$ spacings (assuming Cu radiation was used) with the estimated compositions of the homogenised and where appropriate, co-existing phases.

Table 10.2

Table to show approximate composition of feldspar mixtures.
(Data from Rao 1959)

Mixture	2θ Potash	2θ Albite	Comp. %Or	Comp. %Ab.
100:0	21.06	Absent	100?	--
90.10	21.28	Absent	69	--
80.20	21.30	Absent	66	--
70.30	21.32	Faint Peak	64	--
60.40	21.37	21.84	57	86
50.50	21.40	21.89	55	90
40.60	21.47	21.92	48	93
30.70	21.50	21.98	46	98
20.80	21.50	21.98	46	98
10.90	Absent	21.98	--	98
0.100	Absent	22.01	--	100

As no internal standard was used, it is difficult to work out the composition of the individual phases with any accuracy. Thus the 100% albite does not correlate unless it is assumed that the heating has produced a high albite. Consequently the compositions quoted here for the various phases cannot be regarded as being accurate but they are useful in that they give a general picture of the homogenisation pattern.

From the values in table 10.2 it will be observed that on heating microcline with as little as 10% albite, the bulk composition drops to about 70% . When the reverse is carried out i.e. 90% of albite + 10% of microcline the effect on the albite is slight, indeed as much as 30% of the microcline molecule makes little impression on the bulk composition of the albite phase.

It appears to the present writer that there are two dominant factors affecting the experiments of Rao. The first is that the microcline used in the experiments was not pure but contained some cryptoperthitic albite. This would explain the discrepancy in the value stated by Rao and the composition derived by X-ray. If this is so, then a small amount of heat for a short period would be sufficient to homogenise the cryptoperthite causing the radical change in composition of the microcline observed by Rao. This problem of homogenisation brings us to the second factor which is the more important. It is an acknowledged fact that homogenisation of microcline containing coarse perthite lamellae (vein perthites) is a much more difficult process than the homogenisation of cryptoperthites. Thus it is conceivable that an artificial union of albite and microcline will taken even longer owing to the lack of sufficient contact planes. Consequently it appears that the time allowed by Rao for homogenisation has not been long enough, especially for those mixtures in which more albite has to be introduced into the microcline lattice. It may be that a higher temperature than 1050°C is necessary to effect homogenisation of more albitic mixtures. (Goldsmith and Laves (1954a) have shown the water vapour can have a strong effect on the sanidinisation of microcline at temperature below 700°C. It is probable that homogenisation would also be assisted under such conditions). It is apparent that the stable composition of the albite phase on progressive addition of microcline observed in Rao's values is due to this non-homogenisation affect. The absence of the microcline line in the powder photograph of these mixtures is not surprising, for work on the Greenland material has shown that heating for a few hours is sufficicent to cause the disappearance of the d($\bar{2}01$) line of the exsolved phase. Continued heating up to 200 hours however still causes the d($\bar{2}01$) of the other phase to shift indicating that homogenisation is still progressing.

Bearing these points in mind on Rao's work it appears to the present writer that the most reliable phase diagram yet published is that of Laves (fig.10.8) with modifications to the microcline-sanidine transition line suggested by Goldsmith and Laves (1954a). The results of the present investigation have been used in the construction of another diagram which is discussed in a later section.

Having thus reviewed the present state of phase diagrams in the alkali feldspars it is advisable to mention current usage of terms. Table 10.3 tabulates the main mineral types.

Table 10.3.

Nomenclature of the Alkali Feldspars.

Type	Symmetry	Temp. State	
High Sanidine	Mono.	High	Optic axial plane parallel to (010)
Sanidine	Mono.	High	
Orthoclase	Mono-Tri?	Interm.	Also group name.
Adularia	Mono-Tri.	Low	Originally mono.
Microcline	Tri.	Low.	
Analbite	Tri.	High	High Albite.
Monalbite	Mono.	High	Not natural.
Albite	Tri.	Low	
Anorthoclase	Tri.	Low?	Vaguely defined. Ab_{67-82} (Rosenbusch)

Determination of the Composition of the Alkali Feldspars.

The two methods of determining composition of these feldspars available to the writer were chemical and the X-ray methods. (Both X-ray diffractometer and film recording). The single crystal X-ray method devised by Smith and MacKenzie (1955) was not readily applicable to the available material.

The advent of the X-ray powder method of determining the chemical composition of these feldspars has made the problem of work on the minerals easier. The main contributors to this work have been Bowen and Tuttle (1950) who published a straight line graph showing the change in the d($\bar{2}01$) of these feldspars with composition. (Fig. 10.6). A total of 15 specimens was used for this determination. The specimens were of artificial glass crystallised under water pressure and possessing high temperature characteristics. The d($\bar{2}$01) spacing was correlated with the d(10$\bar{1}$0) of quartz known to occur at 4.2549Å. This graph has since been criticised by Laves (1952), Coombs (1952) MacKenzie and Smith (1956), Smith and MacKenzie (1958) as giving inaccurate results. In any case the graph is not readily applicable to the microclines separated from the Julianehaab granites as it applies only to those feldspars with high temperature characteristics. This could be overcome by the conversion of the microclines to their high temperature form, viz: sanidine, but it has long been thought that this would take several weeks at temperatures close to the melting point, under dry conditions. In this connection alone there seems to be different results from various workers. Spencer (1937) reported that after heating for 300 hours at 1075°C, microclines U and V * had axial planes in the high sanidine position with a small optic axial angle. He also reports the results of Makinen who could not destroy the cross hatch twinning on prolonged heating of the feldspar near the melting point. Dittler and Kohler reported a disappearance of the twinning after 500-700 hours at 1000°C after which the mineral was still triclinic. More recently Goldsmith and Laves (1954a) heated a microcline which was virtually soda free. They showed that after 720 hours at 1050°C it became monoclinic. However as far as the microcline specimens collected by the writer are concerned, heating for close to 700 hours at 1050°C produced no substantial movement toward the monoclinic form

* Specimens used by Spencer were lettered.

and the material retained its characteristic cross hatch twinning. This question will be discussed more fully when the Greenland material is considered more specifically.

From the work on the Greenland material, the data published by Spencer (1957) and Goldsmith and Laves (1954a) there appears to be no set temperature-time conditions to produce a monoclinic alkali feldspar from microcline. It is obvious that the material used by the writer shows much greater resistance to heat than does specimens "U" and "V" of Spencer and the Swiss microcline described by Goldsmith and Laves.

The Results of Chemical and Optical Studies on the Greenland Feldspars.

It is apparent from the previous section that attempts to convert the microclines to their high temperature forms in order to obtain their composition from Bowen and Tuttle's graph (fig. 10.6) would be extremely time consuming and perhaps fruitless. Consequently it was decided that the best method would be to separate out the microclines from the granites for chemical analysis. The technique used for the separation is described in the appendix (section 2). The purity obtained by this method is considered to be better than 99.5% as quartz is eliminated and only small quantities of non-perthitic plagioclase occur. In this connection the X-ray diffractometer was useful in the detection of impurities.

Mid-way through the task of separation and analysis Orville (1960b) published data on the 2θ ($\bar{2}01$) spacings for microclines. The same worker had already improved on the graph of Bowen and Tuttle (1950) by using $KBrO_3$ as an internal standard for the high temperature alkali feldspars. (Orville 1958). $KBrO_3$ having a 2θ of 20.205° is an improvement on quartz as it does not mask the $d(\bar{2}01)$ line of the potash rich types. Thus there was here a good opportunity to check the accuracy of the chemical analysis of the microclines against the values obtained using the figures published by Orville.

The specimens chosen for the study from the Julianehaab rocks are shown in Table 10.4.

Table 10.4.

Rock types from which Alkali Feldspar extractions have been analysed.

23492	Porphyritic Granite, south edge of Gneiss Band.
23805	Porphyritic Granite (Julianehaab Colony).
23877	Sanerutian Granite.
42888	Porphyritic Granite.
42888P	Porphyritic Granite (phenocrysts only).
42896	Microgranodiorite.
43062	Porphyritic Aplitic Granite.
43063	Euhedral Phenocryst Granite.
43064	Euhedral Phenocryst Granite.
43069	Porphyritic Granite from Alangorsuak Peninsula.

Rock 42888 was sampled twice, the first being the bulk analysis of all the alkali feldspar, the second only the phenocrysts. This afforded a good opportunity to test whether there was any significant differences in the two. Of the remaining samples one is from a trachyandesite dyke [23409] and the other from a hybrid dioritic gneiss, [23848] neither of which have been chemically analysed.

Partial analysis of the alkali feldspars from the granites was carried out. The percentages of the Na_2O and

K_2O for these microclines have been recalculated to give molecular percentage orthoclase and albite molecule. The percentage of anorthite (derived by subtraction) was in no case greater than 3½% amounting to 0.8% CaO in the original feldspar. Unfortunately the amount of material available for analysis was insufficient to analyse each specimen twice. Two repeat analyses were carried out on the phenocryst 42888 and 43064. The average difference for K_2O was 0.3% and for Na_2O 0.06%. This means that the expected error when recalculated to percentage Or is less than ± 2% and percentage Ab less than ± 1%. The results of the chemical analysis of the ten feldspars are shown in Table 10.5.

Table 10.5.

Chemical analysis results on ten alkali feldspars.

Specimen	%K_2O	%Na_2O	% Or	% Ab	Total
23492	14.2	1.70	83.70	14.40	98.10
23805	14.96	1.27	88.26	10.73	98.99
23877	13.92	1.65	82.00	13.94	96.06
42888	14.90	1.06	87.91	8.95	96.86
42888P	13.57	1.97	80.06	16.60	96.66
42896	14.85	1.24	87.49	10.47	97.96
43062	13.71	1.85	80.89	15.67	96.56
43063	13.62	1.96	80.35	16.56	96.91
43064	13.57	2.15	80.06	18.08	98.14
43069	13.83	1.84	81.59	15.54	97.13

Optic axial measurements on these specimens are as follows:

	$2V_x$ °
23409	48 - 59
23492	79
23848	--
23805	85
23877	79
42888	78
42888P	--
42896	81
43062	81
43063	77 - 79
43064	84
43069	88

No refractive indices have been determined for these minerals as it was considered that the accuracy of determinations would not be great enough to differentiate the small changes in indices within the group.

Fig. 10.12 and fig. 10.13 illustrate in block diagram form the principal twin directions and optical orientations within the microclines.

Fig. 10.14 shows the optical axial angle measurements (made on the Universal stage) plotted against composition on the modified diagram of Tuttle (1952) after Emeleus and Smith (1959). The specimens from the granites fall at the microcline end of the Low-albite - Microcline Series. Specimen 23409 occurs midway between the Orthoclase - Low albite and Low sanidine - High albite series. Unfortunately the optic axial angle for 23848 is not available.

X-ray Procedure for the Estimation of Alkalis in the Alkali Feldspars.

This procedure is based on the values for mixtures of pure microcline and albite (both low temperature phases) published by Orville (1960). These values are reproduced below in Table 10.6.

Table 10.6

Values for 2θ(201) Feldspar - 2θ(101) $KBrO_3$ for mixtures of microcline and albite (After Orville 1960b) and Sanidine.

Mixture.	Microcline.	Sanidine.
Or_{100}	0.77°	0.74°
Or_{90} Ab_{10}	0.87	0.84
Or_{80} Ab_{20}	0.96	0.94
Or_{70} Ab_{30}	1.06	1.04

The microcline was produced by ion-exchange between natural microcline perthite and molten KCl at 900°C (Wyart and Sabatier 1957). The Na bearing feldspar was formed by dry homogenisation at 1050°C of weighed mixtures of this microcline and a natural low albite.

These figures reproduced in graph form in fig. 10.15 which shows the Sanidine-High Albite line of Orville using $KBrO_3$ as the internal standard, the Microcline line and its projections. It will be seen that the projection line of the microcline curve falls below the Sanidine-High Albite line whereas the value of Low Albite (Smith 1956) is above this line. This means that the graph for Microcline-Low Albite is not linear. The point is actually not an important one for as has been pointed out by several workers (e.g. Rao 1959) there are very few if any known microclines in which there is over 30% Na feldspar in solid solution. It would be of interest to know however the difference between 2θ(201) of the feldspar and the $2\theta(101)$ of the $KBrO_3$ * values for feldspars at the albite end of the low temperature series. On the graph this low albite line is projected as a straight line but this is purely speculative for there are as yet no published data on this range.

Technique. The method of preparing specimens is described in the appendix suffice to say that a small amount of feldspar is ground together with $KBrO_3$ (In this case Analar $KBrO_3$ was used). The settings on the Phillips X-ray Diffractometer with a PW1010 source unit and the PW1050 X-ray goniometer were as follows: CuK radiation, 40 kV, 20 mA, goniometer scanning speed ½°/ min., divergence and scatter slits 1°, receiving slit .1°, chart speed 400 mm./ hr.. Time constant 8 x 1, Rate meter 4.

Generally the material is X-rayed without the internal standard, scanning from 2θ 20° to 34°. This avoids the masking of the 131 couplet by the (110) of the $KBrO_3$ at about 2θ 29.7°. For the measurement of the alkali content of the mineral the standard is then added to the mount and the machine is set to oscillate between 2θ 20° - 22°. This angle takes in the d(101) of the internal standard and the d($\bar{2}01$) of both the potash and soda feldspars. Any quartz in the mixture is also detected within this range. Table 10.7 lists the 2θ values of $KBrO_3$ and Quartz, taken from the A.S.T.M. index. The spacings have been converted to 2θ values for copper radiation using the filter charts of Parrish

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* From now on quoted as $D2\theta$ values.

and Irwin (1953).

Table 10.7.

2θ values for Quartz and Potassium Bromate.

Quartz			Potassium Bromate		
2θ	I/I_1	hkl	2θ	I/I_1	hkl
20.84	35	100	20.205	60	101
26.68	100	101	27.8	100	012
35.56	12	110	29.7	70	110
42.48	9	200	32.93	10	003
			41.10	49	202

The charts for the feldspars used in this study were indexed using the values of Donnay and Donnay (1952) Goldsmith and Laves (1954) and Smith (1956). The values for microcline given by Goldsmith and Laves were quoted as "d" spacings for Fe radiation. These have been converted to 2θ for Cu radiation. The High Albite values quoted by Donnay and Donnay have been questioned by Smith who has repeated their measnrements. He found that there was on average a difference of plus .025° between his values of heated Amelia Albite and the synthetic glasses of Donnay and Donnay. He attributed this to the fact that the quartz standard of the earlier workers had not been used as an internal standard but had been measured separately. This seems to be a valid criticism although Smith does not appear to have considered the fact that synthetic albite may have a different lattice to the heated Amelia Albite. For the sake of completeness, both Smith's and Donnay and Donnay's values for High Albite are given in Table 10.8. Donnay and Donnay values are quoted for the artificial glass mixtures of the soda rich feldspars, whilst microcline values are taken from Goldsmith and Laves

(1954). The sanidine (synthetic glass) values are those of Donnay and Donnay and the natural albite that of Smith (1956).

Table 10.8.

Values of 2θ for the varieties of Alkali feldspars.

Sanidine $KAlSi_3O_8$

2θ	q	hkl
20.945	8	$\bar{2}01$
22.52	3	111
23.475	10	130
24.57	4	$13\bar{1}$
25.75	8	$11\bar{2}$
26.79	9	220
27.13	9	$20\bar{2}$
27.35	6	040
27.66	10	002
29.79	8	131

Microcline $KAlSi_3O_8$

2θ	q	hkl
21.12	6	$\bar{2}01$
22.22	3	111
22.63	1	$1\bar{1}1$
23.20	5	130
23.89	4	$1\bar{3}0$
24.42	1	$13\bar{1}$
24.83	2	$\bar{1}31$
27.45	10	$\bar{2}21$, $\bar{1}12$
26.46	5	220
27.08	4	$20\bar{2}$
27.45	10	$2\bar{2}0$,040,002
29.52	5	131
30.10	5	$1\bar{3}1$

Heated Amelia Albite
$NaAlSi_3O_8$

2θ	q	hkl
22.00	60	$\bar{2}01$
22.915	40	$1\bar{1}1$
23.730	100	$1\bar{3}0$
24.46	35	130
25.630	15	$11\bar{2}$
26.445	25	$\bar{1}12$
27.785	160	040
28.095	360	002
28.525	40	220
29.620	25	$1\bar{3}1$
30.295	30	$04\bar{1}$
30.540	35	$02\bar{2}$
31.610	35	131

Low Albite (Amelia)
$NaAlSi_3O_8$

2θ	q	hkl
22.057	60	$\bar{2}01$
23.070	20	$1\bar{1}1$
23.538	85	111
24.155	70	130
24.306	50	$13\bar{1}$
25.392	35	$11\bar{2}$
25.570	5	$\bar{2}21$
26.418	20	$\bar{1}12$
27.915	360	002
28.325	30	$2\bar{2}0$
30.148	30	$1\bar{3}1$
30.480	50	$02\bar{2}$
31.210	20	131

Table 10.8
(cont.)

Synthetic Albite (High Albite)

2θ	q	hkl
21.975	10	$20\bar{1}$
22.445	8	$1\underline{3}0$
22.870	7	$1\underline{1}1$
23.70	10	$13\underline{0}$
25.71	2	$1\underline{12}$
26.45	2	112
27.77	10	040
28.05	10	002
28.515	9	$2\underline{2}0$
29.57	3	131
31.55		$1\underline{31}$
to	4	$22\underline{2}$
31.63		132

$Na_{.61}\ K_{.39}\ AlSi_3O_8$

2θ	q	hkl
21.58	10	$20\bar{1}$
22.92	8	111
23.75	10	$13\underline{0}$
24.73	1	$13\underline{1}$
25.80	7	112
27.49	10	$20\bar{2}$
27.77	10	002
30.14	6	$13\underline{1}$
30.72		222
to		
30.90		041

$Na_{.71}\ K_{.29}\ AlSi_3O_8$

2θ	q	hkl
21.715	10	$2\underline{0}\bar{1}$
22.87	4	111
23.19	4	$1\underline{1}1$
23.71	10	130
23.95 to	8	200
24.01		$13\underline{0}$
24.625	1	$13\underline{1}$
25.715	4	112
26.005	5	$1\underline{1}2$
27.565	10	220, 040, $20\bar{2}$
27.84	10	$0\underline{0}2$
29.90	1	131
30.64	3	131

The (101) peak of $KBrO_3$ and the ($\bar{2}01$) of the feldspar were scanned at least four times, twice from low to high and twice in the reverse fashion.

The D2θ values obtained with the estimation of the percentage of the microcline molecule and the albite molecule are given below in Table 10.9. In some cases the ($\bar{2}01$) of the albite phase is not detected, either because it is not present or more commonly because of the masking affect of the d(111) of the microcline. In the case of masking an estimate can be made of its position by the small peak on the slope of the d(111). The estimation of the albite phase is made on the assumption that the values from 100 - 90% Albite decrease in a linear manner from the 2θ 22.057° of pure Albite, toward microcline. (See fig. 10.15 which shows the various graphs on one sheet).

Table 10.9

D2θ and composition for 12 Alkali Feldspars.

Specimen	D2θ Potash phase	Comp. % Or.	D2θ Soda phase	Comp. % Or.
23409	0.845 sharp (Orth.)	90.5	1.80 medium	5
23848	Obscured		1.815 sharp	3
23492	0.85 sharp	92	1.77 small	7
23805	.865 sharp	90	masked ca. 1.85	0
23877	.81 sharp	95	masked ca. 1.87	0
42888	.83 sharp	94	1.84 sharp	1
42888P	.82 sharp	95	not observed	
42896	.805 sharp	96	obscured	
43062	.82 sharp	95	1.935	0
43063	.815 sharp	95.5	obscured	
43064	.86 sharp	91	1.90	0
43069	.82 sharp	95	1.82	3

It is noteworthy that both phases within the alkali feldspar, namely the potash and soda phases are relatively pure carrying only small amounts of the other in solid solution, for this has a direct bearing on the phase diagram. This is a common feature of these feldspars and as stated earlier, potash phases carrying over 30% Albite in solid solution are rare. The fact that the albite phase carries little or no potash in solid solution fits well the $KAlSi_3O_8$ - $NaAlSi_3O_8$ diagram of Bowen and Tuttle (1950) (fig. 10.4) for the limb of the solvus is very steep at the albite end so that there is little change of composition as the temperature decreases. The potash end of the solvus is not so steep and consequently with increasing temperature more of the albite molecule can enter into the lattice.

In an effort to obtain the bulk composition of the minerals an attempt was made at homogenisation. The specimens were heated in a tube furnace at 1050°C ± 20°C for varying periods of time.

The heating was carried out at normal pressure and it was thought that 48hrs. would be sufficient to homogenise the specimens. After 48hrs. the $d(\bar{2}01)$ albite line had disappeared but heating was carried out for longer periods to establish that the material was homogeneous and also to discover whether the microclines could be converted to the sanidine phase. This problem is dealt with more fully when the question of homogenisation rates and symmetry changes is discussed.

It was found that after about 160 hours at above 1050°C most specimens were homogenised, some however required over 200 hours. It very soon became obvious that the length of time required varied with each specimen. The difference between $2\theta(\bar{2}01)$ for feldspar and $2\theta(101)$ potassium bromate was then measured and the estimated percentage of potash feldspar read off from the Orville curve (1960b). Table 10.10 gives these values against those obtained by chemical analysis of the same material.

Table 10.10

Chemical composition derived from X-ray analysis compared with that obtained from chemical analysis.

Specimen	Heating time (hours)	$D2\theta$ value	%Potash Feld. Mol. X-ray method	%Potash Feld. Mol. Chemical method	Difference
23409	76*	1.38	37	not determined	...
23492	404	.945	81.5	83.7	-2.2%
23848	36	1.25	51.0	not determined	...
23805	404	.88	88.5	88.2	+0.3%
23877	404	.93	83.5	82.0	+1.5%
42888	$214\frac{1}{2}$	.895	87.0	87.9	-0.9%
42888P	$382\frac{1}{2}$	.95	81.0	81.0	0.0%
42896	$214\frac{1}{2}$	.90	86.5	87.5	-1.0%
43062	279	.965	79.5	81.0	-1.5%
43063	168	.95	81.0	80.3	+0.7%
43064	$214\frac{1}{2}$	.96	80.0	80.0	0.0%
43069	$214\frac{1}{2}$	.93	83.5	82.0	+1.5%

(* Heated 76 hrs. at 800°C as it is a high temperature form.)

This data is reproduced as a graph fig. 10.16 in which the values obtained from X-ray techniques are plotted against those derived from chemical analysis.

From fig. 10.16 and table 10.10 it will be seen that the variation between the two methods is in the ± 2%

range. There is a slight bias for the X-ray method to give values less than the chemical one and this is perhaps attributable to the non-homogenisation of the specimens. The essential point remains that the figures published by Orville for microclines agree within the limit of experimental error with the results obtained from the Greenland material. Fig. 10.17 is a plot of the D2θ values obtained on the homogenised specimens against the results of chemical analysis. From this curve, any D2θ values against composition can be derived. Table 10.11 shows the values obtained from this curve against 100%, 90%, 80% and 70% Or composition. In the same table are reproduced the values of Orville.

Table 10.11

Table of the D2θ values obtained from Fig. 10.27 compared with the values obtained by Orville.

	D2θ values	
Microcline	Present Author	Orville
Or_{100}	.785	.77
Or_{90}	.87	.87
Or_{80}	.96	.96
Or_{70}	1.05	1.06

As can be seen from table 10.11 the values derived here are close to those of Orville so that it seems that results of X-ray analysis on low temperature alkali feldspars can be quoted with confidence. The work carried out on the Greenland microclines shows that the values published by Orville are reliable and chemical composition derived from them are at least as accurate as results obtained by flame photometry.

X-ray Diffraction Charts.

Fig. 10.18 shows a typical X-ray diffraction chart of an unheated alkali feldspar (42896), obtained with Cu radiation (the settings are described elsewhere). As the technique of X-ray analysis of these feldspars has been discussed it is worthwhile describing the features of the chart as an aid to the identification of the various phases present. The principle 2θ spacings of microcline, sandine, low albite, analbite and feldspars of intermediate composition are listed in table 10.8.

The main feature to notice is the masking of the $(\bar{2}01)$ of albite by the d(111) of microcline. The albite line moves into that of the microcline as the percentage of the albite molecule increases, so that the masking becomes complete.

At about 2θ 23.5° a small peak is seen in all the microcline specimens collected from the area under discussion. This occurs between d(130) and d$(1\bar{3}0)$ of the microcline. Such a peak has been described by MacKenzie (1954) as the d(130) of orthoclase in the specimens with which he was concerned. If this is applicable to the Greenland microclines then it is surprising to find orthoclase in a microcline with almost maximum triclinicity. On heating, the peak disappears and the most logical explanation is that the peak is in fact the d(111) of albite. If it had been orthoclase then the intensity should have increased on heating because of increasing disorder. Evidence in support of this conclusion is a very strong peak at about 2θ 27.9° which is the d(002) of albite. MacKenzie (1954) states that 2% of albite is sufficient to produce this strong line.

At 2θ 25.54 there is a peak which does not belong to either albite or potash feldspar. This is interpreted as being due to plagioclase impurities. The presence of quartz is indicated by a peak at 2θ 26.68° but caution must be exercised as one of the albite lines is close to this. A peak at about 2θ 20.85° together with the peak at 2θ-26.68° is good evidence for the presence of quartz.

As the sample was presented as a smear mount, the intensities of similar peaks in different charts cannot be correlated owing to the varying quality of the smear.

Table 10.12 lists the 2θ spacings of the feldspars used in this investigations. These spacings have been corrected relative to the d(101) peak of potassium bromate at 2θ 20.205°. The material was first scanned without the standard from 2θ 20.0° to 31.0°. Then the range 2θ 20.0° to 21.5° was scanned at least four times using the oscillating device, when the bromate had been added and the difference between 2θ(201) feldspar - 2θ(101)$KBrO_3$ noted. From this the correct value of the feldspar peak was deduced and this correction was then applied to all the peaks.

In order to bring out the smaller but important lines it was necessary to allow the stronger peaks to go off the top of the chart. In table 10.12 this is expressed as

*Table 10.12

20 values obtained on Greenland Feldspars,
natural and after heating.

23409. Trachyandesite dyke.

Natural				Heated 76 hours at 800°C			
2θ	I	q	d	2θ	I	q	d
21.04	45	s	$20\bar{1}$	21.59	51	s	$20\bar{1}$
22.04	56	m	$20\bar{1}$	22.90	53	s	111
23.64	61	mp	$13\underline{0}$	23.80	85	s	$1\underline{3}0$
25.39	53	s	$11\bar{2}$	24.75	40	c	$13\underline{1}$
27.56	99	s	040)	25.80	67	vs	$11\underline{2}$
28.83	100+	vb	002)	27.65	100	vb	$20\bar{2}$,002
29.95	40	pc	131	30.15	55	s	$13\underline{1}$
				30.85	45	m	$22\bar{2}$,041

D2θ = .84°
T = ?

D2θ = 1.38
T = 0.

23492 Granite from edge of gneiss band.

Natural				Heated 67 hours at 1050°C				404 hours		
2θ	I	q	d	2θ	I	q	d	2θ	q	d
21.02	100+	s	$20\bar{1}$	21.14	78	s	$20\bar{1}$	21.13	s	$20\bar{1}$
21.97	48	c	$20\bar{1}$	22.39	80	s	$1\underline{1}1$	21.37	s	$1\underline{1}1$
22.31	100+	s	$1\underline{1}1$	22.64	58	s	$1\bar{1}1$	22.69	s	$1\bar{1}1$
22.65	70	s	111	23.22	85	s	$1\underline{3}0$	23.22	s	$1\underline{3}0$
23.21	100+	m	130	24.62	82	s	$1\bar{3}0$	24.04	s	$1\bar{3}0$
23.53	55	s	$1\underline{1}1$ albite	25.53	80	s		25.52	s	
23.91	70	s	$1\underline{3}0$	25.64	80	s		25.68	s	
24.20	55	pc	$1\bar{3}1$, $13\bar{1}$	26.60	100	s	220	26.56	s	220
24.70	40	cs		27.20	88	s		27.15	s	
25.56	96	s		27.50	100+	b	040,002	27.50	b	040 ,002
26.45	100+	m	220	29.49	72	s	$1\underline{3}1$	29.51	m	$1\underline{3}1$
27.02	100+	m		30.22	65	m	$1\bar{3}1$	30.22	s	$1\bar{3}1$
27.41	100+	vb	$\bar{2}20$,040							
27.91	92	s	002 albite							
29.38	90	s	$1\underline{3}1$							
30.16	60	s	$1\bar{3}1$							

D2θ = .85°
T = .96(.77°)

D2θ = .94
T = .912(.73°)

D2θ = .945
T = .90(.72°)

* Abbreviations used for peak quality.

s ... sharp
m ... moderately sharp
p ... poor
b ... broad
vb .. very broad
c ... compound

23805 Big Phenocryst Granite.

Natural

2θ	I	q	d
20.96	90	s	$20\bar{1}$
22.06	45	p	$20\bar{1}$
22.26	67	ms	111
23.16	100+	m	130
23.45	50	p	111 alb.
23.92	95	s	$1\bar{3}0$
24.27	54	s	$13\bar{1}$
24.65	40	p	
24.85	40	p	$\bar{1}31$
25.50	100+	b	
25.62	100+	b	
26.37	98	s	220
26.60	60	s	
27.03	100+	b	$20\bar{2}$
27.35	100+	vb	040,002
27.88	100+	m	002 alb.
29.38	99	s	131
30.14	70	s	$1\bar{3}1$

D2θ = .865
T = .95(.76°)

67 hrs./1050°C

2θ	I	q	d
21.09	86	s	$20\bar{1}$
22.34	75	s	111
22.66	61	c	
23.21	84	s	130
24.02	72	m	$1\bar{3}0$
24.31	58	s	$13\bar{1}$
24.77	55	s	$\bar{1}31$
25.59	91	m	
26.51	90	s	220
27.13	87	m	$20\bar{2}$
27.48	100+	b	040,002
29.50	66	s	131
30.24	70	s	$1\bar{3}1$

D2θ = .875°
T = .90(.72°)

404hrs./1050°C

2θ.08	I	q	d
20.08	60	s	$20\bar{1}$
22.24	58	m	111
22.87	40	c	$1\bar{1}1$
23.21	63	s	130
24.00	52	s	$1\bar{3}0$
24.32	38	c	$13\bar{1}$
24.77	36	c	$\bar{1}31$
25.04	68	s	
25.15	68	s	
26.51	85	s	220
27.14	75	s	
27.44	100+	vb	002 $2\bar{2}0$ 040
29.49	50	m	131
30.20	50	m	$1\bar{3}1$

D2θ = .88
T = .90(.72°)

23848 Hybrid Dioritic gneiss.

Natural

2θ	I	q	d	
20.88	56	s	100	qtz.
22.02	63	s	$20\bar{1}$	alb.
22.35	30	p	$1\bar{1}1$	
22.98	42	m	111	
23.22	44	s	130	mcl.
23.64	68	s	111	alb.
23.98	54	mp	$1\bar{3}0$	
24.30	58	p	$13\bar{1}$	
25.55	58	s		plag.
26.65	100+	b	101	qtz.
27.11	50	m		
27.45	100+	b	040,	002
27.85	100+	vb	062	alb.
29.52	29	vp	131	
29.83	36	m	131	San.
30.25	40	p	$1\bar{3}1$	

D2θ = ?
T = .6(.48°)

23 hours/1050°C

2θ	I	q	d	
20.85	48	s	100	qtz
21.45	45	s	$\bar{2}01$	homog.
21.95	56	s	$\bar{2}01$	plagio.
22.60	38	p		
22.85	44	p	111	
23.53	55	m	130	
24.20	55	p	$13\bar{1}$	
25.53	49	s		
26.65	100+	b	101	qtz.
27.77	100+	vb	220,	002
29.80	44	m	131	
30.40	53	m	$02\bar{2}$	

D2θ = 1.25°
T = 0

23877 Sanerutian Granite.

Natural

2θ	I	q	d	
21.01	100+	s	$20\bar{1}$	
22.10	48	p	$20\bar{1}$	masked
22.29	80	s	111	
22.64	55	s	$1\bar{1}1$	
23.20	100+	m	130	
23.54	54	s	111	alb.
24.01	75	s	$1\bar{3}0$	
24.28	63	cb	$13\bar{1}$	
24.74	48	s	$\bar{1}31$	
25.58	100+	b		
26.42	100+	b	220	
26.63	100+	b		
27.06	100+	b	$20\bar{2}$	
27.45	100+	vb	040,	002
27.91	100+	b	002	alb.
29.42	98	s	131	
30.18	68	s		
30.24	75	s	$1\bar{3}1$	

D2θ = .81
T = .987(.79°)

Heated 67hrs/1050°C

2θ	I	q	d
21.11	76	s	$20\bar{1}$
22.34	74	m	111
*22.67	60	mc	$1\bar{1}1$
24.01	72	s	$1\bar{3}0$
24.30	55	s	$13\bar{1}$
24.76	54	s	$\bar{1}31$
25.48	84	s	
25.55	80	s	
26.55	100+	s	220
27.12	85	s	$20\bar{2}$
27.64	100+	b	040 002
29.49	66	s	131
30.23	64	ms	$1\bar{3}1$
*23.20	83	s	130

D2θ = .92
T = .925(.74°)

404hrs/1050°C

2θ	I	q	d
21.13	59	s	$20\bar{1}$
22.41	57	s	111
*23.23	57	s	130
24.39	44	s	$13\bar{1}$
24.87	40	c	$\bar{1}31$
25.56	65	s	
25.73	60	s	
26.61	84	sc	220
27.21	64	s	
27.55	100+	vb	002 040
29.51	55	s	131
30.26	54	s	$1\bar{3}1$
*24.07	46	s	$1\bar{3}0$

D2θ = .93
T = .887(.71)

42888 Big Phenocryst Granite.

Natural

2θ	I	q	d	
21.03	100+	s	$20\bar{1}$	
22.06	40	s	$20\bar{1}$	
22.28	55	s	111	
22.49	63	s	$1\bar{1}1$	
23.36	99	s	130	
23.57	45	m	111	alb.
23.93	57	s	$1\bar{3}0$	
24.18	49	s	$13\bar{1}$	
25.61	91	s		
25.74	100+	s		
26.45	91	s	220	
27.38	100+	vb	040 002	
27.89	67	m	002	alb.
29.55	55	s	131	
30.23	50	sc	$1\bar{3}1$	

D2θ = .83
T = .975(.78°)

Heated 115hrs/1050°C

2θ	I	q	d
21.06	90	s	$20\bar{1}$
22.32	65	s	111
22.63	40	s	$1\bar{1}1$
23.20	35	s	130
24.00	70	s	$1\bar{3}0$
24.32	40	s	$13\bar{1}$
24.72	38	m	$\bar{1}31$
25.58	85	c	
26.54	100+	b	220
27.10	100+	b	
27.44	100+	b	002 004
29.46	70	s	131
30.22	70	s	$1\bar{3}1$

D2θ = .86
T = .95(.76°)

227hrs/1050°C

Specimen only scanned for D2θ and T values

D2θ = .895
T = .925(.74°)

42888P Phenocryst from Big Phenocryst Granite.

Natural

2θ	I	q	d	
21.03	70	m	$20\underline{\bar{1}}$	
22.15	45	pc	$20\bar{1}$	
22.32	59	m	$1\underline{1}1$	
22.63	38	bc	111	
23.15	65	s	130	
23.31	72	s	$1\underline{1}1$	alb.
23.94	76	s	$1\bar{3}\underline{0}$	
24.26	70	s	$\underline{1}3\bar{1}$	
24.73	48	m	$\bar{1}31$	
25.03	55	s		
25.64	100+	b		
26.51	100+	b	$22\underline{0}$	
27.12	100+b		$20\bar{2}$	alb.
27.44	100+	b	002 040	
27.93	100+	b	002	alb.
28.37	40	bc		
28.87	37	vs		
29.50	50	m	$1\underline{3}1$	
30.19	84	s	$1\bar{3}1$	

D2θ = .82
T = .925(.74°)

115½/1050°C

2θ	I	q	d
21.16	73	s	$20\bar{1}$
22.37	60	s	$1\underline{1}1$
22.68	44	cs	111
23.23	70	s	$1\underline{3}0$
24.02	60	s	$13\underline{0}$
24.94	40	m	$13\bar{1}$
25.53	62	c	
25.70	60	c	
26.58	78	s	220
27.17	79	s	
27.49	100+	b	040 002
29.54	60	s	$1\underline{3}1$
30.23	52	c	131

D2θ = 0.95
T = .86(.69°)

168hrs./1050°C

2θ	I	q	d
21.15	80	s	$20\bar{1}$
22.47	64	s	$1\underline{1}1$
22.67	42	s	$1\bar{1}1$
23.25	82	s	$1\underline{3}0$
24.01	63	s	$13\underline{0}$
24.33	40	m	$\underline{1}3\bar{1}$
24.85	36	p	$\bar{1}31$
25.53	72		
25.68	65		
26.60	100+	b	220
27.17	100+	b	
27.48	100 +	vb	040 002
29.52	60	s	$1\underline{3}1$
30.23	62	s	$1\bar{3}1$

D2θ = .95
T = .86(.69°)

382hrs./1050°C

2θ	I	q	d
21.15	80	s	$20\bar{1}$
22.37	60	s	$1\underline{1}1$
22.67	41	m	111
23			
24			
24			
24			
25			
25			
26			
27.			
27.			
29.			
30.			

D2
T

42896 Microgranodiorite.

Natural					115½/1050°C				227 hrs./1050°C
2θ	I	q	d		2θ	I	q	d	
21.02	78	s	$20\bar{\underline{1}}$		21.07	66	s	$20\bar{1}$	Specimen only
22.05	42	c	$20\bar{1}$		22.32	57	s	$1\underline{1}1$	scanned for
22.32	70	bc	111		22.63	40	b	111	D2θ and T.
23.21	100+	m	130		23.24	62	s	$1\underline{3}0$	
23.60	39	m	$1\underline{1}1$	alb.	23.97	50	s	$13\underline{0}$	
24.00	86	m	$\underline{1}30$		24.37	39	c	$\underline{1}3\bar{1}$	
24.76	40	bc	$\bar{1}31$		24.87	38	c	$\bar{1}31$	
25.60	100+	s			25.53	62	s		
25.71	88	s			26.52	84	s		
26.46	100+	s	220		27.12	68	s		
27.37	100+	vb	002		27.46	100+	vb	040	
			040					002	
27.88	70	sc	002	alb.	29.47	60	s	$1\underline{3}1$	
29.46	67	s	$1\underline{3}1$		30.19	45	m	$1\bar{3}1$	
30.51	75	s	$1\bar{3}1$						

D2θ = .805	D2θ = .897	D2θ = .90
T = .925(.74°)	T = .90(725°)	T = .875(.70°)

43062 Porphyritic Aplitic Granite.

Natural					168hrs./1050°C				279½hrs./1050°C
2θ	I	q	d		2θ	I	q	d	
21.01	100+	m	$30\bar{\underline{1}}$		21.14	80	s	$20\bar{1}$	Specimen only
22.14	60	s	$20\bar{1}$		22.36	62	s	$1\underline{1}1$	scanned for
22.40	58	s	$1\underline{1}1$		22.67	41	c	$1\bar{1}1$	D2θ a nd T.
22.68	45	s	$1\bar{1}1$		23.32	76	s	$1\underline{3}0$	
23.23	74	bc	130		24.02	66	s	$13\underline{0}$	
23.61	57	s	$1\underline{1}1$	alb.	24.31	40	s	$\underline{1}3\bar{1}$	
24.09	85	s	$1\bar{3}\underline{0}$		24.82	36	c	$\bar{1}31$	
24.38	60	s	$\underline{1}3\bar{1}$		25.53	75	s		
24.79	48	m	$\bar{1}31$		25.67	64	c		
25.05	100+	b			26.58	90	s	220	
26.51	100+	b	220		27.14	88	s		
26.74	100+	b			27.47	100+	b	040	
27.11	100+	m						002	
27.56	100+	vb	040		29.51	56	m	$1\underline{3}1$	
			002		30.24	60	s	$1\bar{3}1$	
27.99	100+	b	002	alb.					
29.53	84	s	$1\underline{3}1$						
30.31	97	s	$1\bar{3}1$						

D2θ = .82	D2θ = .945	D2θ = .96
T = .975(.78°)	T = .90(.72°)	T = .90(.72°)

43063 Euhedral Feldspar Phenocryst Granite.

Natural

2θ	I	q	d
21.01	53	s	$20\bar{1}$
22.36	73	s	111
23.20	74	s	$1\underline{3}0$
24.13	68	s	130
25.54	90	ml	
25.62	98	s	
26.44	90	s	220
26.54	83	s	
27.59	100+	b	040, 002
28.14	87	s	002 alb.
29.53	61	m	$1\underline{3}1$
30.25	100+	m	131

D2θ = .815
T = .975(.78)

168hrs./1050°C

2θ	I	q	d
21.15	75	s	$20\bar{1}$
22.36	57	s	$1\underline{1}1$
22.68	42	s	111
23.32	72	s	$1\underline{3}0$
24.04	60	s	$13\underline{0}$
24.33	38	c	$\underline{1}3\bar{1}$
24.83	38	c	131
25.53	70	s	
25.68	62	s	
26.60	84	s	220
27.18	78		
27.48	100+	b	040, 002
29.53	48	sm	$1\underline{3}1$
30.26	55	sm	131

D2θ = .95
T = .90(72°)

43064 Euhedral Feldspar Phenocryst Granite.

Natural

2θ	I	q	d
20.95	100+	s	$20\underline{\bar{1}}$
22.00	46	pc	201
22.25	72	s	$1\underline{1}1$
22.60	43	sc	111
23.14	100+	s	130
23.46	49	bc	$1\underline{1}1$ alb.
23.94	71	c	$13\underline{0}$
24.23	64	c	$\underline{1}3\bar{1}$
24.66	40	c	131
25.48	100+	b	
26.36	90	s	220
27.05	90	s	
27.41	100+	vb	002, 040
27.84	100+	b	002 alb.
29.43	90	s	$1\underline{3}1$
30.18	90	s	131

D2θ = .86
T = .975(.78°)

214½hrs./1050°C

2θ	I	q	d
22.16	76	s	$20\bar{1}$
22.38	61	s	$1\underline{1}1$
22.68	42	m	111
23.23	70	s	$1\underline{3}0$
24.02	65	s	$13\underline{0}$
24.33	42	s	$\underline{1}3\bar{1}$
24.80	37	c	131
25.53	68	m	
25.68	64	m	
26.57	89	s	220
27.17	93	s	
27.48	100+	b	040, 002
29.53	55	s	$1\underline{3}1$
30.24	57	s	131

D2θ = .96
T = ,887(.71°)

43069 Alangorsuak Granite.

Natural

2θ	I	q	d	
21.03	67	s	$20\bar{\underline{1}}$	
22.02	42	ms	$20\bar{1}$	
22.24	45	s	111	
22.45	65	m		
22.70	42	e	$1\bar{1}1$	
23.28	80	m	130	
23.97	65	p	$1\underline{1}1$	alb.
24.04	74	s	130	
24.15	67	m		
24.42	52	c	$13\bar{1}$	
24.86	37	p		
25.77	100	m		
26.52	75	e	220	
27.54	100	vb	040,	002
28.00	85	s	002	alb.
29.55	65	m	$1\underline{3}1$	
30.34	89	s	$1\bar{3}1$	

D2θ = .82
T = .975(.78°)

214½hrs./1050°C

2θ	I	q	d	
21.13	100+	sm	$\bar{2}01$	
22.36	58	s	$1\underline{1}1$	
22.67	44	c	$1\bar{1}1$	
23.22	70	s	$1\underline{3}0$	
24.01	63	s	$1\bar{3}\underline{0}$	
24.31	38	c	$13\bar{1}$	
25.51	64			
25.66	68			
26.56	92	s	220	
27.14	85	s		
27.47	100+	b	040,	002
29.51	50	s	$1\underline{3}1$	
30.22	56	s	$1\bar{3}1$	

D2θ = .93
T = .887(.71°)

100+. The background radiation is generally in the order of 20-30% but no correction for this has been made. Also listed in table 10.12 is the effect on the various lines, of heating for varying periods at a temperature of 1050°C. The significance of this is discussed in a later section.

The Effect of Heat on the Homogenisation Rates of the Alkali Feldspars from the Julianehaab Peninsula.

The prime aim in heating the specimens was to produce homogenisation so that the composition could be derived from the X-ray diffraction charts. Measurements made on the triclinicity (see later section) however proved interesting in themselves and it is thought of value to include them in the discussion on the feldspars.

Heating was carried out for varying periods at a set temperature of 1050°C ± 20°C for periods up to 404 hours. Table 10.13 gives the D2θ values for each specimen after heating.

Table 10.13

D2θ value against heating time.

Specimen	Natural	67	115½	168	214½	227	382½	404 hrs.
23409	.79	1.38*	-	-	-			
23492	.85	.94	-	-	-			
23805	.865	.875	-	-	-			
23848	?	1.25*	-	-	-			
23877	.81	.92	-	-	-			
42888	.83	-	.86	-	-			
42888P	.82	-	.95	.95	-			
42896	.805	-	.897	-	-			
43062	.82	-	-	.945	-			
43063	.815	-	-	.95	-			
43064	.86	-	-	-	.			
43069	.82	-	-	-	.			

* 23409 76 hrs.
* 23848 23 hrs.
* 42896 279 hrs.

It can be seen from this table that homogenisation takes longer than the 48 hours suggested by Orville (1958) or the 96 hours suggested by Rao (1959). The length of time varies with each specimen (as might be expected) and in some cases may be almost 200 hours. It seems likely that for the average microcline perthite a time close to 150 hours should produce homogenisation. In all the microcline specimens heated for less than 100 hours the perthite lamellae disappeared leaving only the cross hatch twinning, yet continued heating showed that homogenisation was not complete. The best criterion is the cessation of movement of the d($\bar{2}01$) line as is seen for specimen 42888P upon continued heating.

Specimens 23409 and 23484 required only 76 hours and 23 hours respectively. The first specimen homogenised and inverted to a monoclinic form at 800°C whilst the latter required temperatures over 1000°C.

Two specimens were examined in detail to observe the homogenisation rates, these were 42888P and 42896. The specimens were heated for varying periods from 1 to 17 hours and then at longer intervals between 100 and 382 hours. Table 10.14 lists the changes in $D2\theta$ values against time.

Table 10.14

To show the changes in $D2\theta$ values against time.

42888P		42896	
Time (hrs.)	$D2\theta$	Time (hrs.)	$D2\theta$
0	.82 (x8)	0	.805
1	.85 (x8)	1	.87
4	.90 (x8)	4	.87
7¾	.92 (x	6	.88
17	.937 (x8)	17	.885
115	.95 x	115	.89
168	.95	227	.90
382	.95		

Figs. in brackets indicate number of times scanned when more than 4 x

This relationship is shown diagrammatically in fig. 10.19a and fig. 10.19b.

The significant fact is the sharp rise in the D2θ values after only a short heating, indicating that the albite which has exsolved can be rapidly put back into the microcline lattice. The slow increase after this initial burst indicates the slow homogenisation of the final coarse albite which amounts to only 1-2% of the composition. Thus if only an approximate value is required for the bulk composition of the feldspar it is probable except in cases of extreme vein perthites that 24 hours would be sufficient to give a reasonable value.

As far as is known there has been only one previous attempt to assess the homogenisation rates. Ernst (1960) (fig. 10.20c) shows a homogenisation curve for a coarse perthite which he claims approximates to separate orthoclase and plagioclase (albite) grains. Unfortunately the sample is not described, but the rate of homogenisation is extremely slow and fairly constant even up to 20 hours of heating. The graph shows both the trend of the albite and the orthoclase phase over the whole of the heating period, so it is obvious that there must be over 10% and probably up to 30% of the albite molecule present. Extending the two lines of the graph so that they intersect (assuming no change of rate in homogenisation) homogenisation would be completed in 100 hours. It is concluded that the rate of homogenisation is obviously a function of grain size for even though it can be attained in 100 hours by progressive assimilation of albite into the microcline lattice in the case of coarse material, the cryptoperthites are partially homogenised within the first hour and thereafter the rate of change is extremely small.

Heating experiments by Ernst (1960) show that oligoclase-andesine laths when mixed with potash feldspar show little or no change. It is therefore quite probable that the necessity of separating out alkali feldspars in order to calculate their composition has now been overcome.

Ernst (1960) states that the size of the particle does not affect the reaction between a separate plagioclase (albite) and alkali feldspar grains, quoting limits of .5 to .147mm. These however in terms of perthite lamellae would amount to an exceptionally coarse vein perthite and the more usual size of the perthite is about 0.05 to 0.01mm and less. The present writer would contest this statement of grain size not affecting homogenisation, as within smaller limits of 0.1mm and less, experiments on natural perthites have shown it to be so. (c.f. homogenisation curve for cryptoperthite and vein perthite.) We are here returning to the problems encountered by Rao in his attempts to homogenise dry mixtures and as these have already been discussed it is convenient to end here.

The State and Meaning of Triclinicity.

MacKenzie (1954) demonstrated using diffractometer charts that the progressive change from triclinic microcline to monoclinic common orthoclase could be tracked by the merging of the d(130) and the d($1\bar{3}0$) spacings. Previously

(1952) he had shown the presence of a monoclinic phase of albite using the coalescence of the $d(111)$ and $d(1\bar{1}1)$.

Goldsmith and Laves (1954a) suggested that the best spacings to use were the $d(131)$ and $d(131)$ (occurring at about 2θ $29-30^{\circ}$). The maximum separation that they had observed between the two peaks was 0.08°. This was defined as "Maximum" microcline (Laves, reported in MacKenzie 1954). Maximum microcline is used to denote triclinic lattice angles of $\alpha = 90^{\circ}39'$, $\gamma = 87^{\circ}47'$ (after Laves 1951a). The triclinicity has been defined by Goldsmith and Laves (1954a) as[*] $T = k(d(131) - d(1\bar{3}1))$ where the value for maximum microcline is conventionally made to be 1. Thus $0.08 \times k = 1$, $k = 12.5$ (where k = standard conversion factor).

Hence a microcline with $T = 1$ is fully ordered whilst a feldspar with $T = 0$ is disordered.

There are several points of technique to note about this excellent method. Goldsmith and Laves (1954a) in the original work used powder photographs and d spacings. The X-ray diffractometer however is now more commonly used, for obvious reasons, so that lines are read directly as 2θ. As d spacings have inverse numerical values to 2θ values (i.e. as d spacings value diminishes the 2θ value increases) it is best to modify the triclinicity equation in the case of the potash feldspars to $T = k(2\theta\,(1\bar{3}1) - 2\theta(131))$. As the maximum difference between the two spacings is 0.8°, then obviously the triclincity factor k must be modified so that $1 = k \times 0.8$. Hence $k = 1.25$. (Guitard et al (1960) however prefer to use

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[*] T for triclinicity instead of $\triangle$ used by Goldsmith and Laves.

use $\Delta = \Delta_1 / \Delta_0 \times 100$ where Δ_0 represents 0.08 of the maximum microcline and Δ_1 the difference in spacing of the d(131) - d(1$\bar{3}$1) of the specimens. Orville (1960) uses the plain values derived from the diffraction chart).

For albites, it is necessary to switch the d{131} spacings in the equation as d(131) has a larger value than d(1$\bar{3}$1). At first sight this suggests that there is a transition from microcline to albite with a T value of 0 somewhere between the two. The explanation however is that whereas in albite α is less than 90°, in microclin e it is greater (Laves 1951a) and as the values of α and γ affect the d{131} spacings there is the abrupt switch of the conventional lattice values at about Ab_{65}.

There is thus available a convenient and simple method of stating the order-disorder relationship within the alkali feldspar group. The use of d(130) and d(1$\bar{3}$0) by MacKenzie (1954) is considered to be inferior to that of d(131) and d(1$\bar{3}$1) because of the masking of the d(130) and d(1$\bar{3}$0) by nearby lines, the d(111) of albite and d(130) of orthoclase also fall in between these lines.

It is now possible to show all the intermediate stages between sanidine and microcline. Obviously the nature of T in the natural state and the rate of decrease on heating is going to provide useful information on the genesis of the rock.

Laves and Goldsmith (1954a) have shown diagrammatically the relations existing between the two end members. A sanidine crystallising out will, if given stable conditions with uniform cooling, follow the curved line upward to maximum ordering producing a microcline. If the cooling is rapid then this disordered state will be retained even at low temperatures. (Fig. 10.21)

The Effect of Heat on the Triclinicity.

Review of previous work:

Triclinicity has been defined by Goldsmith and Laves (1954a) on the basis of the separation of the d(131) and d($1\bar{3}1$) spacings. They have also shown that intermediate stages exist in nature between the value of 1 for fully ordered microcline and 0 for disordered sanidine.

Dry heat experiments by Goldsmith and Laves (1954a and 1954b) shows all variations from a microcline to its conversion to sanidine. In this case there was a gradual diminution in the gap between d(131) and d($1\bar{3}1$) as the sanidine peak became more prominent. Heating experiments with 8,000lb/in^2 H_2O pressure also produced sanidinisation, but in this case there was no intermediate values developed. Instead a sanidine peak developed between the two peaks of the microcline and as the sanidine became more intense, they diminished without any change in position. Thus this conversion cannot be regarded as a diffusive transformation i.e. re-arrangement of Al-Si atoms but a hydrothermal synthesis with the microcline going into solution and being reprecipitated as tiny sanidine crystals. Experiments have shown that sanidinisation proceeds quicker in finely ground material than in coarser material. This has been interpreted by Goldsmith and Laves (1954a) as indicating that reprecipitation was facilitated by the greater surface area of the finely ground material.

Heier (1957) examined potash feldspars from metamorphic areas (using the X-ray powder method) and suggested that the "orthoclase-microcline" transformation takes place close to the granulite-amphibolite facies transition (about 500°C) and in nature is the hydrothermal type demonstrated by Goldsmith and Laves (1954a).

Rao (1960) demonstrated that the triclinicities of alkali feldspars from xenolithic pre-Cambrian gneisses decreased as the contact with intrusive nordmakites was approached. In this case, the transformation must have been fairly dry for intermediate values of T are quoted. The mechanism is thought to be "heat transfer across the contacts".

Guitard et al (1960) also relate triclinicity of the alkali feldspars to metamorphism and metamorphic zones, with orthoclase in the catazone and intermediate and maximum microcline in the mesozone. They claim that the symmetry of the feldspars is not related to the types of granite as Marmo (1958) postulates, but to its position in the metamorphic series.

Triclinicity Measurements on Feldspar from Julianehaab Peninsula and a Discussion of Changes Induced by Heat.

Table 10.15 lists the change in triclinicity of the 12 specimens with time. Figures in brackets indicate the actual distance between $2\theta(1\bar{3}1)-(131)$.

Table 10.15

Changes in triclinicity with time, for the specimens heated at 1050°C.

	Natural	67	115	168	227* 214	279	382	404	hrs.
23409	?	0.	-	-	-	-	-	-	
23492	(.77) .96	.91	-	-	-	-	-	.90	
23805	(.76) .95	.90	-	-	-	-	-	.90	
23848	(.48) .60	0.0	-	-	-	-	-	-	
23877	(.79) .81	.925	-	-	-	-	-	.887	
42888	(.78) .975	-	.95	-	.925*	-	-	-	
42888P	(.74) .925	-	.86	.86	-	-	.85	-	
42896	(.74) .925	-	-90	-	.875*	-	-	-	
43062	(.78) .975	-	-	.90	-	.90	-	-	
43063	(.78) .975	-	-	.90	-	-	-	-	
43064	(.78) .975	-	-	-	.887	-	-	-	
43069	(.78) .975	-	-	-	.887	-	-	-	

Fig. 10.22 is a linear plot of the difference in $2\theta(131)-2\theta(1\bar{3}1)$ against the triclinicity of the unheated specimens. This is a convenient method of illustrating the range of triclinicity in the 12 specimens. It can be seen from this that the Sanerutian and related granites have values which bring them together on the graph.

Table 10.16 lists the changes in triclinicity and also the value of $2\theta(1\bar{3}0)-(130)$of specimens 42888P and 42896 which were studied in greater detail. Figures in brackets are values of $2\theta(1\bar{3}1)-2\theta(131)$.

Table 10.16

Changes in T. and {130} on heating.

42888P

Time (hrs.)	T.	$2\theta(1\bar{3}0)-(130)$
0	.925 (.74)	.775
1	.912 (.73)	.790?
4	.900 (.72)	.760
17	.860 (.69)	.760
115	.860 (.69)	.760
168	.860 (.69)	.760
382	.850 (.68)	.760

42896

0	.925 (.74)	.770
1	.906 (.725)	.760
17	.880 (.710)	.780?
227	.875 (.700)	.760

Fig. 10.23 is a graphical representation of the changing triclinicities and $2\theta(1\bar{3}0)-(130)$. It can be seen from this that there is a rapid movement within a short time followed by a small gradual decrease in the distance between the two peaks (c.f. homogenisation curves.)

It is noticeable that apart from the specimens 23409 and 23848 none of the microclines came near to being transformed to sanidine. In addition, no significant change in optic angle was noted, and the familiar cross hatch twinning persisted even up to 400 hours at over 1000°C.

The Effect of Sodium on Triclinicity.

Fig. 10.24 is a graph of the composition of the feldspars against triclinicity before heating. As the T. value before heating represents the microcline phase, this has been plotted against the percentage of the Or molecule in the potash phase. Apart from two specimens there is a strong suggestion of alignment. This linear relationship is apparently upset after heating, but it is noticeable that the Sanerutian and related types are still together. However it is possible to draw in a series of parallel lines through the various points in this graph. The general trend of these suggests that as the percentage of the albite molecule increases the triclinicity decreases, but no definite conclusion can be reached owing to the scattering of points. This scattering could be due to the difference in inherent temperatures states within each specimen. In order to overcome this, the composition of each specimen has been plotted against the difference in triclinicity between the natural and homogenised mineral. Fig. 10.25 shows the relationship of the two factors.

It appears from this that there is a definite tendency for the albite molecule to affect triclinicity values. As can be seen from Fig. 10.25a as the percentage of albite increases the amount of shift in the T values also increases. It is to be noted that specimen 23409 and 23848 have been omitted from the graph as they become monoclinic on heating.

In order to show the relationship between the decrease in triclinicity and the movement of albite back into the microcline lattice, the shift in d($\bar{2}01$) on homogenisation has been plotted against the shift in triclinicity. Fig. 10.25b shows the same features as fig. 10.25a in that with increasing sodium the triclinicity decreases.

It is interesting that this problem has been commented on in recent literature. Goldsmith and Laves (1954b) state that on putting approximately 20% albite into the microcline lattice, the triclinicity is not significantly changed. In a footnote on the same page (p. 115) they state that triclinicity can be changed by putting in additional albite (presumably more than 20%) so as to form a solid solution series between microcline and albite.

It must be remembered that the material used in the present study has a fairly low percentage of albite molecule so any conclusions on its effect on the triclinicity of Greenland microclines must be restricted to this range.

MacKenzie (1954) states (p. 364) "It seems possible that variations in the lattice of microcline might be directly related to their chemical composition." and also "It is conceivable ..... that only by exsolution of albite to reduce the amount held in the potash phase can the lattice angles approach those of a 'Maximum microcline'" (p. 365). This latter statement is repeated again by MacKenzie and Smith (1959) in reply to the proposal by Ferguson et al (1958) that the presence of sodium during cooling is essential to the formation of microcline. MacKenzie (1954) suggests that this control of lattice angles by sodium fits into the order-disorder theory. "Perhaps the Si and Al atoms cannot order beyond a certain limit until the soda and potash phases have unmixed to the extent that each is almost a pure end member of the solid solution series" (p. 366). Recently MacKenzie (personal communication) has stated his belief that the greatest effect on the triclinicity is its temperature state but that chemical composition does also have an effect.

Rao (1959) states that changes in triclinicity observed by him, using mixtures of albite and microcline show that soda has a definite influence on triclinicity. Orville (1960) writes "The departure from monoclinic symmetry as measured by $2\theta(131)-(1\bar{3}1)$ of these feldspars varies according to the Na-feldspar content ... The change in $2\theta(131)-(1\bar{3}1)$ can be attributed strictly to the partial substitution of K by Na.

Table 10.17 shows the values derived by Rao (1959) and Orville (1960) for the effect of soda on triclinicity.

Table 10.17

The Effect of Sodium on Triclinicity after Rao and Orville.

Rao (1959)			Orville (1960)		
% Microcline	% Albite	T.	% Microcline	%Albite	T.
100	-	.94	100	10	.96
90	10	.85			
80	20	.76			
70	30	.76	70	30	.76
60	40	.74			

From these values, it can be seen that the greatest effect is produced when 20% albite is added to the microcline, thereafter, addition of albite causes only a small change.

Table 10.15 shows that specimen 42888P with just less than 10% albite in solid solution has a T value of .85°

after homogenisation, which is close to that given by Rao. Specimen 23848 which contains about 50% of the albite molecule transforms to monoclinic symmetry on heating. This change in T from .60° to 0 cannot be regarded as totally due to the entry of albite into the lattice, but it must also be a function of its temperature state. It is worthy of note however that the specimen showed no change after heating 24 hours just below 800°C and it required temperatures over 1000°C to effect homogenisation.

Utilisation of Triclinicity Values.

Goldsmith and Laves (1954b) concluded that as variable triclinicities can be found in different regions of the same crystal, the reliability of such values as a geological thermometer was not good.

Rao (1959), Orville (1960) and the present writer have shown experimentally that the presence of albite in solid solution has an effect on the T value, whilst MacKenzie (1954) has expressed this opinion from a purely theoretical point of view.

It is significant however that the lowest recorded T value induced by albite in solid solution is 0.74, and this occurs when 40% of the albite molecule is forced back into the microcline lattice. (Actually only the movement of Na and K is involved, with readjustment of the cell size.) The likelihood of dealing with a microcline containing so much albite in solid solution is remote (there is doubt if such a microcline exists). For microclines with appreciable amounts of albite in solid solution (in the natural state) some adjustment can be made, for the composition of the potash phase can be derived from the X-ray pattern. For example a perthitic microcline on homogenisation by heating for 96 hours has a triclinicity of .74 and a bulk composition of $Or_{60}Ab_{40}$, it is fairly certain that such a microcline corresponds to a fully ordered type. If however the T value of a microcline drops from 0.60 to 0 on heating then some information can be derived on its original thermal state even though it may have a composition of $Ab_{50}Or_{50}$.

Discussion of the Results Obtained on the Greenland Specimens.

The results obtained on the determination of composition on these specimens has already been discussed. It is intended in this section to discuss the diffraction charts generally and the triclinicity more specifically.

The work done on the microclines from the Julianehaab granite suite, the trachyandesite dyke and the hybrid dioritic gneiss has proved most interesting as well as providing some useful information on the parent rocks themselves. It is significant that all the microclines from the granites approach the "maximum" microcline with those having the lowest T value being richer in sodium (with the exception of 42896). However it is still possible to differentiate between the microcline of the Sanerutian phase of activity simply by triclinicity values in the natural state (see fig. 10.22). Fig. 10.26a also brings out this clustering effect within these related types. Fig. 10.26b shows that the estimated temperature of crystallisation increases as T for homogenised specimens decreases. This is another way of demonstrating the effect of albite entering the microcline lattice.

Specimen 23409 the alkali feldspar phenocryst from a trachyandesite dyke gave much information on the temperature state of the dyke and has also provided data on the symmetry change from monoclinic to triclinic. The composition of the specimen after homogenisation was $Or_{37}Ab_{63}$ and this is very close to the boundary between monoclinic sanidine and triclinic albite. The natural specimen has very broad ill-defined peaks in the region of d(131) and d$(1\bar{3}1)$ with a ?(131) sanidine at 2θ 29.95° and a strong sandine d(130) peak at 2θ 23.6°. Both Na and K phases are strongly defined by the d$(\bar{2}01)$ spacings. Fig. 10.27 shows the pattern before and after heating. It is concluded that the feldspar is close to the monoclinic symmetry in its natural state and can be best defined as an orthoclase. On heating however the pattern becomes much clearer with the d(130) and d(131) of sanidine well defined. The feldspar required only a short time at temperatures below 900°C to be sanidinised so that it is quite probable that the mineral was in an almost disordered state before heating. This is not an altogether surprising fact for the feldspar originally crystallised as a sanidine and rapid cooling of the dyke body would prevent appreciable ordering. The specimen also substantiates the experiments of Laves (1952) and MacKenzie (1952) who found that the symmetry change occurred in this region of $Or_{37}Ab_{63}$

at room temperature. The ambiguity of the pattern in the d(131) region shows that the mineral cannot be defined as definitely triclinic, however the broad d(131) sanidine peak suggests that it is not fully monoclinic. The answer is that the feldspar is triclinic but the state of ordering is very small. Any increase of soda in the lattice would have resulted in a greater T value. Consequently the results on this feldspar suggest that there is a transition region between the monoclinic and triclinic symmetry. The extinction angle nX'onto (010) of 4° on (001) is additional evidence for the triclinic nature of this specimen.

The perthitic albite appears to possess high temperature characteristics and peaks at 2θ 25.83 and 2θ 27.79 are convincing proof of this. This is further evidence to support the fact that the feldspar has been cooled quickly at the time of intrusion.

Specimen 42848 from the hybrid dioritic gneiss, contained impurities of quartz and plagioclase. The X-ray diffractometer chart of the unheated material is consequently complicated by these minerals and some of the peaks present difficulties as to their identification. The d($\bar{2}$01) of the Na phase is strongly developed but the K phase is masked by quartz. It appears that both microcline and sanidine lines are present with the d(131) of sanidine between the d(131) and d(1$\bar{3}$1) of microcline (fig. 10.28 shows the pattern before and after heating). Unfortunately the d(130) of sanidine is masked by a strong albite line at 2θ 23.6° but the distance between 2θ(1$\bar{3}$0)-(130) for the microcline is less than that found in "maximum" microcline. The presence of the sanidine peak also shows the intermediate character of the feldspar in question.

On heating (23Hrs. at 1050°C) the homogenised d($\bar{2}01$) phase appears but the d($\bar{2}01$) of the plagioclase remains, even though it has shifted slightly, from 2θ 22.02° to 21.95°. Continued heating (36 hours) effects no change so that it may be assumed that homogenisation is complete and no further albite is entering the alkali feldspar lattice. Homogenisation occurs quickly but cannot be attained below 1000°C. The stability of the d($\bar{2}01$) of the plagioclase shows that no Na atoms are being released and this observation has been confirmed by Ernst (1960).

Specimen 42888P, the alkali feldspar phenocryst differs considerably from the feldspar of the granite as a whole. In fig. 10.25a this phenocryst shows marked similarities to the Sanerutian and related types and it is tempting to correlate these two in time. This however will be discussed more fully when the genesis of the granites is considered.

The features of most of the granites are very similar. Heating to homogenisation produces the same effect in all of these minerals namely the coalescence of the d($\bar{2}01$) peaks of microcline and albite, the disappearance of the d(111) albite peak between the d(130) and d($1\bar{3}0$) of microcline and the disappearance of d(002) albite peak at about 2θ 28.0°.

A Study of the Alkali Feldspar Solvus with Special Reference to the Feldspars of South-West Greenland.

There can be no doubt that the exact disposition of the alkali feldspar solvus is as yet after fifty years of speculation, still not known.

The discussion of the solvus has been perhaps dealt with most fully by Laves (1952) who realised that the solvus as drawn by Bowen and Tuttle (1950),(fig. 10.4), did not necessarily apply to the microcline-albite series. From experimental evidence, he suggested that it was not only composition which controlled the temperature of exsolution but also the ordering processes (p. 559). Hence, materials with a higher degree of ordering had a solvus whose summit was below that of high temperature disordered feldspars. Fig. 10.29 shows his interpretation of the relations of the two solvii. This means that a feldspar crystallising out slow enough to allow ordering will become immiscible at a lower temperature than one which cools at a rate which does not allow much ordering. The potash phase of this latter type may become ordered in time and consequently a microcline will be produced which has exsolved from albite along the sanidine-analbite solvus.

It is quite possible that there will be a series of solvii which will be determined by the appropriate rate of ordering in the cooling feldspar.

Looking at this problem with the information derived from the feldspars from South-West Greenland it appears that the solvus of Smith and MacKenzie (fig. 10.9c) does not fit any of the observed features of these minerals. The curve of Bowen and Tuttle published by Smith and MacKenzie (fig. 10.9b) is a better interpretation of the solvus with respect to these minerals.

The information on the co-existing phases within the feldspars from the Julianehaab feldspars would suggest that the lower limit of the solvus i.e. for fully ordered microclines, occurs in the range of Or_{95-90}. This means that with almost full ordering, the potash phase of the microcline can carry from 5-10% of the albite molecule in solid solution.

Fortunately one of the feldspars show only a little ordering, and from this, a composition of the potash phase can also be derived by X-ray means. Specimen 23409, is almost monoclinic and yet contains only 9-10% of the albite molecule in solid solution (see table 10.9). Specimen 23848 with a T value of 0.6 would also have given valuable information, but unfortunately the potash d($\bar{2}01$) line is masked by quartz. Even so, the mere fact that this is so, is sufficient to indicate that it too is low in soda. Hence we are faced with the problem of having a range of triclinicities from almost fully ordered to fully disordered which show little variation in the composition of their potash phase. This can be explained if it is assumed that the X-ray method gives an incorrect estimate of the composition of the potash phase. As has been shown in a previous section, the results of this method agree fairly closely with those obtained from chemical analysis. The alternative explanation is that the side of the albite-microcline solvus is very steep, probably resembling that displayed by Laves (1952) (fig. 10.29.)

The variation in composition of the potash phase for the granitic microclines can be explained either as an original feature or as a manifestation of the different cooling-ordering rates of each mineral. A feldspar whose ordering process was slow would have a solvus between the two limbs of the Or side of the Laves (1952) diagram (fig. 10.29 point X).

The information available from these studies is not directly relevant to the solidus-liquidus part of the phase diagram. However it is thought that the derivation of composition of the co-existing phases together with the determination of the triclinicity of a series of alkali feldspars has given enough information to be able to modify the solvus with some degree of confidence.

As has already been discussed, the sides of the microclines-albite solvus are thought to be very steep on both sides, so that as soon as exsolution commences both exsolved phases are relatively pure and free from significant quantities of the other. Thus when homogenisation is carried out, the reverse procedure takes place and the process is extremely rapid. This indicates that the process of exsolution in nature also occurs rapidly so that an ordered potash rich feldspar exsolves almost all of the albite molecule immediately on reaching the solvus.

This solvus for the ordered microcline-albite series is shown in fig. 10.30 as curve A., that of the sanidine and analbite as curve B. (partly after Smith and MacKenzie 1958). The line D-E, is the order-disorder boundary first drawn in by Laves (1952). The present writer has modified this somewhat for the microcline-sanidine transition has been shown by Goldsmith and Laves (1954a) to be 500°C instead of 700°C. The albite-analbite transition is retained at 700°C. As has been shown in the homogenisation experiments and the effect of sodium on the triclinicity of microclines in this account, there is a definite lowering of the T. value as sodium enters the lattice of microcline. Thås effect although slight will probably modify the transition line at the potash rich end so that instead of sloping upwards toward the albite end it will remain horizontal, until the increasing compositional effect overcomes the homogenisation trend, probably at about $Or_{80}Ab_{20}$. From there on there will be a progressive rise in the order-disorder line as it approaches the albite end, of the diagram.

It will be seen from Fig. 10.30 that whereas the sanidine-analbite solvus cuts the order-disorder line (triclinic-monoclinic line) the microcline-albite series does not. The evidence for the position of the microcline-albite line is fairly conclusive. Homogenisation studies by the present writer has shown that the microclines can be fully homogenised without crossing over the order-disorder line (i.e. without becoming monoclinic). This indicates that there is a definite energy barrier to be overcome before a homogenised microcline can become monoclinic as has been noted by all writers who have attempted this (e.g. Spencer 1937, Goldsmith and Laves 1954a)

Specimens in this study which have homogenised and become monoclinic have had intermediate triclinicities in their natural state, i.e. have had affinities close to the sanidine-analbite curve or somewhere between the two solvii. This means that homogenisation probably occurs after sanidinisation, i.e. the solvus cuts the transition line. It is conceivable therefore that on heating, the two phases meet the transition line (points F and G) but are forced over it into the monoclinic state through the necessity to follow the solvus in the course of homogenisation.

Specimens 23409, 23848, and the granitic microclines can now be fitted into this picture of the phase diagram. The granitic microclines can be homogenised by following solvus A of fig. 10.30. As this solvus does not cross the transition line D-E it requires a much longer time at over 1050°C to acquire sufficient energy to produce disorder. Specimen 23848, is a microcline of intermediate triclinicity (.6) but heating over 1000°C causes homogenisation and complete disorder. Hence the solvus for this feldspar (which has a composition of $Or_{49}Ab_{51}$) must just cross the transition line, but the overlap cannot be great as temperatures below 1000°C are insufficient to complete the change.

Specimen 23409 with a triclinicity near 0, homogenises quickly and crosses over the transition line at temperatures below 1000°C because its solvus also overlaps the order-disorder boundary, and because it is already in a high temperature state.

It is obvious from these remarks that the writer believes that each alkali feldspar has its own unique solvus which is controlled by two dominant factors, namely composition and cooling rate. The cooling rate influences the rate of ordering in the crystal, which in its turn controls the actual temperature at which exsolution starts.

Feldspar Geothermometry and its Application to Julianehaab Rocks.

The principle of the feldspar geothermometer was first proposed by Barth (1934) who later enlarged upon its general application by publishing a graph (fig. 10.31), which relates the ratio of distribution of the soda (in terms of the albite molecule) in potash and plagioclase feldspars to temperatures of formation (1956) Barth (1956) states "Since soda feldspar (albite) is soluble in both potash feldspar (orthoclase) and lime feldspar (plagioclase) one would expect albite when crystallising at a given temperature to distribute itself between the two latter with a constant ratio of distribution."

There are however various difficulties in using this method as a geothermometer. Barth himself admits that " ... the composition both indirectly, by inducing structural inversions and directly, influences the distribution of soda and that consequently the feldspar geologic thermometer is not accurate". It must also be remembered that in the area under consideration there have been several metamorphisms and that the distribution of the albite molecule will represent at least in part the last temperature of crystallisation. The distribution can of course be also modified by the metasomatic introduction of alkalis.

Provided it is understood that the temperatures obtained are of a purely relative value, the feldspar geothermometer can be a useful tool, especially if used on a set of rocks from the one province. As an exact temperature indicator it is unreliable and must be treated with caution.

The composition of 12 co-existing alkali feldspars and plagioclases have been determined to obtain relative temperature measurements. These have been plotted on the $Na\,Al\,Si_3O_8$ - $KAl\,Si_3O_8$ - $Ca\,Al\,Si_3O_8$ diagram (fig. 10.32). The compositions of the alkali feldspars are obtained from chemical and X-ray analysis and those of the plagioclase from refractive index (Chayes 1952b) determinations and the extinction X' onto albite twins on sections normal to (010) according the conventional Michel-Levy method.

Table 10.18 lists the co-existing phases of albite in alkali and plagioclase together with the k values and corresponding temperature values derived from Barth (1956), where k = % Ab in alkali feldspar/% Ab in plagioclase feldspar.

Table 10.18

List of co-existing phases of Albite in Alkali Feldspar and Plagioclase.

	% Ab Alk. Feld.	% Ab Plagio.	k	Temp.	Rock type.
23409	63.0	90.0	.7	970	Trachyandesite.
23492	14.7	77.0	.19	470	Contaminated granite.
23805	10.8	75.0	.14	420	Porphyritic granite.
23848	49.0	85.0	.51	800	Hybrid dioritic gneiss.
23877	14.5	80.0	.18	460	Sanerutian granite.
42888	9.2	70.0	.13	400	Porphyritic granite.
42888P	17.2	70.0	.24	515	Porphyritic granite.
42896	10.7	70.0	.15	430	Microgranodiorite.
43062	16.2	76.0	.21	490	Porphyritic Aplitic Gr.
43063	17.1	80.0	.21	490	Euhedral Phenocryst Gr.
43064	18.4	80.0	.23	500	" " " "
43069	16.0	70.0	.22	495	Alangorsuak granite.

The problems of using this method of thermometry are well displayed here. For example, in the case of 42888P the analysis of the almost pure alkali phenocryst and the alkali feldspar from the groundmass proved to be different and the problem then becomes one of a temperature difference of over 100°C (assuming that the plagioclase is homogeneous). The question of interpretation will be dealt with when the genesis of the granites is discussed but it would appear that some metasomatic action has been involved to produce the compositional difference. If this is the case then it is hardly acceptable to assume the ratio of distribution of the albite is controlled by temperature.

The value of 800°C derived from the phenocryst of specimen 23848 seems to be high. The rock itself is of hybrid origin occurring at the margins of a dioritic body possessing an even grained texture with only occasional large phenocrysts. It does seem probable that the phenocryst is of metasomatic origin, and hence foreign to the mineral assemblage in the rock itself.

Specimen 23409 whose k value gives a temperature of 970°C is a member of the alkali dyke suite and the temperature appears to be fairly realistic. The exact value is in some doubt however as the plagioclases within the rock are strongly sericitised so that their composition cannot be quoted with any degree of confidence. It might be that they are more basic (i.e. contain more of the anorthite molecule) in which case the temperature would be higher. A possible interpretation of this would be that the plagioclases are xenocrysts which are unstable in the dyke-rock (hence their alteration) and have been derived from a more basic magma source. If such is the case, then it would be difficult to use their composition as a means of determing the temperature of formation.

The values obtained for the granites are considered to be more realistic and the fact that the younger intrusive granites give consistently higher temperatures than the porphyritic older types adds weight to this conclusion.

Figs. 10.26a and b are plots of the T values against the temperature values obtained on the feldspar specimens. It will be noticed that there is a definite tendency after homogenisation for specimens with smaller T values to have higher temperature values. Similarly, the maximum temperatures are obtained from those specimens which became monoclinic after only short heat treatment. This obervation fits well into the order- -disorder theory and has also been noted by Heier (1957) for Norwegian feldspars.

Fig. 10.33 shows in diagrammatic form the general range of temperatures estimated for the specimens examined. It will be noted that the older granites have lower temperatures than the Sanerutian granite (except the value derived for 42888P) whilst the intrusive and hybrid rocks have much higher values.

One further point in conclusion. It should be noted that the temperatures derived by this method represent the final temperature of crystallisation and that the values quoted are simply the lowest at which the rock consolidated.

CHAPTER 11.

The Application of Modal Analysis to Granite Variation, and a Discussion on the Development of a Technique for the Analysis of Coarse Grained Granites.

Introduction

Modal analysis (the estimation of the volume percentages of the individual minerals in a rock) has been used successfully for some years as a means of demonstrating variations within large rock masses. The history of the development of modal analysis has been fully dealt with by Chayes (1956) whose excellent account need not be repeated.

Many arguments for and against the use of modal analysis results have been put forward, difficulties such as grain size, the number of counts required, the Holmes effect all have been suggested as drawbacks to the system. Chayes (1949, 1951, 1956) has probably been one of the most ardent supporters of the system, and this in itself is heartening as he is both petrologist and statistician.

In the practical sense, the most recent workers Chayes (1951, 1952c) and Whitten (1959, 1960) have used successfully the point count results in the application of granite variation. More recently, Whitten (1960) has shown that it is possible to detect variations within the Thor granodiorite in Donegal which correspond to the observable "ghost" stratigraphy within the xenolithic remnants. The so called palimpsestic stratigraphy had already been demonstrated by Pitcher (1952), for this granodiorite, on the basis of xenolithic horizons within the rock mass. Later, Whitten has shown that even though not detectable in hand specimen, mineralogically, the variations persist through the granodiorite itself.

The mapping of the Julianehaab Peninsula and surrounding area has revealed certain features in the structure of the granite and the xenoliths which can be interpreted as "ghost stratigraphy". Let it be said however, that the frequency of pre-existing country rock within the area is far less than that of the Thor District of Donegal and the process of granite emplacement has been carried much nearer to completion in the Greenland area.

It seemed that an attempt to carry out an "analysis" of the available specimens to determine whether any such systematic variation existed might prove to be a valuable indicator in elucidating the evolution of the granitic rocks. There were two draw-backs to the idea, first the sampling had not been carried out with this in view and secondly, the variation within the xenoliths was negligible so that any correlation would prove difficult.

The problem was at first tackled by a systematic point count of all the available granite material, the counts being up to and over two thousand. The results of this are shown in fig. 11.1 plotted as the ratio of plagioclase to alkali feldspar to quartz. Identification of the alkali feldspar was facilitated by staining, using a modified Chayes (1952) and Rosenblum (1956) method. This is described in the appendix (Section 3). From fig.11 it will be seen that there is a marked scattering of the points without any apparent order or meaning. The dotted lines indicate the granodiorite-quartz monzonite-granite fields. It was thus forcibly made apparent that the acceptance of the accuracy and methods of modal analysis on the coarse grained granites had not been justified. To test this it was obvious that one specimen would have to be checked several times to determine the limits of error.

<u>The Results of Repeat Measurements on one Specimen</u>.

As it appeared that the dominant factor in producing variation was the coase grained nature of the rocks it was decided to choose a specimen showing this feature. Ten separate modal analyses were performed on ten different rock sections from specimen 42888, a porphyritic granite from the south coast of the peninsula just west of Julianehaab township. All the sections were stained and a point count carried out with a .2 cm. gap between the traverses and 2,000 counts. When the results of these measurements were plotted (fig. 11.2) it was found that the variation within the leucocratic constituents was considerable. The variation of the individual minerals is set out below in Table 11.1.

Table 11.1 Results of Modal Analysis on the Ketilidian Granite 42889.

Mineral Constituents	Limits (%)	Range %	Standard Deviation %
Plagioclase	27.0 - 49.8	22.8	9.0

The suspicion that there were large errors in the values obtained for coarse grained rocks was thus confirmed.

The question of the finer grained Sanerutian granites and the accuracy of modal analysis results obtained on them was however still in doubt. A similar experiment was tried with ten thin sections of specimen 23882, from Karrarmiut. Table 11.2 tabulates the results obtained from these measurements and fig. 11.3 is a triangular diagram showing these values plotted as percentage plagioclase, microcline, and quartz. It can be seen that all the points fall close together suggesting that results obtained for the finer grained granites are reliable.

As a matter of technique, the slides were counted twice from opposite directions and the average taken. In addition one of the sections was point counted at right angles to the normal traverse direction without appreciable difference to the value. The variation and standard deviation for 23882 are given below:-

Table 11.2 Results of Modal Analysis on Sanerutian Granite 23882.

23882 (ten sections)

	Limits %	Range%	Standard Deviation %
Plagioclase	31.7 - 37.3	5.6	1.61
Microcline	28.6 - 35.2	6.6	2.13
Quartz	29.4 - 34.1	4.7	1.46
Biotite	1.4 - 3.5	2.1	0.56
Accessories	0.3 - 2.2	1.9	0.49

With regard to the range, it is unlikely that fine grained rocks are perfectly homogeneous throughout so that it would be erroneous to expect the range to be 0.

Comparison with Other Results

It is of interest to compare these results with similar measurements made by Chayes (in Fairbairn et. al. 1951) Sixteen modal analyses of the Gl. Granite* have been carried out by Chayes and these have been recalculated by the writer so that plagioclase, alkali feldspar and quartz total 100%. and plotted on a triangular diagram (Fig. 11.4). The standard deviation and range are given in table 11.3.

Table 11.3. Results of Modal Analysis on G.1. (After Chayes).

Constituents.	Limits(%)	Range%	Standard Deviation.
Plagioclase	29.1 - 33.0	3.9	1.4
Potash Feldspar	32.0 - 37.1	5.1	1.4
Quartz	25.5 - 29.6	4.1	1.4
Biotite	2.2 - 4.2	2.0	.6
Muscovite	0.7 - 1.9	1.2	.4
Opaques	0.4 - 1.4	1.0	-

As a final attempt to assess the accuracy of modal analysis and to obtain comparisons with my own results honours students were asked to carry out point count analysis on one section (42888), thus each student used the same slide in turn. The results are plotted in fig. 11.5 and it will be seen that there is appreciable variation between the operators.(This can be attributed in part to the inexperience of the operators)..

Combined Rock and Section Analysis and its Application to Coarse Grained Granitic Rocks

Recently several writers have suggested techniques for the estimation of the modal values for coarse grained rocks. (See Emerson 1958; Jackson and Ross 1956; and Fitch 1959).

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* G.1 Granite is the Westerly Rhode Island Granite, on which there is much detailed chemical and mineralogical information (Fairbairn et. al. 1951).

These have the disadvantage of being restricted to the rock so that the finer grained material cannot be identified.

Using a suggestion by Dr. C.H. Emeleus as a basis, the coarse grained specimen 42888 was used again in an effort to obtain reproducible results. The rock itself was cut so that a large flat surface was obtained about 55 sq. centimetres in area. This surface was then ground and stained for alkali feldspar, the phenocrysts over 3 mm. were then outlined in ink (both microcline and plagioclase) and the rock, point counted. This is done by tracing off the outline of the rock together with the phenocrysts and laying the tracing on graph paper. Traverses at set intervals can then be done, counting plagioclase phenocrysts, microcline phenocrysts and matrix. The thin section is next examined and a point count carried out in which all phenocrysts over 3 mm. are omitted. The section is point counted twice in opposite directions and the average taken. The results are then recalculated, so that the total is the same as that otained for the matrix on the rock analysis. The values for plagioclase and microcline can then be added so that the total is 100%. The results of these operations for the ten sections are set out in table 11.4 and plotted in fig. 11.6. Although there is still a scatter there is obviously a grouping of the results equal to that found for G1. and far superior to earlier results obtained on only the thin section. The range and standard deviation are given in table 11.5 for these improved values for 42888.

Table 11.4 Detailed Results of Combined Rock and Thin Section Modal Analysis of 42888

Thin Sections:

	1	2	3	4	5	6	7	8	9	10
Plag.	41.5	38.7	39.5	39.0	37.5	42.5	42.0	39.5	39.8	43.6
M/cl.	20.5	19.4	21.5	17.5	19.0	20.7	20.5	20.7	20.2	21.2
Qtz.	22.5	25.0	23.0	22.0	27.0	20.0	25.5	25.5	27.0	20.5
Amph.	5.5	4.9	3.0	8.5	3.5	5.5	4.2	5.0	4.5	4.0
Biot.	9.0	10.7	12.0	10.5	10.5	9.0	6.0	9.3	8.5	9.0
Acc.	1.0	1.3	1.0	2.5	2.5	2.3	1.8	Tr.	Tr.	1.7
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Thin Sections recalculated to total 80.0%

	1	2	3	4	5	6	7	8	9	10
Plag.	33.2	31.0	31.5	31.4	30.0	34.0	33.6	31.7	32.0	35.0
M/cl.	16.5	15.6	17.3	14.0	15.2	16.6	16.5	16.5	16.3	17.0
Qtz.	18.0	20.0	18.5	17.7	21.5	16.0	20.5	20.5	21.5	16.4
Amph.	4.5	4.0	2.5	6.5	2.8	4.4	3.4	4.0	3.6	3.2
Biot.	7.0	8.6	9.5	8.4	8.5	7.2	4.8	7.3	6.6	7.2
Acc.	.8	.8	.7	2.0	2.0	1.8	1.2	Tr.	Tr.	1.2
Total	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0

Final Modal analysis, with addition of 5.0% Plag. phenocrysts, 15% Microcline phenocrysts to thin section results.

	1	2	3	4	5	6	7	8	9	10
Plag.	38.2	36.0	36.5	36.4	35.0	39.0	38.6	36.7	37.0	40.0
M/cl.	31.5	30.6	32.3	29.0	30.2	31.6	31.5	31.5	31.3	32.0
Qtz.	18.0	20.0	18.5	17.7	21.5	16.0	20.5	20.5	21.5	16.4
Amph.	4.5	4.0	2.5	6.5	2.8	4.4	3.4	4.0	3.6	3.2
Biot.	7.0	8.6	9.5	8.4	8.5	7.2	4.8	7.3	6.6	7.2
Acc.	.8	.8	.7	2.0	2.0	1.8	1.2	Tr.	Tr.	1.2
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Plagioclase, Microcline and Quartz retotalled to 100%

	1	2	3	4	5	6	7	8	9	10
Plag.	43.6	41.5	42.0	44.0	40.5	45.0	42.6	41.5	41.0	45.3
M/cl.	36.0	35.5	37.0	35.0	35.0	36.5	35.0	35.5	35.0	36.3
Qtz.	20.4	23.0	21.0	21.0	24.5	18.5	22.4	23.0	24.0	18.4
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Figures underlined represent maximum or minimum value obtained for a particular mineral.

Table 11.5 Results of Combined Rock and Section Modal Analysis for 42888.

42888	Limits(%)	Range %	Standard Deviation %	
Plagioclase	35.0 - 40.0	5.0	1.61	) When
Microcline	29.0 - 32.3	3.3	0.70	) recalculated
Quartz	16.0 - 21.5	5.5	1.76	) to 100%
Hornblende	2.5 - 6.5	4.0	1.07	
Biotite	4.8 - 9.5	4.7	1.30	
Accessories	Tr. 2.0	2.0	.50	

If the values are recalculated so that plagioclase, microcline and quartz equal 100% they can be compared with the original estimates. Below is given the ranges found when only thin section was used and also the improved rock and thin section value.

	Slide only (Range)	Slide and Rock (Range)
Plagioclase	26.0%	4.8%
Microcline	32.5%	2.0%
Quartz	17.5%	6.5%

The averages for the individual minerals obtained using the first method are given below together with the averages obtained with the improved method:-

42888	Thin Section	Rock and Thin Section
Plagioclase	39.0	37.0
Microcline	30.0	31.0
Quartz	19.0	19.0
Hornblende	3.0	4.0
Biotite	7.0	7.5
Accessories	2.0	1.5

On recalculation to 100% for plagioclase, microcline and quartz.

Plagioclase	44.5	42.5
Microcline	34.0	35.5
Quartz	21.5	22.0

This final result is as expected, as the discrepancies within individual sections owing to phenocrysts are compensated over the ten slides. Consequently the two averages agree very closely, the thin section technique requires about ten sections to obtain an accurate result, the other method needs only one section and a rock slice.

Summary and Conclusions

It has been shown that point count analysis of coarse grained rocks is totally unreliable if only single thin sections are used. A combination of point counts on the rock slab and thin section is suggested so that allowance can be made for the phenocrysts present in the whole rock. Ten sections from the same rock have been used and it is shown that the results obtained are as good as those obtained by Chayes on the G1 granite and by six different operators working on the same section. It has also been demonstrated that the average value for the constituent minerals obtained from ten thin section point counts is close to the values given when combined rock and thin section methods are employed. Ten thin section point counts on a finer granite without appreciable quantities of phenocrysts gave reproducible results indicating that such values will be reliable when used in connection with quantitative studies.

Results of Quantitative Analysis on the Ketilidian and Sanerutian Granites

The initial fear that collecting of specimens had not been suitable for this purpose was amply confirmed early in the experimental stage of this work. Specimens collected at short intervals along the south coast of the Peninsula were examined and modally analysed using the method outlined in the previous pages. When plotted on a triangular diagram with the apices total feldspar, total mafic minerals and quartz there was a significant scatter of these Porphyritic granites (represented by P on Fig. 11.7) On Fig. 11.7 Sanerutian and related granites are plotted as well as results from the Microgranodiorite. Despite the scatter associated with the Porphyritic Granites they still remain distinct from the Sanerutian types and the Microgranodiorite. The relationship of the Porphyritic Aplitic Granite to the Sanerutian Granite is amply born out from this study for samples of the granite, when plotted fall well within the younger granite field (see Fig. 11.7 points marked A). The differences noted in appearance and field characteristics between the Porphyritic and Sanerutian granites is carried through into their mineralogy and bulk composition, and there can be little doubt that this is due primarily to a difference in genesis. The Microgranodiorite again is of a different bulk composition, confirming the observations made in the field. This is primarily due to a decrease in quartz and a concomitant increase in dark minerals.

Only one modal analysis is available for the Euhedral Phenocryst Granite due to the lack of suitable material. This analysis places the granite well within the boundaries of the Porphyritic granites as can be seen from Table 11.6 which lists all the results obtained on the granite material. The conclusions drawn from the

Table 11.6 Results of Modal Analysis on Granitic Rocks

							Recalculated to 100%		
	Plag.	M/cl.	Qtz.	Amph.	Biot.	Acc.	Plag.	M/cl.	Qtz.
23329	28.0	34.0	37.2	-	0.8	Tr.	28.2	34.3	37.5
23374	44.5	23.1	31.9	-	Tr.	0.5	44.8	23.2	32.0
23399	37.2	27.7	30.9	-	4.2	Tr.	39.0	28.8	32.2
23812	35.7	29.7	30.6	-	4.0	Tr.	37.0	31.0	32.0
23857	29.1	47.5	15.5	0.5	4.9	2.5	31.5	51.5	17.0
23873	48.4	18.9	21.4	3.9	6.2	1.2	54.6	21.3	24.1
23877	39.7	25.0	29.6	-	5.4	0.3	42.0	26.5	31.5
23882	34.0	31.8	31.1	-	2.2	0.9	35.2	32.8	32.0
42802	32.0	30.3	34.0	-	1.9	1.8	33.2	31.5	35.3
42864	32.0	36.2	24.0	0.8	7.0	Tr.	34.7	39.3	26.0
42871	39.3	26.5	23.0	2.3	7.5	1.4	44.2	29.8	26.0
42872	37.7	22.3	25.1	6.4	8.2	0.3	44.3	26.2	29.5
42874	41.1	28.6	20.2	2.2	7.5	0.4	45.8	31.8	22.4
42875	53.0	24.3	13.4	3.0	5.5	0.8	58.6	26.7	14.7
42896	46.5	18.0	15.6	7.2	12.7	Tr.	58.0	22.5	19.5
42926	47.8	29.2	15.8	1.8	4.6	0.8	51.5	31.4	17.1
43062	35.2	26.9	32.5	-	4.0	1.4	37.3	28.5	34.2
43064	47.7	29.0	14.5	1.8	5.0	2.0	52.3	31.8	15.9

23329	Sanerutian	(10/040845)
23374	Sanerutian	(10/072867)
23399	Sanerutian	(10/087824)
23812	Sanerutian	(10/087854)
23857	Porphyritic Quartz Monzonite	(10/051864)
23873	Ketilidian	(10/141822)
23877	Sanerutian	(10/126808)
23882	Sanerutian	(10/137821)
42802	Sanerutian	(10/126820)
42864	Ketilidian	(10/064813)
42871	Ketilidian	(10/056809)
42872	Ketilidian	(10/054809)
42874	Ketilidian	(10/052804)
42875	Ketilidian	(10/049802)
42896	Ketilidian, Microgranodiorite	(10/008811)
42926	Ketilidian	(00/964848)
43062	Porphyritic Aplitic Granite	(10/108958)
43064	Euhedral Feldspar Phenocryst Granite	(10/093948)

petrographic observations seem therefore to be confirmed (Chapter 6).

The data plotted on Fig. 11.7 and listed in Table 11.6 suggests that it is possible to differentiate the various granites found within the area and also is an aid to the recognition of the affinities of the more unusual types. Thus it is shown that the Porphyritic Aplitic Granite is related to the Sanerutian Granite and the Euhedral Feldspar Granite to the Ketilidian Porphyritic Granites. Unfortunately, the number of analyses completed on the Porphyritic Granites is far from sufficient to bring out any significant variations within this group. Such a task would require careful analysis of systematically chosen specimens in large numbers, a task beyond the scope of this work. Nevertheless, it is suggested that the method described here is sufficiently sensitive to differentiate the granite types found within the area.

Some time was spent in trying to perfect a method whereby modal analysis could be completed in bulk using infrared techniques. The method and principle are described in the appendix (Section 4), but it is necessary to insert here the writer's belief that with sufficient experimental control of the conditions and sample preparation (a formidable task!) the technique could be used with confidence to carry out analyses with speed and accuracy.

The data from modal analysis can be carried farther, for it provides useful information with regard to the possible origin of the Sanerutian Granite. Fig. 11.8 is a triangular diagram with the apices as quartz-potash feldspar(Or)-Albite(Ab). For the purposes of this diagram, the plagioclase (Composition Ab_{70-100}) is plotted as albite. (A presidence created by Orville 1960a). Actually this is a fairly true representation of the Sanerutian Granites as most of these do have albitic plagioclase. Shown on Fig. 11.8 is the 740°C liquidus curve at 2,000 bars water pressure of the Synthetic Granite System(after Tuttle and Bowen (1958). The broken line of roughly circular shape is the maximum concentration of analyses of plutonic rocks with more than 80% normative quartz+albite+orthoclase taken from Washington's Tables (1917) (after Tuttle and Bowen 1958).

The purpose of Fig. 11.8 is to show the concentration of the Sanerutian Granite within the 740°C liquidus curve and the coincidence of these points with the outlined maximum. The 740°C curve has been chosen because it marks the upper limit of the thermal low at 2,000 bars pressure. With decreasing temperature the liquidus moves closer to the contoured area for the maximum concentration of plutonic rock analyses. The minimum for the Synthetic Granite System at 2,000 bars lies very close to this contoured area and any increase in pressure tends to move it away in the direction of the Albite apice. (Tuttle and Bowen 1958).

There can be little doubt of the inference of this data, for the coincidence of the thermal valley of the liquidus surface in the system $NaAlSi_3O_8$ - $KAlSi_3O_8$-SiO_2 to the maximum obtained when plutonic rocks of "granitic" aspect are also plotted can hardly be fortuitous. It is suggested by Tuttle and Bowen (1958) that the bulk of granites are formed as the result of crystal $\rightleftharpoons$ liquid equilibria, i.e. magmatic processes.

A similar argument can now be applied to the data on the Sanerutian granites which all lie within or close to the outlined maximum area and close to the ternary minima. (Ab-Or-SiO_2) for low to moderate water-vapour pressures. It is suggested by the writer that the evidence here presented is a strong indication of the magmatic origin of the Sanerutian granite.

The Porphyritic Granites are also plotted on Fig.11.8 showing that they are not related to the outlined areas. The inference is either that these granites originated from a magma whose crystallisation ceased before the liquidus reached the thermal low (in this case, the scattering of points would suggest contamination from an extraneous source), or that the rocks originated in some other way. The available information from this technique cannot of course give the complete answer to this problem but it can be used constructively together with field and petrographic data.

Conclusions.

Modal analysis data on various "granitic" rocks from the Julianehaab district shows that the Sanerutian Granites are distinct from the older Porphyritic Granites. In addition, the Porphyritic Aplitic Granite is thought to be strongly related to the younger granite whilst the Euhedral Feldspar Granite has affinities to the Porphyritic Granites. The Microgranodiorites are a distinctive group of rock types which can be identified by their bulk mineralogical composition.

The data from modal analysis is used to show that the Sanerutian Granite could have originated by the differentiation of a granitic liquid or by selective remelting of granitic rocks as the compsotion of these granites falls consistently close to the ternary minima of the Ab -Or - SiO_2 system. The maximum of analyses of plutonic rocks of granitic aspect whose normative quartz + albite + orthoclase exceeds 80% also is very close to the plot of Sanerutian Granites. The data on the older Porphyritic Granites is not conclusive, but it is shown that they are not related to the thermal low of the Or - Ab - Qtz. system.

CHAPTER 12

The Geological Evolution of the Julianehaab District
Summary and Conclusions

> "I affirm therefore, that we have nothing to fear from the results of our inquiries, provided they be followed in the laborious, but secure road of honest induction."
>
> Rev. A. Sedgwick (1830).

Throughout this study, the dominating factor has been the problems concerned with the genesis of the Julianehaab Granites. It has been stated in several different ways in recent geological literature, that the interpretation put upon a particular rock by a geologist, depends largely on his previous experience in that particular field. Unfortunately the writer can claim no such experience to draw upon, and yet this has meant an "open minded" approach to a virgin problem. It is with this thought in mind that he presents the summary and conclusions of the geological evolution of the Julianehaab District, in the hope that "honest induction" will not be forfeited too much, for pure speculation.

The older Porphyritic Granites are probably the most problematical element in the Julianehaab area. These represent the latter part of the Ketilidian sequence in which are preserved the remnants of the Arsuk-Sermilik Series. In assessing the origin of these granites, it must be remembered that they represent part of the Basement rocks of Southern Greenland and that they have been subjected to several metamorphic periods whose nature and intensity is largely unknown. The decision as to whether they are metasomatic or igneous seems to the writer a simplification of the problem although numerous geologists have done this in the areas in which they studied. This idea has been aptly summarised by Wyllie and Tuttle (1961):

> "It has been evident for some time that the root of the "granite" problem" is buried not only beneath mountain ranges, but also in the geologists' choice of words."

It has already been noted in Chapters 2 and 4 that preserved within the older granites is a dominant E.-W. to E.N.E. - W.S.W. trend brought out in the form of the xenolithic bodies and also foliations and lineations both within granite and xenolith. This direction is not peculiar to the Julianehaab District for it has been noted in adjoining areas by Allaart (1958-59) and Windley (1960). The work of Cloos (summarised by Balk (1937) on granite batholiths has shown that xenoliths often conform to the shape of the intrusion and may be interpreted as the floating remnants of pre-existing rocks, aligned by the flow of the invading magma. Some of the structures seen on the coastal sections in the south of the Julianehaab Peninsula could well be interpreted as this so called "flow banding".

Dr. Ramsey (1961) (personal communication), having seen similar structures in the Lewisian of Western Scotland and also in Switzerland, suggests that they are the result of metamorphic segregation within the granites, the metamorphism obliterating all previous structures and imposing a uniform structure onto the area. This is an interesting suggestion when applied to the area in question, for it is possible that the remarkable conformity in granite structure and xenolith orientation, could well be the result of ultrametamorphism "stamping" this pattern on the rocks.

A third suggestion which would account for the granite- xenolith relations is that applied tentatively by Pitcher to the Thor Granodiorite in Donegal (1952). In this case it is proposed that the xenolith orientation and foliations and lineations in the granite, represent the remnants of a previous rock sequence converted in situ, to a granite rock. The evidence presented for the Donegal rocks is very strong, for stratigraphy and fold structures seen in the surrounding country rock can be followed within the xenolithic rocks. There can be little doubt that the profusion of xenolithic material within the Thor Granodiorite is not equalled by the older Julianehaab Granites and as a direct consequence the evidence available is much less.

Throughout the foreging discussion, most of the xenolithic rocks referred to have been those elongate, thin basic gneiss streaks prominently aligned on the south coast. A major feature of the area however, is the very large gneiss horizon which is continuous across the peninsula in a direction conformable to the smaller xenoliths. This rock "horizon" in many ways complicates the problem for are we to believe that it too was oriented by a magma? If the granites originated by the metamorphic differentiation of a more basic rock type or by the forcible alignment of a series of basic bodies within a granite as Ramsay suggests, then the gneiss band must have lain conveniently in the correct orientation or some extraordinary differentiation process has been in operation. Over all, the gneiss horizon seems to indicate that it represents a part of the original rock sequence which has offered efficient resistance to the granitising agents. If this is the case, can it then be suggested that the smaller bodies originated by a similar process?

In this connection it is worth re-iterating that the bodies preserved within the older granites are(with the exception of the quartzite horizon in the north of the peninsula which is again conformable to the general trend), fine grained massive hornblende gneisses. This indicates that the remaining rocks are of the type to be expected if such a granitising process had been in operation.

In opposition to this idea, are the obviously agmatitic borders and disoriented blocks found on the northern margin of the gneiss band, which would indicate a mobile granitic material. Similarly the junction between the dioritic amphibolite and the granite (Fig. 3.17) in the central part of the peninsula, adds weight to this contention.

The vertical foliation and banding seen in the gneiss band, especially on the island of Mato, suggests a largely metamorphic origin, for the banding in no way resembles a sedimentary relic feature and is more likely due to a metamorphic segregation with acid bands being intercalated with more basic. The banding, folding and refolding observed within the gneiss is probably a pre-granite feature as no folding later than Ketilidian Granites is known in this area. (the Kuanitic dykes are not folded).

The available field evidence thus poses many problems, each idea on the origin of the granite being apparently irreconcilable with some of the field observations. It therefore seems inevitable that a compromise will have to be reached between the several hypotheses. There can be little doubt that the older granites were in part mobile at certain periods and this would account for the intrusive nature of the contacts with the dioritic amphibolites and the gneiss band. The zone of brecciation in the south-west of the main peninsula could also be accounted for by the presence of a magmatic granite, this explaining the absence of granite blocks.

Petrographic evidence has been presented in the foregoing descriptions of the granites to show that metasomatism has in part been active, and the presence of the large microcline porphyroblasts within the granites have been interpreted as part of the same process. In one of these granites (42888) the phenocrysts had a markedly different composition to that of the alkali feldspar in the groundmass, and this is regarded as further support for this contention.

The reality of metasomatism as a geological process has been proved in several cases, both in observable petrographical details and also in experimental work. In the latter case an example is the famous description by Adams (1930) of the two magnesite bricks, where it was shown that Al_2O_3, CaO, Fe_2O_3 and possibly SiO_2 had passed across the contact from one brick to the other. In the same way, diffusion is the only mechanism by which the homogenisation of perthitic feldspars can take place, and it is suggested that this is accomplished by the movement of the soda atom (Chapter 10).

Further proof of diffusion of some elements is given by MacKenzie (1960) who describes an experiment in which tiny albite crystals were held at 700°C for a week in the presence of circulating water. After this period it was found that nepheline porphyroblasts had grown among the albite crystals, indicating that the silica had been leached out. Other experiments by Tuttle and Bowen (1958) show the reality of diffusion. In one case described (p.89), powdered granite was exposed to circulating vapour at a high temperature and pressure. It was found that the quartz and feldspar components were largely extracted and deposited in the cooler portions of the pressure vessel, leaving monoclinic pyroxene and garnet. In the same section, the writers also state that the charges in the pressure vessel were found to have lost weight due to the diffusion of vapour through "pin holes" in the platinum foil crucibles. The material carried by the vapour was deposited in the cooler parts of the apparatus and in so doing set up a concentration gradient in the vapour which promoted transport of further material.

MacKenzie (1960) states: "It is difficult to reconcile these observations ... (i.e. the leaching of silica by circulating vapour) with the idea that a major factor in the formation of granitic rocks is the transfer of material through the medium of water vapour or other volatiles" (p.383). He does not, however, suggest that the deposition of silica and feldspar forming materials would localise at some cooler region in the crust and it is this localisation which might be the cause of metasomatic granites. In the same article Mackenzie says: "Much has been written on the subject of the growth of large porphyroblasts of feldspar in xenoliths and in rocks of the contact zones of the granites and it is interesting to have experimental evidence that large porphyroblasts can grow in a relatively short time by the action of water vapour on solid silicates, provided that a composition gradient exists" (p.384). With the large microcline crystals developed in the granites in mind, the writer adds his assent to this statement.

It would seem fortunate that some do prefer the "crucibles and triangles and more complex geometry that seems to go with them" and others hold to the axiom "Let us go into the field ... for evidence of granitisation" (Read 1951) for they appear to the present writer, largely complementary.

Regarding field evidence, Read (1951) describes several examples of "ghost stratigraphy" all of them showing the resister bands of quartzite, metadolerite or limestone and it is interesting to note that the first two rock types are found on the Julianehaab Peninsula, within the granite. More recently Whitten (1960) has detected the palimpsestic stratigraphy within the Thor Granodiorite itself. This was achieved by a systematic and careful modal analysis of the granitic material, which indicated that the observed regular variations in composition of the xenoliths could be detected in the granodiorite also. Modal analysis of specimens from the older Porphyritic Granites of the Julianehaab District showed that a great deal of variation existed within these granites (Chapter 11) and this is thought to be the result of original variations within the parent rocks.

It is concluded that the Porphyritic Granites were generated largely in place by the introduction of potash, silica and possibly alumina and sodium, but as the composition of the original rock is unknown this cannot be stated with any certainty. In places, there was sufficient energy to make the granite mobile and there is no doubt that there was at least one period in which the rock was in a plastic state, as evidenced by the distortion of the Kuanitic dykes (Fig. 5.1).

The Sanerutian Granite and the related Porphyritic Aplitic Granite have been shown to be intrusive into the Porphyritic Granites and it is suggested that these granites are magmatic in origin. Further proof of this is the banding developed locally within these granites and their intrusive relationship to the Kuanitic dykes. Modal analysis data

(Chapter 11) shows that the Sanerutian and Porphyritic Aplitic Granites fall into the low temperature trough of the silica - alkali - feldspars - water system (Tuttle and Bowen 1958) indicating that they could have originated by the partial fusion (palingenesis) of the older granodioritic rocks. In this connection, petrographic and modal analysis data is used to show that the Euhedral Feldspar Phenocryst Granite has close affinities to the Porphyritic Granites, yet has been modified by the intrusion of the Sanerutian Granite which is immediately adjacent to it.

The recognition of the two granite generations, the older Ketilidian and the intrusive Sanerutian Granite was largely accomplished by the observations made on the Kuanitic dykes (Chapter 5). It has been shown that these rocks were intruded into the Ketilidian Granites and yet were extensively cut and invaded by the Sanerutian Granites. It is concluded that the metamorphism and distortion seen within the dykes was probably the result of the generation and emplacement of the younger granite.

Lying within the granites are dioritic amphibolites, a gabbro-norite pluton and unusual agmatitic bodies. The amphibolites it is suggested, represent metamorphosed plutons (one of which still possesses layering) and the gabbro-norite rocks are shown to be relics of a larger, differentiated mass, lying within an envelope of biotite amphibolites. These amphibolites were formed by the metamorphism and consequent alteration of the igneous rocks and petrographically, the mineralogical changes can be followed in detail.

Field evidence indicates that the dioritic amphibolites are older than the gabbro-norite body but no definite conclusion can be reached as to the relative ages of the latter pluton and the Porphyritic Granites, although it is of pre-Kuanitic age.

The agmatites, it is concluded, are probably pseudo-agmatites, formed by the interaction of a hot basic rock against a cooler acid magma. Definite conclusions regarding these bodies however, require more detailed field observations, for the implication of this feature is that there was an intrusion of ?dyke material early in Sanerutian times. This in turn shows that the Kuanitic and Sanerutian periods to some extent overlap.

The Garder period is represented on the Julianehaab Peninsula by a series of alkaline dykes, a camptonitic sill and large dolerite dykes. A detailed time sequence has been worked out using dyke and fault intersections and it demonstrated that many of the fault zones have moved at least twice.

A discussion of the alkali feldspar problem and data on feldspars from several granite types as well as alkali dyke and gneissic rocks, shows that there are chemical and structural differences within the feldspars of these rocks. Chemical analysis and X-ray analysis of these feldspars agree closely and measurement of the degree of ordering in these minerals indicates a long stable period, with "maximum microcline" closely approached by most of the granite microclines. The significance of the intermediate triclinicites of the dyke and gneiss microclines is also discussed. The values obtained during this study have been used to calculate the last temperature of recrystallisation of these rocks and it is suggested that the granitic rocks last crystallised between 400 and 500°C.

In conclusion: the area studied has provided an abundance of evidence of the "Granites and Granites" connotation of Read (1947) and the following quotation taken from the writings of the same person expresses clearly the opinions formulated in this study:

> "Just as I believe that there are some magmatic granites, so do I believe some metasomatic operations in plutonism go on in the wet as well as dry. There is no unique solution for the major problems of the plutonic rocks - we have to judge the evidence presented by each case."
>
> H.H. Read (1948)

CHAPTER 13

Appendix

The purpose of this appendix is to describe adequately the techniques and apparatus used in the present study.

1. Optical Measurements

Refractive indices have been measured on over 40 amphiboles and as many biotites. In addition a small number of nY values have been determined for pyroxenes from the gabbros, dolerites and alkaline rocks. In the case of the hornblendes the following "rules of thumb" helped in the identification of the appropriate orientations for measurements. The pleochroism is always a good indication of the section, as in the amphiboles studied a deep green or green blue indicates a section close to nZ whilst colourless or straw yellow is nX. In addition those sections generally have a large birefringence. Sections with straight extinction in most cases give nY and nZ as b = nY and in monoclinic crystals the angle between the crystallographic directions c and b is 90°. As is well known nX in hornblendes is the most unreliable indice to determine and this was soon apparent to the writer. A series of refractive index liquids were used for all measurements, these were checked using the Leitz-Jelly refractometer. The spacing between individual liquids was approximately 0.005 so that the accuracy of the measurements is considered to be ± 0.002 to 0.003. This was considered of sufficient accuracy as there were no chemical analyses available to justify more elaborate measuring techniques. nX and nZ are all quoted as nX' and nZ' indicating that this was the minimum (nX) or maximum (nZ) indice found. nY could be checked against the interference figure where the section is normal to an optic axis.

In the case of the alkali amphiboles, caution must be used in the use of pleochroic colours as an aid to the section orientation as the absorption scheme is reversed with the development of negative elongation. Unfortunately this is paralleled by the alkali pyroxenes so that pleochroism in this respect can not be used to differentiate the two.

Refractive index measurements on biotites were restricted to nZ'. Sections used were isotropic (001 flakes) with a centred acute bisectrix figure which was pseudo-uniaxial indicating that nZ and nY were almost equal. In most cases the true value for nZ was measured but the measurement of indices in this mineral is always bedevilled by their platey nature, often the edges are turned up and the Becke line is caused not by the difference between the mineral and the balsam but between two plates of biotite of slightly different orientation.

It is realised that this foregoing discussion is only elementary optical mineralogy but in the short experience of the writer numerous students of geology fail to grasp the fundamental concepts and as a consequence are prepared to spend considerable time on chemical analyses of minerals but never tackle the optics of the mineral concerned.

Optic Axial angles quoted in the foreging text have been measured on the Leitz five-axis stage and corrected for the difference between nY of the mineral and the refractive index of the glass hemisphere, using the graphical correction of Fedoroff (Winchell 1949).

Only values where both axes were seen are quoted. The accuracy of the optic axial angle measurements in the hornblendes is considered to be ± 1½°, but this must increase in the case of the microclines whose angle approaches 90°.

2. Separation of the Alkali Feldspars and X Ray Technique Used for their Identification

The method used in the present study is, like most separation techniques lengthy and frequently tedious, Initially, one feldspar was separated out, after two weeks work but with practice and refinements sufficient feldspar was extracted in 1½ days for analysis and X-ray investigations.

The granite is first crushed using a steel mortar and pestle (a mechanical crusher will speed up this process) and sieved through silk (bolting cloth) mesh. From this, two powders are obtained, one containing grains in the range 110 to 130 and the other of finer grain than 130. (This splitting quickens the process in the magnetic separator). The grains are washed with distilled water and the dust floated off. A rapid apparatus for this is that described by Frost (1959) and termed an elutriation tube. Unfortunately, the specific gravity differences of the minerals with the possible exception of the opaque material, is insufficient to cause any separating but it is very effective as a size grader and for washing off the dust which adheres to the surface of all the grains. If this apparatus is used, then the grains are washed afterwards in distilled water to remove alkali contamination by the water.

From the initial granite there are now two or three powders of varying grades which can be now transferred to the magnetic separator. Any magnetite (which is usually present in quantity) can be quickly separated off by setting a fairly high amperage and moving a folded piece of paper containing the grains across the magnet. The magnetite is pulled up the sides of the paper away from the rest of the powder and by deft manipulation, is then completely separated and packed away. The various grades are put into the machine one at a time. At first the magnet is tilted to a very high slope about the axis normal to the chute and a high amperage passed through it. Usually only a small tilt is required about the axis parallel to the chute as the light non magnetic grains fall quickly through whilst the hornblendes and some biotites are held back or are pulled to the magnetic side. In many cases, this one run is sufficient to produce a fairly clean white powder. If the separation is not complete the forward tilt of the magnet is decreased and the side tilt increased. At the same time, the flow of the powder is slowed to allow time for the magnet to act. It is difficult to give exact settings used as each rock has to be treated individually according to the properties of the amphibole and biotite. (In a few cases, biotite proved to be difficult to remove and the method of panning across a piece of paper was used (Hess 1960)).

The powders next are transferred to a bromoform-benzene bath of 3-4 cm. depth held in a deep crystallising dish. The density of the liquid is controlled by addition of benzene if too heavy or bromoform if too light. A tablet of known density is used to measure the density of the liquid which is kept close to the S.G. of albite (2.60 - 2.62). Small quantities of the powders are sprinkled into the dish, the liquid agitated covered and left. After 5 to 10 minutes, a scum of lighter material settles on the top and this is extracted by suction through a drawn out glass tube with a large reservoir on the end. The grains on top of the liquid are skimmed off together with some of the liquid within a matter of seconds and then these can be separated by passing through a fine filter paper. The liquid is then put back and a further agitation settling and extraction procedure commenced. When all one powder has been put through the liquid the heavier grains can be separated using a filter paper. The suction separator is a simple glass tube leading into a fairly large test tube which acts as a reservoir. All the joints are air tight to ensure good suction and the use of a small hole a few centimetres behind the orifice is an additional elaboration. (See Savolanti and Tyni 1960). This allows the suction to be controlled by the finger.

It is essential to ensure that after one feldspar type has been dealt with the suction apparatus is thoroughly cleaned, so that there is no contamination.

The separated powder can now be checked in a refractive index oil lower than balsam and the process repeated if there are still large quantities of quartz or plagioclase present. If not, the remaining few unwanted grains can be hand picked, using again a suction picker.

In recent papers, alternatives to bromoform-benzene mixtures have been proposed, such as acetylene tetrabromide - acetone(Barth 1956) and Dimethyl Sulfoxide-bromoform (Meyrowitz, Cuttita and Hickling 1959) but neither of these has been used in the present study.

X-ray Technique, for use on Alkali Feldspars

Owing to the lengthy procedure necessary to extract large quantities of alkali feldspar it was not practicable to use the standard mounting technique owing to the large amounts required. For the same reason the techniques described by Holland et al (1955) and Adams and Rowe (1954) were not used, although the reproducibility obtained by these writers using their techniques was much better than that using smear mounts. Adams and Rowe (1954) also give a useful summary of other mounting techniques whilst Buerger and Kennedy (1958) suggest the use of a specially cut quartz crystal to overcome dispersion effects in the glass mounting slip.

The use of an internal standard which could act as a check on the accuracy of measurement meant that normal "smear" mounts could be used with some degree of confidence. The feldspar is ground together with a very small quantity of potassium bromate (sufficient to cover the corner of a spatula) for about 1 - 2 minutes. As the strongest peak of the bromate is used, large quantities are unnecessary. The mixed material is transferred to a glass slip about 4 cm. long and put into a small pile at one end. Two or three drops of acetone are allowed to flow into the powder and immediately the spatula is rubbed over the mixture, so as to cover about one third of the glass slip. The movement must be quick and the spatula only moved four or five times and drawn away at the crucial moment when the mixture is becoming viscous. The technique although simple generally takes time to master, so it is desirable that some experimentation be carried out on a powder which is dispensable before using precious feldspar fractions. Measurement of the X-ray diffraction charts is carried out in the conventional manner (described by Chayes and MacKenzie 1957). The method is as follows: about 2/3 the way up, the peak is marked, and the position of each limb of the peak noted. From these values the average is obtained which gives the position of the peak with reference to its centre of gravity rather than the actual summit of the peak. Usually the two values, one obtained by averaging, the other by noting the peak summit, are extremely close.

During the work on the alkali feldspars it was necessary to heat the mineral to over 1000° C. This was done in a furnace with a narrow diameter tube the specimens were held in small platinum crucibles which were placed one inside the other. In this way, three powders could be dealt with at a time as there were four small crucibles available. These were placed in a larger crucible which gave the stability necessary when with-drawing from the furnace. It was found that a platinum wire, attached to the large crucible formed an effective though crude means of withdrawing the specimens.

. Selective Staining Techniques.

Alkali Feldspar.

Staining thin sections for identification of alkali feldspar was first described by Gabriel, Alton and Cox (1929), and modifications of this have been described by Keith (1939) and Chayes (1952). More recently Rosenblum (1956) has described a technique which is a refinement of the Chayes' method. Since then, several writers, in the course of descriptions of their own work have commented on the methods and described modifications. During the course of the work on modal analysis on the Greenland material the present writer has stained over 100 thin sections to facilitate rapid recognition and as a method of emphasising textural relationships.

Equipment: Sodium cobaltinitrite, hydrofluoric acid, Coplin jar, sand bath, tongs, protective clothing for use with the HF acid.

Method.

Thin sections must be dry, free from surface balsam or cementing material ("Durofix" is commonly used to hold the section together). If a cover slip is already on the section, this can be removed either by lifting off with a razor blade or by the use of heat (about 50°C.) The excess balsam is removed with methylated spirit and the "Durofix" by gentle rubbing with a cloth dipped in acetone.

The sand bath is warmed such that water held in a polythene dish reaches just over 20°C. The water is discarded and sufficient HF added to the dish to well cover the bottom. (The dish used in this case was the bottom half of an empty HF bottle, the diamter of which is sufficient to allow the slide to rest across the top without preventing the fumes reaching the rock slice.)

When heated through, the HF should fume and this may be encouraged by agitating the dish. When the white fumes are seen the slide is placed face down across the top of the dish and left there for 15 sec. If the HF is fuming strongly, it is better to remove the slide after 10 sec. A few seconds are allowed so that any condensation on the slide disappears and then placed in the Coplin jar containing a concentrated solution of sodium cobaltinitrite (A Coplin jar is a tall container in which a series of projecting ridges hold the slide vertically in place.) The solution is made up by mixing 60 gm. of sodium cobaltinitrite with 100 ml. of water, the cobaltinitrite being moderately easy to dissolve.

After 20 seconds the slide is removed from the staining media and rinsed to remove all the excess stain. The actual time in the stain controls the intensity of the yellow colouration. When washing caution must be exercised as prolonged rinsing removes the stain. At this stage if the stain has taken it will be obvious even on the wet section, which is best left to dry, face up on an absorbent cloth.

If the stain has not affected the slide, there are several reasons which should be checked over. The balsam and "Durofix" have not been removed from the section; the slide was placed face up over the acid; the HF was not fuming; the staining solution was either too old or too weak; the slide was wet when etched; the slide has been washed too long; there is no alkali feldspar in the section. (The latter possibility can of course be checked by also staining a rock which has well developed potash feldspar).

To avoid damaging the thin section it is important not to over-etch, as this causes the edges of the slice to curl up allowing the stain to creep under. In addition, immediately after etching, the surface of the slice is soft so contact with hard surfaces must be avoided. This is one of the advantages of the Coplin jar.

The procedure has to be modified when rock surfaces are stained, generally the slab is placed face down in contact with the acid for about 15 - 20 seconds and then the stain poured over the etched surface.

<u>**Nepheline**</u>

The staining technique was used for rock slabs only and the method is that described by Shand (1939) in which the surface is covered with phosphoric acid for 3 minutes, gently washed and then stained with a .25% solution of methylene blue for 1 minute. The result is a deep blue stain, which picks out nepheline phenocrysts preferentially.

<u>**Plagioclase**</u>

The method described by Bailey and Stevens (1960) unfortunately was published after the major part of this modal analysis data had been compiled. The application of this technique would undoubtedly facilitate identification in hand specimen and facilitate modal analysis procedure.

4. Infrared Absorption Techniques

The attempt to utilise infrared absorption as a technique for the determination of volume percentage in granites was initiated by the work of Lyon et.al(1959). The technique described there showed that it was possible to use infrared quantitatively to estimate quartz, alkali feldspar and plagioclase feldspar percentages. The literature on the subject is extensive especially in its application to chemical compounds which are non-silicates. Launer (1952) gives a good account of the theory of infrared techniques and deals especially with silicate minerals. Hunt and Turner (1953) give the characteristic peaks for quartz, orthoclase and albite, whilst Thompson and Wadsworth (1957) have attempted to use the technique for determination of plagioclase composition. An actual method of determining the proportions of several compounds in one mixture is given by Heigl et.al (1947) using "Base Line Densities". This method, appears to the writer to be the best technique to use on quantitative studies on granites.

Theory. The vibration frequencies of atoms in a solid are in the order of 10^{12} to 10^{14} cycles. As infrared rays have similar frequencies, then when these rays are passed through the solid some differential absorption takes place. The amount of absorption depends on the proximity of the vibration values of the infrared to those of the solid. As minerals are structurally dissimilar then their absorption spectra will also differ so that they can be identified.

Technique.

The silicate is presented as a compact pellet in combination with a halide (in this case KI) and then placed in the infrared spectrophotomer and scanned from about 5 to 16 microns (wavelength). The preparation of the pellet is all important as is the grinding of the sample, for it has been shown by Hunt et. al (1950) that if the powder is greater in size than 5 microns then the absorption bands are poorly defined due to the refraction of the infrared rays with a consequent scattering. This latter fact proved to be the major difficulty in the present investigation.

In preparing the pellet, the rock is ground to as fine a grain as possible (below 5 microns diameter is really necessary) either by hand or mechanically (there are several proprietary brands of machines which will carry out this operation effectively). 0.5 mg. is required for the pellet but it is more accurate to weigh out 2.0 mg. and add 1200 mg. KI, thoroughly mix and then take out one quarter of the powder. The mixing of the rock and halide should be done carefully with further grinding. The powder is next transferred to an all metal die, care being taken to ensure that all the powder goes into the die. A suction pump is used to evacuate the die for two minutes and then pressure applied (ten tons/sq. inch) for 3 minutes. This procedure must be standardised so that pellets of reproducible thickness can be produced. It is advisable to scan two pellets made from the same mixture to ensure that it homogeneous, and the pellet weighed immediately after.

The spectra of quartz, microcline and plagioclase together with that obtained on G1 are reproduced in fig. 13.1. It can be seen from these that quartz and microcline are distinctive but the plagioclase is not. This must be due in part to the failure of the grinding to reduce the powder below the standard size. In addition it was found that the height of the two peaks of quartz between 12.5 and 13 microns wavelength were unreliable, the absorption on one was never consistently greater than in the other. This again is attributed to the grinding failures.

If the grinding and pellet manufacture can be standardised there is little doubt that the infrared absorption spectra could prove to be a rapid and accurate method of determining the volume percentages of quartz, plagioclase and microcline in granites. Unfortunately the dark minerals, especially biotite do not give satisfactory absorption spectra so that the technique is not completely comprehensive.

The first stage in the procedure would be to make up a set of standards of known quantities of quartz, microcline and plagioclase and thus obtain a set of "templates". This would give a fairly accurate assessment of the proportions of the three minerals. More accuracy will be obtained by employing the "Base Line Densities" method of Heigl et.al (1847) in which an accuracy of ± 1% is claimed.

Several attempts were made to standardise the technique using samples of quartz, microcline, plagioclase and G 1 Granite (The Westerly Rhode Island Granite). Unfortunately the patterns obtained were not consistent, especially the quartz and G 1 and this is thought to be mainly due to to the failure to reduce the grain size below 5 microns.

5. Chemical Methods

The methods adopted for the partial analysis of the alkali feldspars, specimens of granite and gneiss are those described by Shapiro and Brannock (1956) and later modified by Riley (1958).

About 0.1 gm. alkali feldspar and 0.5 gm. rock sample (all previously dried at 105° C) were used for analysis. In the case of the minerals, K_2O and Na_2O only were determined. Unfortunately, sufficient material to carry out duplicate analysis was not available except in two cases. The granite specimens were all analysed twice for K_2O and Na_2O (two were also analysed for CaO) and the gneiss specimens were analysed twice for K_2O, Na_2O and CaO (with two exceptions in the case of CaO) K_2O and Na_2O were determined on the flame photometer and CaO by titration of Versene against murexide.

The ten alkali feldspar specimens used are described in Chapter 10, the granite specimens were the rocks from which the feldspars had been separated and the ten gneiss specimens were taken as representative of the various rock types developed along the length of the band.

The results of the partial chemical analysis are given in Table 13.1.

Table 13.1. Results of Partial Chemical Analysis.

Feldspar.

	% K_2O		% Na_2O		% CaO	
	(1)	(2)	(1)	(2)	(1)	(2)
23492	14.19		1.71			
23805	14.96		1.27			
23877	13.92		1.65			
42888	14.90		1.06			
42888P	13.38	13.76	1.93	2.00		
42896	14.85		1.24			
43062	13.71		1.85			
43063	13.62		1.96			
43064	13.68	13.47	2.17	2.12		
43069	13.83		1.84			

Granites.

	% K_2O		% Na_2O		% CaO	
	(1)	(2)	(1)	(2)	(1)	(2)
23492	3.98	3.94	4.50	4.44		
23805	4.18	4.34	3.59	3.55		
23877	4.75	4.81	3.71	3.75		
42888	4.32	4.21	3.58	3.54	3.18	
42896	3.12	3.11	4.39	4.34		
43062	4.73	4.74	4.09	4.04		
43063	4.80	4.74	4.06	3.92		
43064	4.77	4.78	4.21	4.40		
43069	4.69	4.87	4.06	4.08	3.15	

Gneisses.

	% K_2O		% Na_2O		% CaO		Description
	(1)	(2)	(1)	(2)	(1)	(2)	
42979	3.08	3.07	4.91	4.95	4.39		Acid gneiss
43001	2.56	2.45	4.44	4.44	6.17	6.31	Gneiss w.acid strks.
43002'	4.73	4.53	3.35	3.33	6.52	6.59	Acid vein
43002	2.57	2.67	5.01	5.05	4.76	4.60	Gneiss,no vein
43004	2.77	2.73	3.06	2.95	7.36	7.10	Gneiss
43027'	2.10	2.13	4.11	4.07	6.52	6.32	Gneiss w.vein
43027	1.87	1.92	3.95	4.07	6.56	6.11	Gneiss,no vein
43028	3.18	3.18	3.87	3.82	5.39	5.35	Gneiss w.veins
43029	2.00	1.94	3.13	3.01	7.28		Gneiss
43087	3.35	3.37	2.39	2.40	6.09	6.06	Banded gneiss

6. Photomicrographs

All the photomicrographs in this thesis were taken by the author. The camera used was a single lens reflex (Edixa Reflex B) and focussing was carried out on the ground glass screen using the eye magnifier which was built into the camera. The camera body only was used and the optical system was that of the microscope. Planar eyepieces were used (The Cooke-Troughton & Simms "Complan" x10 and the Leitz "Periplan" x8). Most of the photographs were taken either with the Leitz 3.2x or the C.T. & S. 5x objectives. Both these show some distortion around the periphery of the photograph but of the lenses available these two were found to show this to the least degree.

The camera body, together with four accessory rings, was attached to the tube of the microscope by a simple adaptor which clamped onto the microscope just below the eyepiece. The best results are obtained when the field iris on the microscope is stopped about 2/3 down and the illumination (a high intensity lamp) is fully open. It may be necessary to remove the upper lens of the condenser to fully illuminate the microscope field.

The film used was a slow, fine grained type (Adox film K.B,14) with a speed rating of about Din 14. Exposure times using this film and camera position were determined by trial. For plane polarised light, with the iris closed down, approximately 2 seconds and in polarised light approximately 4 seconds exposure was given.

The film was developed in Neofin Blue which was made up as follows:- (Windisch 1956).

Solution A - 10 gm. Metol
50 gm. Sodium Sulfite (anhydrous)
1,000 c.c. Water (Boiled)

Solution B - 50 gm. Anhydrous Sodium Carbonate
1,000 c.c. Water (Boiled)

25 c.c. of Solution A and 25 c.c. of Solution B are added to 250 c.c. of water, and the film developed for 9 minutes at 18°C. Fixing and washing procedure used were of standard techniques, although a short fixing time helps to keep grain at a low level (about 5 minutes).

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